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Science and Technology Review
Lawrence Livermore National Laboratory
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Science & Technology REVIEW

January
February 1996

Lawrence
Livermore
National
Laboratory

Groundwater Cleanup with Hydrostratigraphic Analysis

Also in this issue:
Micropower Impulse Radar

About the Cover

Returning groundwater to its natural state is high on priority lists at Lawrence Livermore National Laboratory. Our feature article this month describes how groundwater cleanup at the Laboratory is progressing faster than anticipated, thanks to new developments in hydrostratigraphic analysis. This multidisciplinary "smart pump-and-treat" approach maximizes extraction as it links data on physical properties of sediments, groundwater, and contaminants. This all translates into fewer wells, less time, and lower cost. We will be sharing our comprehensive cleanup know-how with other environmental restoration projects.

Cover photos: James Stoots

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About the Review

The Lawrence Livermore National Laboratory, operated by the University of California for the United States Department of Energy, was established in 1952 to do research on nuclear weapons and magnetic fusion energy. *Science and Technology Review* (formerly *Energy and Technology Review*) is published ten times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments, particularly in the Laboratory's core mission areas—global security, energy and the environment, and bioscience and biotechnology. 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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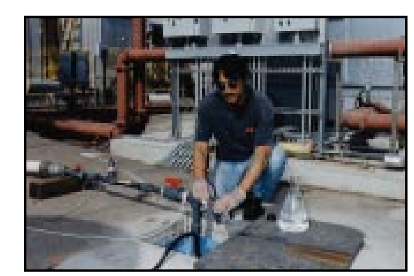

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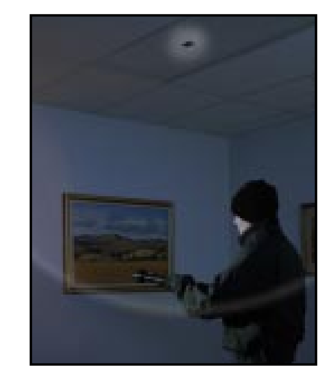

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Collaboration for advanced tissue welding system

Livermore and Conversion Energy Enterprises (CEE) of Spring Valley, New York, have embarked on a cooperative venture aimed at developing a prototype automatic medical system for laser welding of tissue. LLNL will lend its expertise in lasers, computers, optics, and microtool development.

Tissue welding would be faster than traditional methods, could be used in areas difficult to reach, would make better joints, speed healing, and decrease risk of complications.

Current methods for binding tissue together are stitching and stapling. While functional, both can allow puckering around the wound and seepage of fluids. For some difficult-to-get-at locations, stitching or stapling is just not possible.

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Blood-gas monitoring system under development

The Laboratory and Novametrix Medical Systems Inc. of Wallingford, Connecticut, are seeking to develop a quick, easy, noninvasive way to monitor blood for substances such as oxygen, carbon dioxide, anesthesia, or alcohol.

Important for monitoring the condition of patients, measurements of such gases in the bloodstream are used during surgery or routinely throughout the day.

The objective of the collaboration is to develop a way to use light projected through skin to read blood gases more accurately. In conducting the work, LLNL expertise in optics, fiber optics, and signal processing will be combined with Novametrix's experience in developing blood gas monitoring instruments.

Contact: Howard Nathel (510) 423-3262 (hnathel1@llnl.gov).

Optical system for carpal tunnel surgery

The Laboratory has teamed with Envision Medical Corp., a manufacturer of medical video camera systems, located in Santa Barbara, California, to develop technology that will help surgeons to perform the endoscopic carpal tunnel release procedure.

So far, endoscopic surgery to correct hand problems due to repetitive stress has had limited success. One problem is that the surgeon cannot get an adequate view of the interior of the hand. The joint project seeks to produce a better endoscopic camera video system for minimally invasive surgeries such as carpal tunnel surgery.

The Cooperative Research and Development Agreement (CRADA) will make use of LLNL's knowledge of optics, sensors, computer imaging, and microtools to improve surgical success and to reduce both post-operative pain and the current national yearly price tag for direct and indirect costs of carpal tunnel syndrome—estimated at $10 to $15 billion.

Contacts: Robert Van Vorhis (510) 423-1693 (rlvv@llnl.gov) or Steve Burastero (510) 424-4506 (burastero1@llnl.gov).

Mammoth Mountain mystery unraveling

Working with the U.S. Geological Survey (USGS), Laboratory scientists have been helping unravel the mystery of the death of trees in California's Mammoth Mountain area and the near-asphyxiation of a Forest Service Ranger in 1990.

In the August 24, 1995, issue of *Nature* magazine, members of the USGS group and Lab scientist John Southon wrote that they believe seismic activity deep inside the mountain is causing emissions of magmatic carbon dioxide (CO_2) similar to those observed in other volcanic areas like Mt. Etna and Mt. Vesuvius.

Southon, a member of Livermore's Center for Mass Spectrometry, said his principal role in the investigation has been to provide the expertise of LLNL's radiocarbon group to confirm the conclusions reached by the primary USGS researchers.

Lab scientists, for example, aided the USGS team by distinguishing emissions of magmatic CO_2 from those resulting from naturally occurring biological activity. Recently Laura Hainsworth, a post-doctoral fellow in the group, has been using carbon-14 measurements on individual rings in the tree remains to determine whether there is a correlation between CO_2 emissions and seismic activity at Mammoth. She plans to extend this work to other volcanic sites like Mt. St. Helens.

Contact: John Southon (510) 423-4226 (southon1@llnl.gov).

CD-ROM package aids breast cancer researchers

The Laboratory has assembled the first CD-ROM library of mammogram images that is designed to help researchers perfect computer software for detecting one early sign of breast cancer.

The 12-CD package contains digitized images of mammograms exhibiting microcalcifications, an early cancer indicator that can be very small and difficult to see. The Laboratory's high-end digitizer was able to produce digital images at a resolution of 35 micrometers.

The mammograms include documented conditions ranging from harmless cysts to malignant tumors. Because the CD images are of known diagnosed conditions, breast cancer researchers can process the images with their computers to see whether their programs can detect the actual calcifications in the CD mammograms.

Each image in the CD-ROM library, developed in collaboration with the University of California Medical Center in San Francisco, is accompanied by a matching image that marks the exact location and extent of any lesions.

Contact: Laura Mascio (510) 422-0924 (mammoo-db-help@llnl.gov).

True 3-D motion computer imaging developed

Livermore computer scientists have developed the next step in computer imaging—true 3-D motion imaging. The system, dubbed "CyberSight," can digitally capture and display moving 3-D subjects to a degree of realism never before achieved.

CyberSight works by first capturing a subject on video using a stereo camera system. Instead of placing markers on the subject as reference points (as is done in current motion-capturing systems), line patterns are projected onto the subject. The pattern data is picked up by the cameras and fed to a computer, which transforms the data into complete surface reconstructions, in motion and high resolution, to exact measurements.

The Laboratory is seeking opportunities to commercialize the CyberSight technology and to expand it into different applications through licensing or joint development. Possible uses for CyberSight range from greater cinematic realism to improved control of industrial robots. CyberSight has potential applications in the medical area, for example, to analyze the movement of patients with cerebral palsy or to assist surgeons in the effects of plastic surgery. In security applications, CyberSight might provide a reliable facial recognition system. Defense applications might involve 3-D modeling of material deformation under stress or determining proper fit for military equipment, such as gas masks.

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Subatomic solution sought for "dark matter" mystery

A search is under way at Livermore for the answer to one of the most profound mysteries of the universe: the nature of dark matter. Dark matter constitutes as much as 90 to 99% of the universe. Astrophysicists know it is there because its gravitational pull keeps our own Milky Way galaxy from flying apart. But positively identifying the invisible material is another story. Theories range from large planet-like objects to microscopic axions.

At Livermore, a powerful electromagnet is being used to search for axions. If the existence of axions is confirmed, the finding would have a sudden and dramatic impact on how astrophysicists worldwide view the basic construct of the universe.

If axions do exist, they likely weigh a billion and perhaps a trillion times less than the lightest known particle, the electron. Furthermore, their interaction with matter and radiation is expected to be extraordinarily weak, which has posed a major challenge in even conceiving of an experiment that could detect them, let alone carry out such a search.

The research team's solution is a specially made 4-m-high, 12-ton magnet that has been lowered into a cylindrical hole in the floor of a secluded building at the Laboratory. The strong magnetic field will stimulate the axions to convert into a very weak microwave signal in a tunable microwave cavity resonator with state-of-the-art cryogenic amplifiers. Searching for the axion is very similar to tuning one's car radio very slowly, looking for a weak station.

The experiment is a collaboration of Livermore, Massachusetts Institute of Technology, University of Florida, UC Berkeley, Lawrence Berkeley National Laboratory, University of Chicago, Fermi National Accelerator Laboratory, and Institute for Nuclear Research of the Russian Academy of Sciences in Moscow. Approved for construction in January 1993, the $1.4-million experiment took more than two years to assemble. Researchers began taking data in November 1995.

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Allenby, Dimolitsas join LLNL management team

Braden Allenby has joined the Laboratory in a two-year term appointment to lead LLNL's new strategic initiative of long-range unified energy and environmental programs. Allenby is a leading researcher on industrial ecology, the science of balancing ecosystems with industrial systems.

Director Bruce Tarter said that Allenby will help the Laboratory create a "strategic, integrating framework for long-range program and resource development" for the Laboratory's energy and environmental programs.

Allenby comes to Livermore from AT&T, where he was vice president of research for technology and environment. After his two-year tenure at Livermore as director of energy and environmental systems, he will return to AT&T's global manufacturing and engineering organization.

Spiros Dimolitsas has joined the Laboratory as Associate Director for Engineering. Dimolitsas, formerly with COMSAT, held a series of positions of increasing responsibility in areas of signal processing and noise filtering; speech, image, and data transmission; network quality; and communications systems engineering. His most recent COMSAT assignment was director of program development.

In announcing the appointment, Director Tarter cited Dimolitsas' COMSAT experience as particularly relevant to the Laboratory. Tarter commented, "His company, like Livermore and institutions elsewhere, is undergoing serious self-examination of mission and methods.

"He has had experience with significant changes in funding expectations and resource allocations. He has responded with decisions and practices that strengthened the company and raised revenue while maintaining a focus on the value of the individual employee."

Patents and Awards

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

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Joe W. Gray Daniel Pinkel	**Methods for Chromosome-Specific Staining** U.S. Patent 5,447,841; September 5, 1995	A method of staining target chromosomal DNA, employing labeled nucleic acid, blocking nucleic acid and chromosomal DNA in in-situ hybridization. Labeled repetitive segments are substantially blocked from binding to the chromosomal DNA, while hybridization of unique segments within the labeled nucleic acid to the chromosomal DNA is allowed, permitting detection of hybridized labeled nucleic acid containing unique segments.
Daniel L. Birx Phillip A. Arnold Don G. Ball Edward G. Cook	**Air and Water Cooled Modulator** U.S. Patent 5,448,580; September 5, 1995	A compact, reliable, high-average-power magnetic compression circuit having a lifetime greater than 5,000 hours, with an average power greater than 8 kW, which can deliver at least 20-kV pulses of less than a 200-ns duration at a repetition rate greater than 4 kHz and peak power output of at least 5 MW. A solid-state switched magnetic compression circuit uses printed circuit board technology with a physical layout that provides sufficient air and water cooling.
William D. Daily Abelardo L. Ramirez Robin L. Newmark Kent Udell Harley M. Buettner Roger D. Aines	**Dynamic Underground Stripping: Steam and Electric Heating for In Situ Decontamination of Soils and Groundwater** U.S. Patent 5,449,251; September 12, 1995	A process for removing localized underground contamination of volatile organic compounds by heating a contaminated area using steam injection and electric currents to vaporize the contaminants, and then removing the migrating subsurface fluids and vapor by vacuum extraction and liquid pumping. Injection and extraction wells are constructed within or around the periphery of the contaminated area.
Daniel D. Dietrich Robert F. Keville	**Mini Ion Trap Mass Spectrometer** U.S. Patent 5,451,781; September 19, 1995	A miniature ion cyclotron resonance (ICR) mass spectrometer that combines a unique electron source and mass analyzer/detector in a single device, and is mounted into a hollow permanent magnet, for detecting environmental pollutants or illicit substances. Its low power consumption makes portability possible.
Alan D. Conder Ronald E. Haigh Keith F. Hugenberg	**Triggerable Electro-Optic Amplitude Modulator Bias Stabilizer for Integrated Optical Devices** U.S. Patent 5,453,608; September 26, 1995	An apparatus for applying a DC bias modulation to a conventional integrated optical Mach-Zehnder electro-optic modulator. A DC bias box contains four basic interrelated circuits: a trigger circuit, a ramp and hold circuit, a negative peak detection circuit, and an adjustable delay circuit. The DC bias box ramps the DC bias along a transfer function curve to any desired phase or point of operation.

Awards

The **American Physical Society** has bestowed two awards for physics excellence to groups of Laboratory employees. The first, for **excellence in plasma physics** is shared by a nine-person team that includes **Steve Haan, Dave Munro, and Steve Weber** from X Division in the Physics and Space Technology Directorate; **Russell Wallace** of the Chemistry and Materials Science Directorate; **Gail Glendinning, Joseph Kilkenny, and Bruce Remington** of the Inertial Confinement Fusion (ICF) Program in the Lasers Directorate; and two University of Rochester scientists. The second, the **Simon Ramo Award for outstanding doctoral thesis research**, has been awarded to **Chris Decker**, a post-doctorate staff member of X Division.

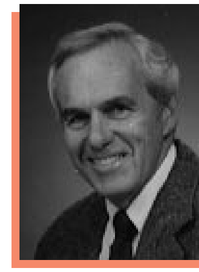
For his work in providing a means for more reliable mammography, **José Hernández** has been cited for **Outstanding Technical Contribution** from the **Hispanic Engineer National Achievement Awards**. Hernández, an electrical engineer at the Laboratory, was instrumental in the development of a full-field digital mammography system.

Brian MacGowan and Bruce Remington have been made **fellows of the American Physical Society** in recognition of their outstanding contributions to physics. Their fellowships come from the Division of Plasma Physics and cite MacGowan's work in short-wavelength x-ray lasers and Remington's experiments in Rayleigh–Taylor instability.

The American Physical Society also honored **Luiz Da Silva** with the **Nuclear and Plasma Sciences Society Early Achievement Award** from the Institute of Electrical and Electronics Engineers. Da Silva was cited for his work in the development of x-ray lasers and their applications to probing plasmas and biological imaging.

Marriann Silveira, Tom Boock, and Al Huntley of the Laboratory's Energy Management Program and **Clark Scott,** Water Shop supervisor, journeyed to Washington, D.C., recently to receive **Federal Energy and Water Management Awards** for their respective groups.

Commentary on Environmental Restoration



Harry Galles
Head, Environmental Protection Department

SINCE contaminants were first detected in groundwater and soil at the Laboratory, we have been working to find the best ways to mitigate the problem, always with the goal of doing the job in the shortest time possible in the most cost-effective way possible. We are fortunate to have at the Laboratory a multidisciplinary staff accustomed not only to taking a science-based approach to problem solving but also to being innovative in finding and pursuing creative solutions to difficult problems.

We began using standard environmental restoration industry methods to attack the groundwater contamination at Livermore. But in our search for more cost-effective solutions to accomplish the cleanup, we have developed and are applying several new and modified tools to attack the problem. Most of these tools can be applied to remediation projects anywhere.

Hydrostratigraphic analysis, derived from practices in the oil and gas industry, is a relatively new tool in groundwater applications. We have found it useful for characterizing the site—for organizing our accumulated data on geology, hydraulics, and chemistry into a three-dimensional, conceptual model of our subsurface. Computerized groundwater modeling is another tool, which helps us to forecast how the subsurface will respond to various remediation treatments. It also helps us to optimize cleanup efforts—with the goal of reducing total cleanup costs. While groundwater modeling is by no means new, we have developed several new models with interactive visualization software, which can be used by groundwater remediation planners at virtually any site.

The standard method for removing contaminants from groundwater is "pump-and-treat," which involves pumping contaminated groundwater to the subsurface and then treating it to remove the contaminants. By applying our modeling capabilities and by managing our extraction well field efficiently, we have developed a "smart" pump-and-treat system that can clean groundwater to below regulatory-mandated concentrations significantly faster than the conventional application of the pump-and-treat method.

Congressional budgetary pressure plus the necessity to remediate environmental contamination require that innovative, cost-effective methods for environmental restoration be developed to address environmental problems effectively and affordably. One such method is dynamic underground stripping (see *Energy & Technology Review*, April 1994), which we developed in collaboration with UC Berkeley. We used it to remove gasoline from groundwater and soil. Electrical heating and injected steam mobilize the gasoline contaminants for extraction and subsequent above-ground treatment. This demonstration project took less than a year to remove approximately 7,600 gallons of gasoline that would have taken decades to remove at a significantly higher cost with conventional technology. We are also evaluating other in-situ bioremediation and enhanced thermal treatment methods for cleanup operations here.

As this work has progressed over the 13 years since contamination was first discovered at Livermore, we have been learning. We know much more about the site than we did in 1983, plus we also have learned about the various steps in the planning and cleanup process. The characterization phase—during which we drilled many dozens of monitor wells, took hundreds of soil and groundwater samples, and collected a variety of other valuable data—would today proceed differently because we learned how to more effectively characterize a contaminated site. We have advanced the state of the art of groundwater modeling and use it to greatly shorten cleanup times, making both conventional and innovative groundwater remediation methods less costly. We have developed a better understanding of and techniques for removing volatile organic compounds, fuel hydrocarbons, and other hazardous materials from soil and groundwater.

Our dedicated team of scientists, engineers, and technicians is successfully pursuing a complicated groundwater remediation program at Livermore. We want to give this country a return on its investment in the Laboratory by bringing the site cleanups to completion as cost effectively and as quickly as possible, and then transferring our accumulated know-how to industry so it can be put to use on other environmental restoration projects.

Groundwater Cleanup Using Hydrostratigraphic Analysis

Individual contaminant plumes are effectively targeted for hydraulic capture and cleanup by a Livermore team of researchers. Their use of hydrostratigraphic analysis integrates chemical, hydraulic, geologic, and geophysical data, which results in a three-dimensional conceptual model of the subsurface area.

A world-renowned center of applied scientific research, Lawrence Livermore National Laboratory is the source of some of the most complete characterizations of nature, from the human chromosome to the atom. Yet few people realize that the Livermore site itself is also one of the most well-characterized sites in the U.S., if not the world.

Some 30 hydrogeological cross sections for the site recently have been prepared using a newly developed methodology that incorporates data from over 500 boreholes drilled as part of the Laboratory's groundwater cleanup program. The cross sections reveal a complex maze of geological zones underlying the Livermore site and beyond. In depicting various underground geologic strata, the cross sections are of more than passing academic interest. They show the location of underground contaminants and the distribution of extraction and monitoring wells constructed to monitor, remove, and treat those contaminants. The overall data also show the nature of the interconnectedness of the strata and migration of contaminants within them.

What's more, thanks to an innovative groundwater cleanup strategy known as "smart pump-and-treat," the cross sections measured over the past seven years reveal the indisputable shrinkage and hydraulic control of plumes of contaminants called volatile organic compounds (VOCs) that once posed a risk to local municipal water supplies (Figure 1).

Decisions and Visualizations

The cross sections are the result of a process, called hydrostratigraphic analysis, that allows scientists to integrate chemical, hydraulic, and geologic data into a detailed, three-dimensional model of the subsurface environment.[1] As an integral part of smart pump-and-treat for the past two years, the process demonstrates that the Livermore groundwater cleanup efforts are being conducted in a comprehensive and cost-effective manner. The success of the process is drawing inquiries from federal agencies and other national laboratories eager for more information on better ways to characterize, monitor, and clean up groundwater contamination at Superfund sites across the U.S.

Hydrostratigraphic analysis is proving to be an effective management tool for making better-informed and more timely decisions regarding groundwater cleanup. These decisions include positioning and designing extraction and monitoring wells, prioritizing the construction and phased startup of remediation systems, managing the extraction of subsurface contaminants, finding the sources of past contaminant releases, and evaluating the effectiveness of the remediation systems.

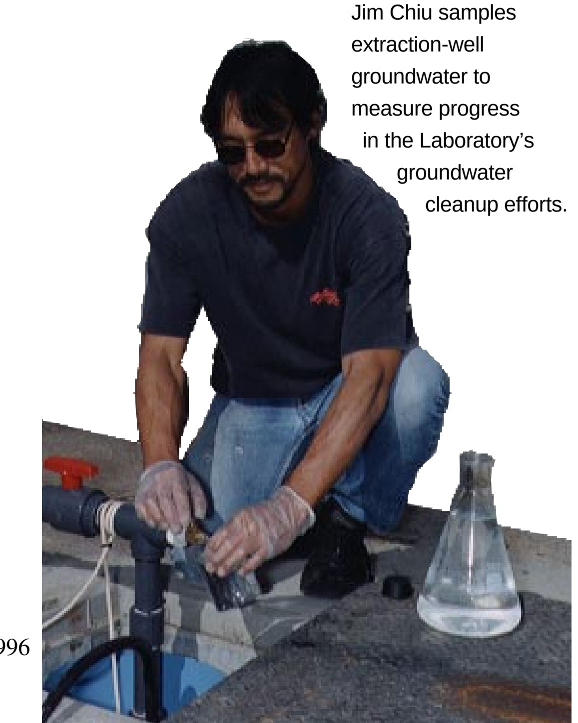
The technique is also an effective visualization tool for presenting complex geologic and groundwater remediation issues to the Department of Energy, federal and state regulatory agencies, and the local Tri-Valley community. In addition, hydrostratigraphic analysis forms the basis of two- and three-dimensional computer simulations of groundwater contaminant transport using advanced physics codes to estimate cleanup times, costs, and design parameters. Finally, it should prove to be a valuable method to evaluate the effectiveness of innovative cleanup technologies, such as dynamic underground stripping.

Before implementing hydrostratigraphic analysis in early 1994, Laboratory environmental experts had constructed numerous maps and cross sections showing the distribution of hazardous materials known to be residing in some of the complex geological strata underlying the site[2,3] (see sidebar on p. 10). Although these maps formed a solid basis for planning the groundwater cleanup at LLNL, they could not be directly used to implement cleanup because the subsurface contaminant pathways were not shown or well understood. Hydrostratigraphic analysis is an extension of this previous hydrogeologic work performed at LLNL.[4,5] The contaminants of greatest concern are two VOCs dissolved in water some 50 to 200 feet* below the ground. They are primarily the industrial solvents perchloroethylene (PCE) and trichloroethylene (TCE).

Pump-and-Treat

Although the estimated volume of the solvents in the subsurface is only about 200 gallons, the concentrations in groundwater range up to about 10 parts per million in some areas (state and

*Hydrogeologic measurements use U.S. units rather than metric.



Jim Chiu samples extraction-well groundwater to measure progress in the Laboratory's groundwater cleanup efforts.

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federal maximum contaminant levels for the two compounds are 5 parts per billion). All together, past discharges of these materials from a number of areas at the site have contaminated approximately 3 billion gallons of groundwater below the Laboratory and immediate vicinity covering approximately a square mile.

The VOCs formed several underground plumes below the Laboratory, some of which have traveled slowly off site underneath Vasco Road and beyond the Laboratory's western boundary. Because of estimated migration paths and flow rates, the plumes were judged to pose a potential risk to municipal water supply wells located about 1.5 miles to the west. The U.S. Environmental Protection Agency evaluated the contamination using a Hazard Ranking Scoring System and decided to list the site on the National Priorities List (Superfund). As a result, the Laboratory was charged by state and federal environmental regulatory agencies with cleaning up the contaminated groundwater and stopping the westward migration of the plumes.

The primary remediation technology in use at the Livermore site is groundwater pump-and-treat. This technique uses a network of extraction wells that pump contaminated groundwater to the surface for treatment to remove contaminants. A network of monitoring wells is used to track the effects of groundwater extraction and measure how effectively the Laboratory is hydraulically capturing and cleaning up the plumes. Minimizing the cost of groundwater cleanup using pump-and-treat technology requires a thorough understanding of the hydrogeologic factors that control the flow and transport of contaminants in the heterogeneous subsurface.[6]

Improving the Maps

"In the early years of the environmental restoration program, emphasis was placed on locating source areas and identifying strata that needed to be cleaned up, not necessarily on the logistics of how to clean them up," notes LLNL hydrogeology team leader Rick Blake. "As we planned cleanup and began implementation, we realized that more needed to be understood about how the contaminated strata are interconnected. What we lacked was a site-wide road map of the subsurface, which would allow us to target specific contaminated zones and enable us to place our extraction wells at optimum locations to meet our cleanup objectives."

In the initial phases of the cleanup project, Livermore experts used two-dimensional maps and cross sections plus scientific and engineering estimates as they placed wells throughout the site and off site (Figure 2). Although these hydrogeologic cross sections showed individual permeable zones in detail (see Figure 3), "we realized that if we could group these zones into units that are hydraulically interconnected, we could simplify implementation," explained Blake.

The Livermore site and surrounding vicinity are underlain by a complex network of alluvial silts, clays, sands, and gravels that are tens to hundreds of feet thick. Known as the Upper and Lower Livermore Formations, these formations were deposited by multiple streams within the past 2 million years. The sand and gravel channels within these formations serve as migration pathways for various contaminants. Compounding this complexity, the shifting of tectonic plates underlying California has tilted the geological strata, causing groundwater and any dissolved contaminants to travel westward at a rate of about 70 feet per year.

Multidisciplinary Approach

Because of its complexity, the Livermore subsurface cannot be fully characterized using geology alone. "We knew we had to take a more multidisciplinary approach to get the job done," notes Blake.

Together with Weiss Associates hydrogeologists Michael Maley and Charles Noyes, Blake developed the hydrostratigraphic framework for the site. A geologist with 15 years of experience in the oil and gas industry, Blake was familiar with stratigraphic analysis used by oil and gas companies for decades in their search for new accumulations of petroleum and natural gas. "The key to unlocking the details of the strata underneath the Laboratory

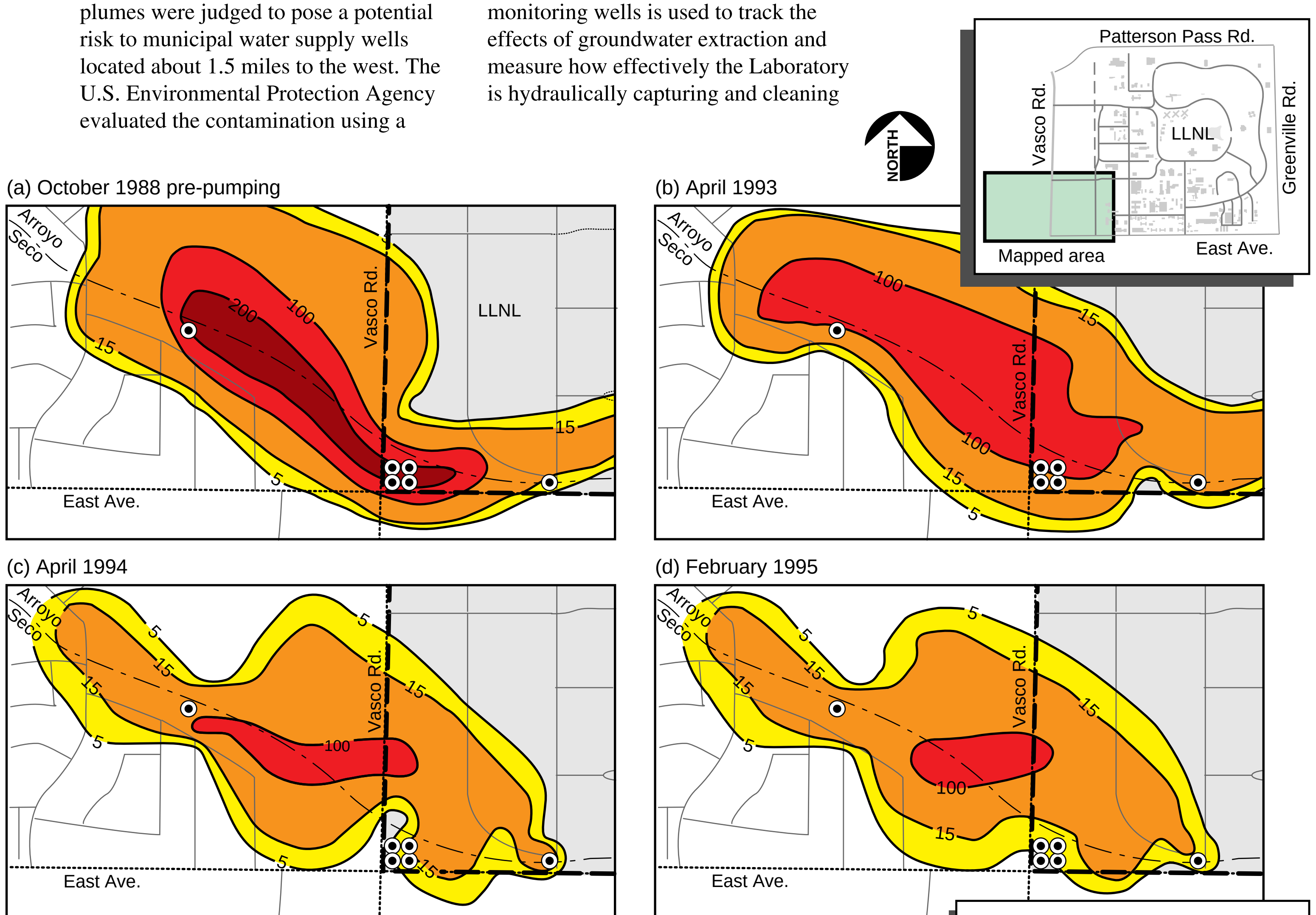


Figure 1. Concentration maps of the western edge of LLNL illustrate the decrease in PCE concentrations over six and a half years resulting from hydraulic capture and PCE mass removal at extraction well locations.

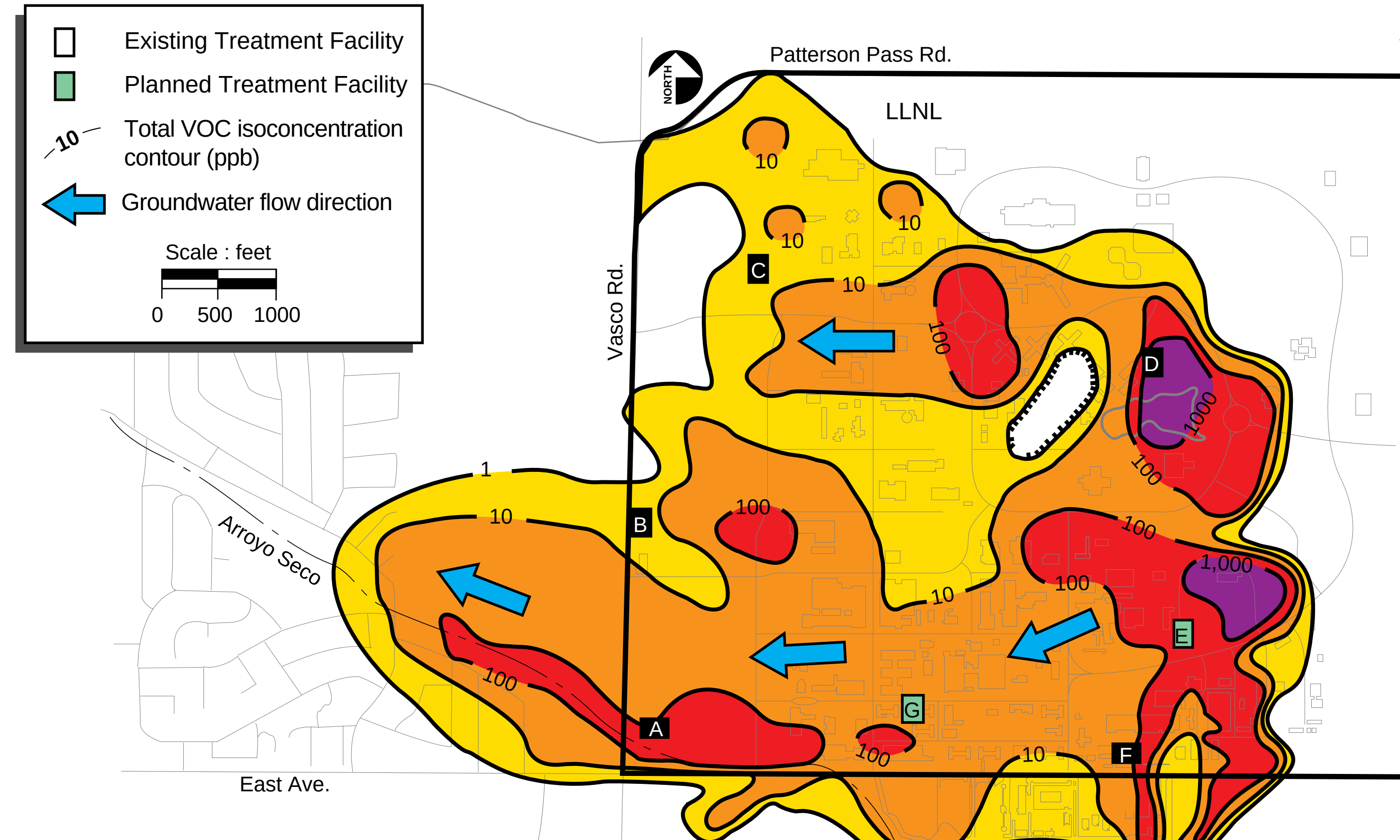


Figure 2. This type of two-dimensional contaminant plume map was used initially for preliminary planning of LLNL pump-and-treat groundwater cleanup.

Origins of Cleanup Efforts

Much of the groundwater contamination underlying the Livermore site originated in the early 1940s when the U.S. Navy converted some 640 acres from agricultural use into a flight-training base and aircraft assembly and repair facility. Most of the contaminant releases from this time are believed to have been solvents used to clean airplanes, their engines, and associated parts. Smaller releases of gasoline, diesel fuel, and other compounds are also known to have occurred.

From 1950 to 1954, California Research and Development Co., a subsidiary of Standard Oil, occupied the southeastern portion of the site. This marked the beginning of testing with radioactive materials at the site and probably the first releases of small amounts of tritium (a radioactive isotope of hydrogen) to the environment.

Since the Laboratory's founding in 1952, additional releases are attributed to localized spills, landfills, disposal pits, broken sewer lines and pipes, and leaking tanks. Releases of solvents were the most prevalent, although small releases of polychlorinated biphenyls (PCBs), metals, radionuclides (primarily tritium), gasoline, and pesticides also occurred.

In 1983, LLNL personnel detected VOCs (volatile organic compounds) on site and in domestic water supply wells just west of the site that were in concentrations above maximum contaminant levels (MCLs). The Laboratory immediately informed the regulatory agencies and owners of private wells nearby and provided city water hookups to affected residences. The State of California issued a regulatory order in 1984 to investigate groundwater quality underlying LLNL and off site, ultimately leading to investigation of more than 350 potential release sites.

Because the VOC concentrations exceed drinking water standards and are in groundwater within 1.5 miles of a municipal water supply, the U.S. Environmental Protection Agency placed LLNL on the National Priorities List (Superfund) in 1987 for cleanup. Other environmental problems, such as leaking underground tanks and closure of hazardous waste management facilities, are managed under this program, too. In response, the Laboratory drew up a comprehensive remedial action plan, which was reviewed by regulatory agencies, the DOE, and the public. Where MCLs vary between state and federal regulations, the Laboratory must observe the stricter level.

Pilot groundwater cleanup began in fiscal year 1989. To date, more than 200 million gallons of VOC-contaminated groundwater have been extracted, treated, and then either put into a recharge basin or reused.

The Laboratory's Environmental Restoration Division, part of the Environmental Protection Department, is the focal point for the development of restoration and waste treatment techniques needed for environmental cleanup on site and off site. For efficient soil and groundwater cleanup, program scientists and engineers have developed and are using advanced sampling, monitoring, and two- and three-dimensional modeling techniques for underground cleanup operations. Hydrostratigraphic analysis provides the necessary framework to successfully carry out this effort. This so-called "smart" approach saves time and money compared to conventional pump-and-treat groundwater cleanup programs. The Laboratory also has evaluated treatment methods for VOCs in groundwater, including ultraviolet light/hydrogen peroxide oxidation, air stripping, and solar detoxification. Steam flooding and soil heating were conducted to remediate a gasoline spill from the 1970s.

was to integrate the oil and gas industry technology with hydrogeologic approaches used in the environmental cleanup industry," he says.

Hydrostratigraphic analysis accomplishes this task by linking data on physical properties of the sediments, groundwater, and contaminants from extraction and monitoring wells. This information includes:

- Descriptions of geologic formations and their physical properties, including borehole geophysical logs, in which electrical currents and gamma radiation detectors create distinct signatures revealing the nature of subsurface rock and sediment types and their contained fluids.
- Hydraulic test data, including evaluation of the response of observation wells during aquifer pumping tests to determine the extent of hydraulic communication, or water movement, from one geologic stratum to another.
- Groundwater elevation data measured in monitoring wells for evaluating groundwater flow directions.
- VOC concentrations in soil and groundwater for mapping contaminant distributions.[7]
- Plume "signatures" based on the ratios of VOC concentrations, which can be used to trace an individual contaminant plume back to its source area.

Since 1984, these data have been collected at LLNL by staff and environmental consultants using rigorous standard operating procedures as well as quality assurance and control protocols. Strict adherence to these procedures has resulted in an enormous database of high-quality environmental data concerning the site.

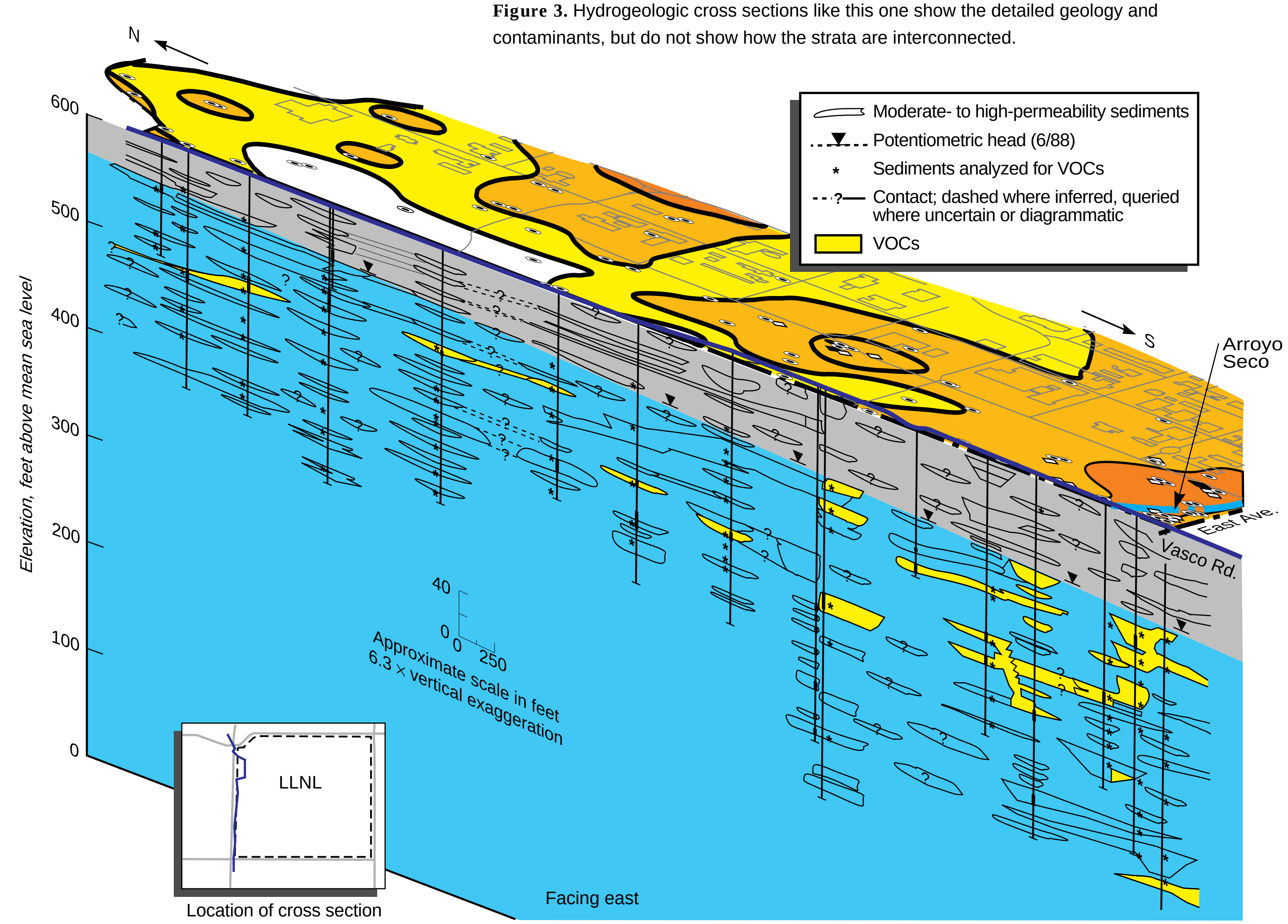
Although Livermore-developed software is used to display much of this subsurface data on maps and cross sections (Figure 3), the actual process of data integration is performed manually by the geologists and hydrogeologists. During this process, subsequent revisions of the working maps and cross sections ensure that they honor all of the independent data sets used to develop the final interpretation. "This is the most laborious and tedious part of the process, but one that is absolutely critical for developing a technically defensible, comprehensive interpretation," says Blake. "As you can imagine, with 30 interconnected cross sections, once you change interpretations on one cross section, changes cascade through most of the others, requiring many hours of careful, painstaking revisions."

Pathways Revealed

Careful analysis of hydraulic data from monitoring wells revealed that many of the underlying strata, once believed to be geologically and hydraulically separate, are actually interconnected. This interconnectedness became evident when active pumping at one well resulted in the water level being drawn down in other wells around the site. These wells, although drilled to varying depths in what appear to be separate permeable zones, as shown in Figure 4, actually tap into a single hydraulically interconnected unit.

Using data and observations such as these, Blake and coworkers found that the underlying Livermore site and neighboring area just west of the Laboratory are divided into seven layers, called hydrostratigraphic units (HSUs), each stacked on top of the other with low-permeability sediments separating one HSU from another. Figure 5 is a cross section showing VOCs above cleanup levels in each hydrostratigraphic unit. Because low-permeability boundaries limit water moving between HSUs, contaminants mostly travel within individual HSUs during their slow migration westward.

Figure 3. Hydrogeologic cross sections like this one show the detailed geology and contaminants, but do not show how the strata are interconnected.



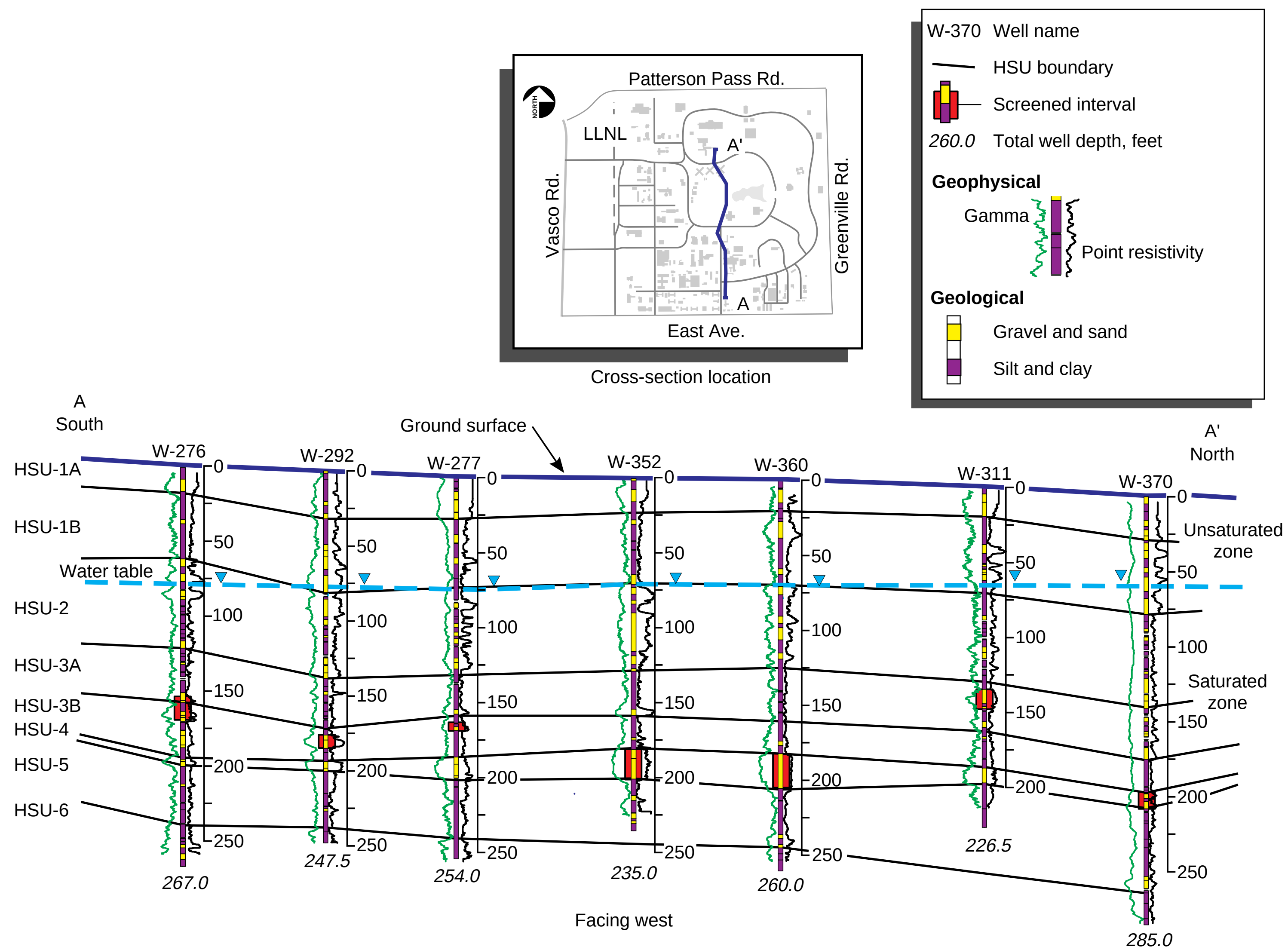


Figure 4. This hydrostratigraphic cross section shows geologic and geophysical borehole data that researchers gathered for correlating subsurface hydrogeology. Hydrostratigraphic unit (HSU) interpretations were cross checked and refined using hydraulic and chemical data.

The seven HSUs that form the hydrostratigraphic framework are the key feature of 30 cross sections the team developed to cover the site and surrounding areas. The cross sections represent a working hypothesis of the subsurface structure that continues to gain definition as more field data are gathered and analyzed.

Together the HSUs contain information on the geology of the site, the present location of contaminants and their migration pathways, the three-dimensional geometries of individual plumes, and the relationship between plumes and their sources at the surface.

These cross sections and maps are used to optimize the locations of extraction and monitor wells, to ensure adequate hydraulic control of plumes, and to maximize contaminant removal. They also show the relationship between contaminant source areas and VOC plumes within HSUs.

Controlling Migration

Figure 5 also shows that VOCs tend to migrate within the confines of individual HSUs. Transport between HSUs, however, may occur where the low-permeability sediments separating the units are indistinct or missing. Thus, it may be necessary to redefine HSU boundaries as new field data are collected. Because of the general westward dip of the geological strata, VOCs initially present near the surface are found at increasing depths from east to west within a unit. In addition, once VOCs migrate vertically downward from source areas through the vadose zone (the area above the water table) and encounter the saturated zone, their transport becomes primarily lateral and follows the groundwater flow direction within the HSU.

HSU-5, in the eastern portion of Figure 5, shows this relationship. A source near an old salvage yard in the southeastern quadrant of the site introduced VOCs into HSU-5 several decades ago. Once the VOCs migrated into the saturated zone, groundwater carried them laterally westward within HSU-5. Figure 5 shows how extraction wells have been placed to target VOCs in HSU-5 close to the source area as well as near the higher concentrations on the western edge of the plume.

Figure 6 is a north–south cross section along the western edge of the site, looking eastward. Similar to Figure 5, Figure 6 shows that VOCs originating from sources to the east in this area are found mainly in HSUs 1B and 2, with minor contamination in HSU-3A. Plumes in these three units are being remediated by extraction wells located at two treatment facilities in the Laboratory's southwest corner.

Making Steady Progress

Maps such as Figures 5 and 6 are allowing the Laboratory to minimize the number of wells needed for site cleanup and compliance monitoring, and in turn reduce expenditures for wells and pipelines. At Treatment Facility A alone, the number of extraction and monitor wells necessary for cleanup was decreased by about 20% by using hydrostratigraphic analysis. Together with accompanying pipelines and other infrastructure, that reduction translates into significant cost savings, on the order of $500,000 per treatment facility.

HSU methodology also is allowing overall cleanup to progress faster than expected because Laboratory staff now

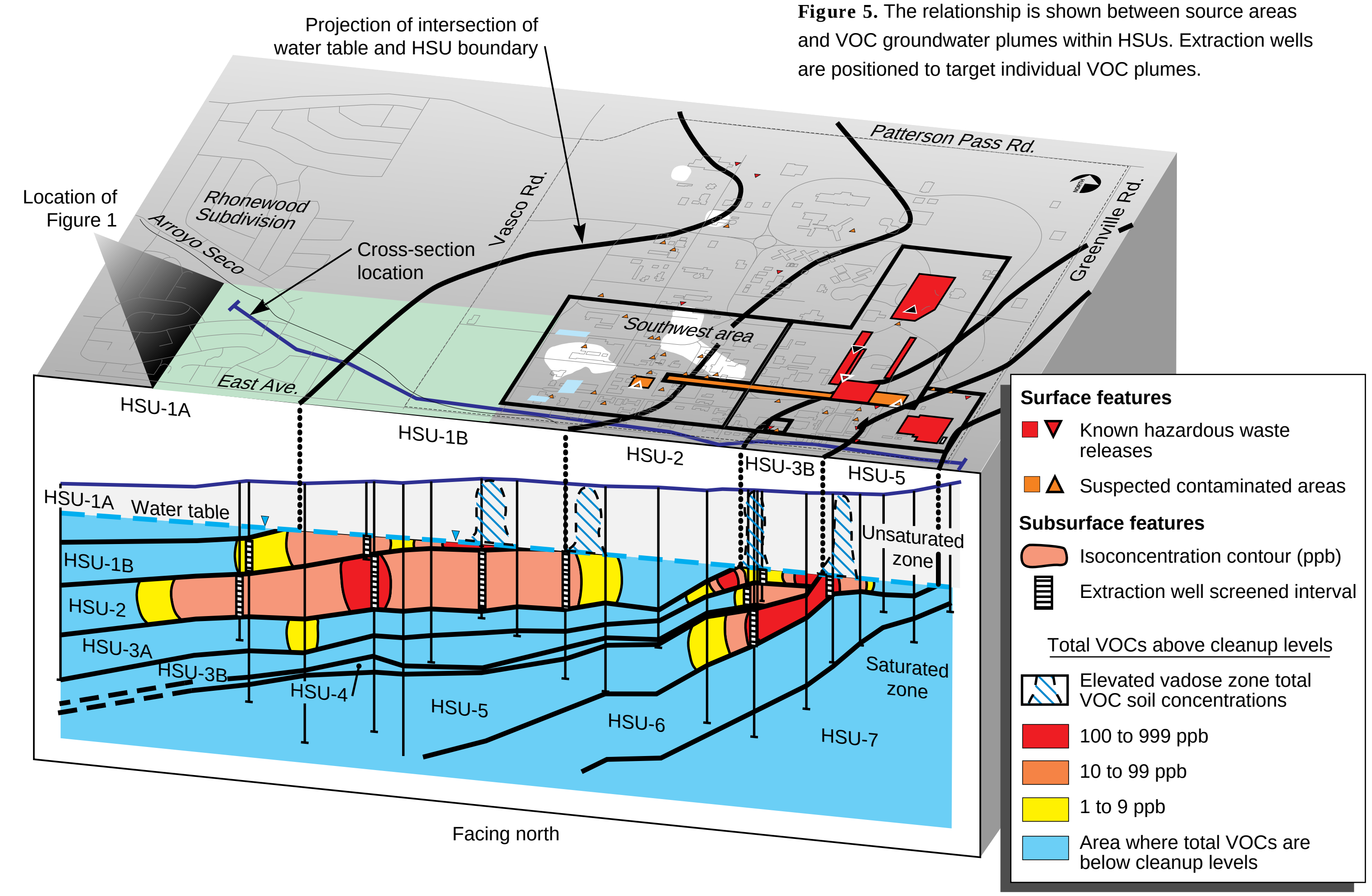


Figure 5. The relationship is shown between source areas and VOC groundwater plumes within HSUs. Extraction wells are positioned to target individual VOC plumes.

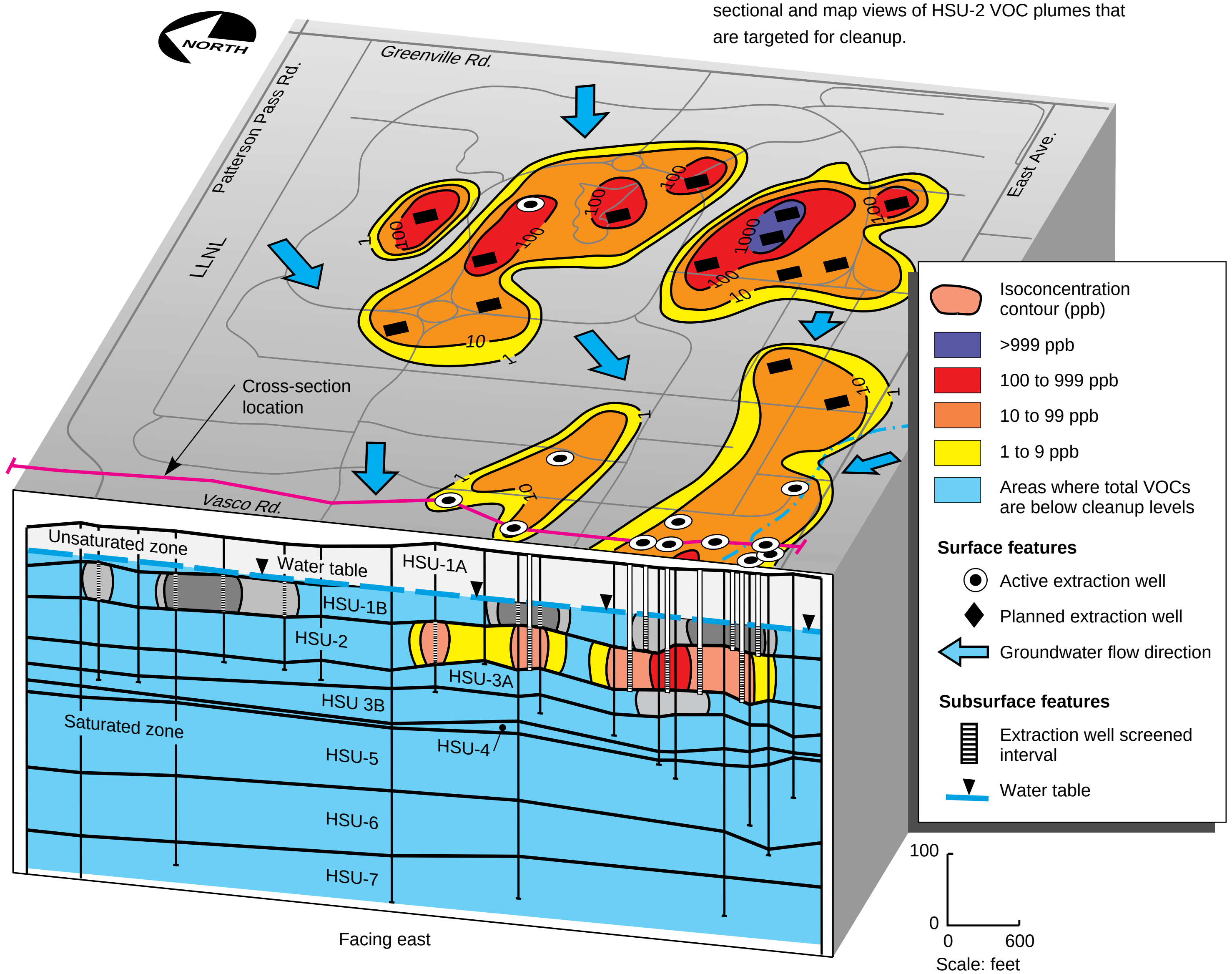


Figure 6. This block diagram shows both cross-sectional and map views of HSU-2 VOC plumes that are targeted for cleanup.

have even better information for placing the extraction wells for maximum effect. Through smart pump-and-treat, PCE concentrations in HSU-2 along the western margin of the site have been reduced from over 1,000 parts per billion to less than 100 parts per billion over the last seven years. The newly installed extraction wells and associated pipelines that were designed using the HSU methodology have accelerated the cleanup and may allow cleanup objectives to be reached in another 10 to 15 years rather than the Laboratory's original estimate of 50 years.

The steady progress of the Lab's groundwater cleanup effort can be seen back in Figure 1, the sequence of four maps covering the time period October 1988 to February 1995. Together the maps show a dramatic decrease in VOC concentrations in HSU-2, illustrating the capacity of hydrostratigraphic analysis to effectively monitor plume changes as remediation work proceeds.

The maps have proven to be an effective communication tool with the public as well as with regulators. In community and regulatory-agency meetings, researchers have used graphics depicting hydrostratigraphic analysis to clearly convey the extent of the Laboratory's commitment to clean up contaminated groundwater and to illustrate the success of the efforts to decrease VOC concentrations and thereby reduce any potential dangers to municipal water supplies.

In a time of shrinking federal budgets, a very important goal is to use hydrostratigraphic analysis to demonstrate that the Laboratory's groundwater cleanup efforts are being conducted in the best, most cost-effective manner possible. Stresses Blake, "Our ultimate goals are to accelerate the VOC plume cleanup process, demonstrate that the plumes no longer pose an environmental threat, and be the first federal environmental site in the U.S. to be removed from the Superfund list."

Key Words: hydrostratigraphic analysis, groundwater, groundwater restoration and remediation, hydrostratigraphic unit (HSU), pump-and-treat.

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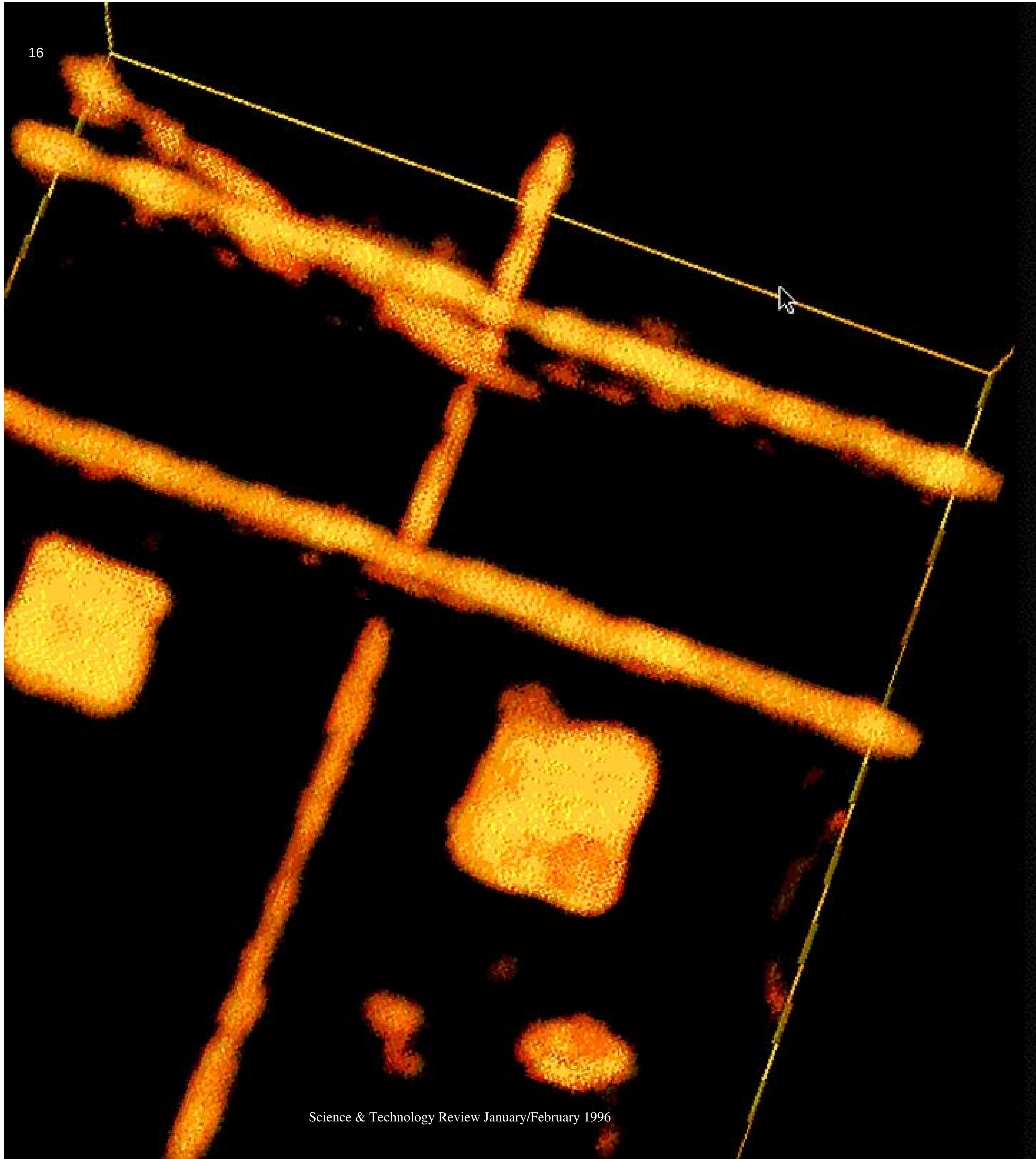
About the Scientist

RICHARD G. BLAKE joined the Laboratory in 1992 as an environmental scientist/hydrogeologist. He graduated with a B.S. (1977) and an M.S. (1983) in geology from California State University, Los Angeles. He is currently the Hydrogeology Team Leader in the Environmental Restoration Division of the Environmental Protection Department. Blake also spent twelve years in the California oil and gas exploration industry: seven years for PG&E's subsidiary Natural Gas Corporation of California, and five years as Fleet Oil Co.'s vice president. His publications include papers about California oil and gas exploration, stratigraphy and sedimentation, engineering geology and geologic hazards, hydrogeology, and environmental restoration.



Micropower Impulse Radar

A new pocket-size radar that operates up to several years on AA batteries and costs only a few dollars is stimulating Laboratory research efforts and a variety of industrial products. Its many potential uses include security, rescue operations, and health monitoring.

RADIO detection and ranging (radar) was first developed in the 1920s. Most of us associate radar with combat scenes in movies or an occasional speeding ticket. Conventional radar uses beamed and reflected microwave energy to detect, locate, and track objects over distances of many miles. Almost all types of radar were developed for defense applications, and they continue to be used by the military and a few civilian organizations. Commercial use has been limited primarily because most radar systems are large, and they can be complex and cost $40,000 or more. A dramatic change in radar use is imminent, resulting from work done at LLNL.

We have invented and patented a fundamentally different type of compact, low-power radar system called micropower impulse radar (MIR), which is orders of magnitude less expensive to produce than other conventional radars. Unlike conventional radar, which sends out continuous waves in bursts, MIR uses very short electromagnetic pulses and can detect objects at much shorter range. The new technology has become

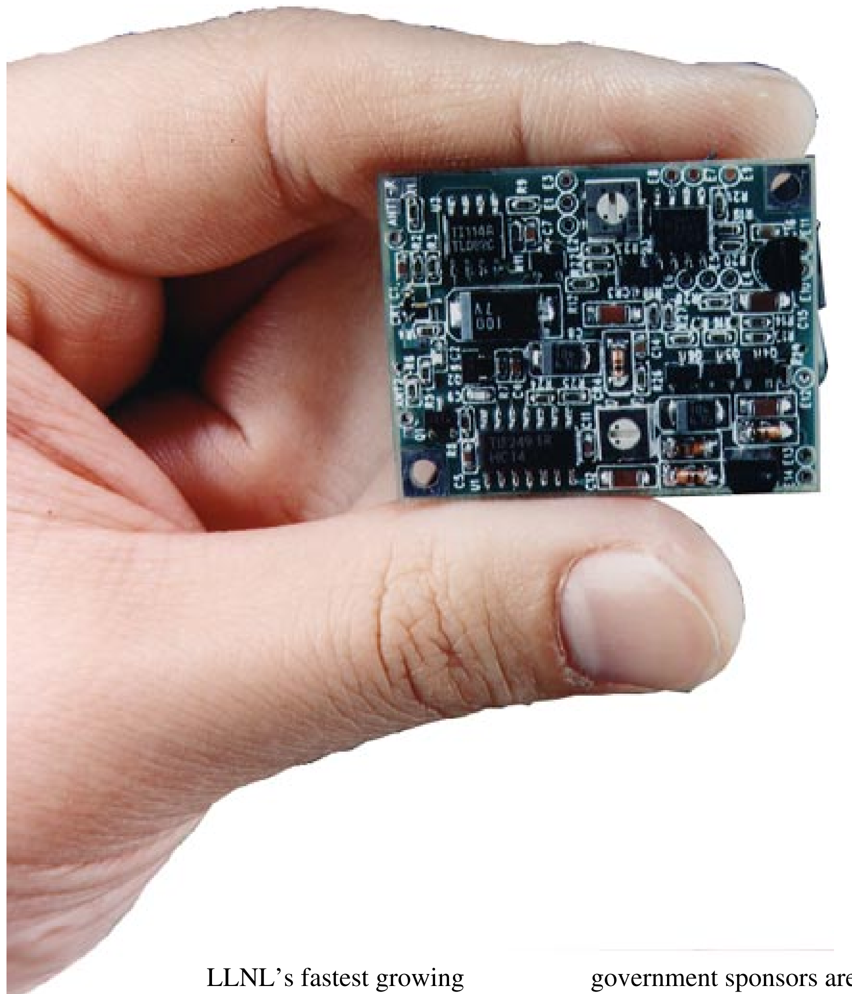


Figure 1. The micropower impulse radar (MIR) proximity sensor board.

LLNL's fastest growing technology transfer activity primarily because of its low cost and extraordinary range of applications.

Among the scores of uses under investigation for MIR are new security and border-surveillance systems; underground, through-wall, and ocean imaging; fluid-level sensing; automotive safety, including collision-avoidance and intelligent cruise-control systems; "smart" devices such as lights, heaters, and tools that automatically turn on or off; and medical diagnostics.

The technology has potential use in finding earthquake survivors under rubble and in monitoring for sudden-infant-death syndrome. Various government sponsors are interested in low-cost, lightweight MIR sensors in areas of defense, law enforcement, transportation infrastructure, and the environment. Envisioning perhaps hundreds of other uses, Tom McEwan—the electrical engineer who invented MIR—has compared the new technology to the Swiss Army knife.

The Genesis of MIR

MIR, with origins in Lawrence Livermore's Laser Programs Directorate, is now being developed by that directorate's Imaging and Detection Program. The Laboratory is home to the 100-trillion-watt Nova laser. Developed for nuclear fusion research, the ten-beam pulsed Nova laser generates subnanosecond events that must be accurately recorded. In the late 1980s, Laboratory engineers began to develop a new high-speed data acquisition system to capture the data generated by Nova and the next-generation laser system, the National Ignition Facility. The result was a single-shot transient digitizer—a 1993 R&D 100 Award winner described in the April 1994 issue of *Energy and Technology Review*.[1]

The LLNL transient digitizer, which is the world's fastest, functions as a high-speed oscilloscope combined with a digital-readout device. The instrument records many samples from single electrical events (a brief signal called a "transient"), each lasting only 5 nanoseconds (5 billionths of a second). Compared to competitive products, such as the best oscilloscopes, the transient digitizer is much smaller and more robust, consumes less power, and costs far less.

While developing the transient digitizer, project engineer McEwan had an important insight. The sampling circuits developed for it could form the basis of a sensitive receiver for an extremely small, low-power radar system (Figure 1).

MIR Components

The principal MIR components are shown in Figure 2: a transmitter with a pulse generator, a receiver with a pulse detector, timing circuitry, a signal processor, and antennas. The MIR transmitter emits rapid, wideband radar pulses at a nominal rate of 2 million per second. This rate is randomized intentionally by a noise circuit. The components making up the transmitter can send out shortened and sharpened electrical pulses with rise times as short as 50 trillionths of a second (50 picoseconds). The receiver, which uses a pulse-detector circuit, only accepts echoes from objects within a preset distance (round-trip delay time)—from a few centimeters to many tens of meters.

The MIR antenna determines much of the device's operating characteristics. A single-wire monopole antenna only 4 cm long is used for standard MIR motion sensors, but larger antenna systems can provide a longer range, greater directionality, and better penetration of some materials such as water, ice, and mud. Currently, the maximum range in air for these low-power devices is about 50 m. With an omnidirectional antenna, MIR can look for echoes in an invisible radar bubble of adjustable radius surrounding the unit (Figure 2). Directional antennas can aim pulses in a specific direction and add gain to the signals. We can separate the transmitter and receiver antennas, for example, to establish an electronic "trip-line" so that targets or intruders crossing the line will trigger a warning. We are also exploring other geometries with multiple sensors and overlapping regions of coverage.

Behind MIR Technology

Impulse Radar

Conventional radar sends out short bursts of single-frequency (narrow-band) electromagnetic energy in the microwave frequency range. Other radars step through multiple (wide-band) frequencies to obtain more information about a scene. An impulse, or ultrawide-band, radar such as MIR sends individual pulses that contain energy over a very wide band of frequencies. The shorter the pulse, the wider the band, thereby generating even greater information about reflected objects. Because the pulse is so short, very little power is needed to generate the signal. MIR is unique because it inexpensively generates and detects very fast (subnanosecond) pulses. The drawback of using short, low-power

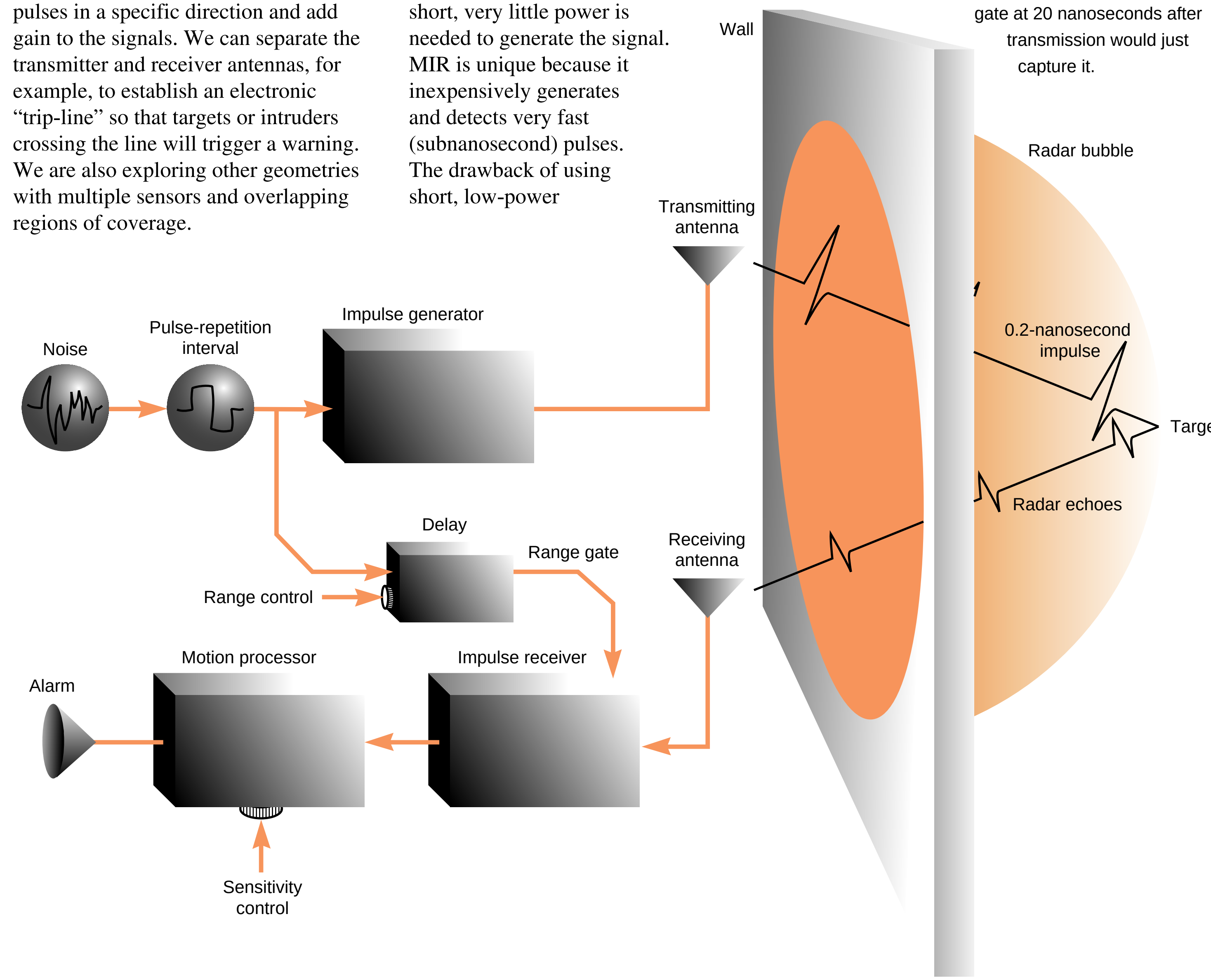
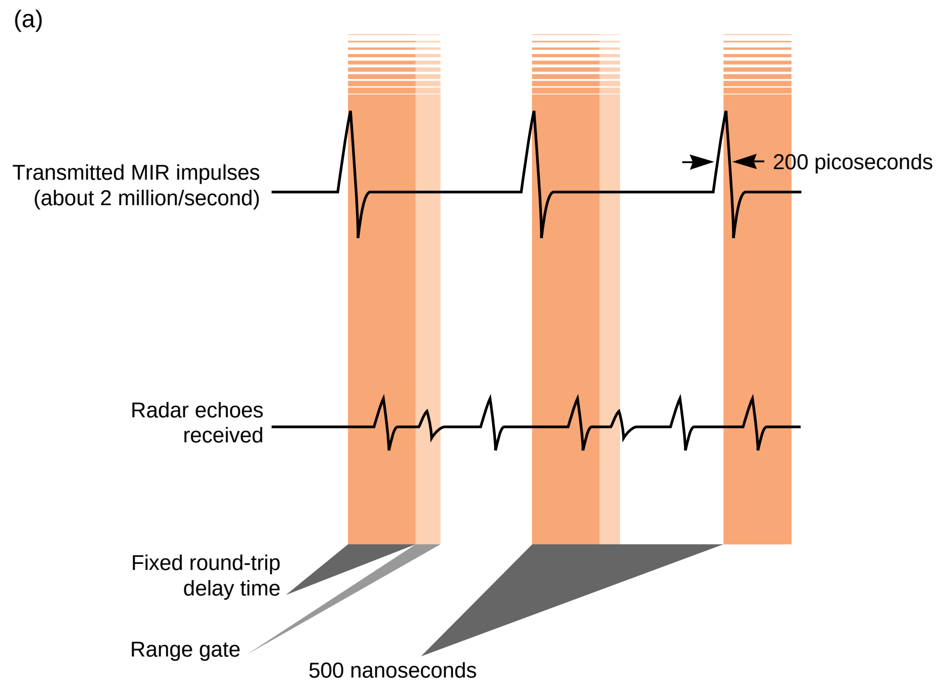


Figure 2. In an MIR motion sensor, a transmitting antenna radiates a pulse that is about 0.2 nanoseconds long. Reflections from targets return a complex series of echoes to the receiving antenna. The return signal is sampled at one range-gate time by an impulse receiver containing a voltage sampler along with an averaging circuit and amplifier. The detector listens at the appropriate time for an echo. For an object about 3 m from the MIR, the sampled gate at 20 nanoseconds after transmission would just capture it.



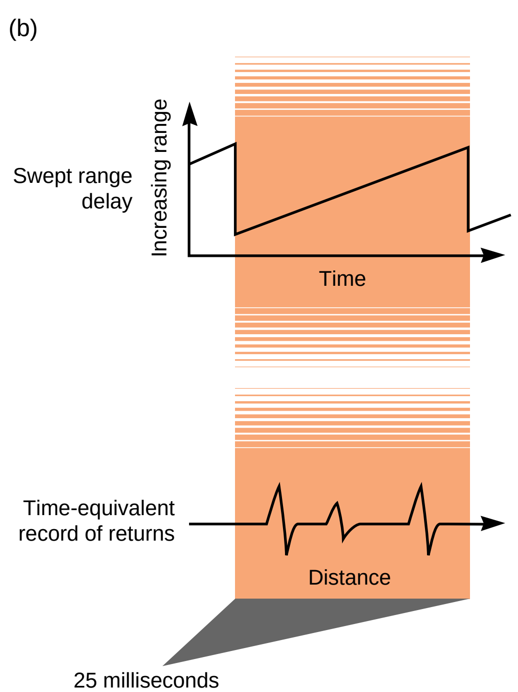


Figure 3. (a) Following an impulse transmitted by MIR, a range gate opens briefly after a fixed delay time to sample the received radar echoes. (b) To obtain a more complete record of returns for more sophisticated applications, we sweep the range delay over various delay times to obtain target information at different distances. We have effectively slowed down the radar signal by about a factor of 1 million to get an "equivalent-time" record of radar returns that can be correlated to object distances. (Pulses pictured here are not to scale.)

pulses is that less energy can be measured on the radar returns. We solved this problem by transmitting many pulses rapidly and averaging all returns.

The advantages of producing and detecting very brief radar impulses are considerable:

- The target echoes return much information. With short pulses, the system operates across a wide band of frequencies, giving high resolution and accuracy. The system is also less susceptible to interference from other radars.
- Battery current is drawn only during the short time the system is pulsed, so power requirements are extremely low (microamperes). One type of MIR unit operates for several years on two AA batteries.
- The microwave power associated with pulsed transmission is exceedingly low (averaging tens of microwatts) and is medically safe. MIR emits less than one-thousandth the power of a cellular telephone.

Range-Gated Radar

Transmitted energy from any radar is diffracted and scattered by objects in the field of view, such as cars, trees, or people. Larger and more conductive objects generally produce larger returns. Because the wavelength of MIR signals in air is currently about 15 cm, we can easily detect objects of that size or larger at distances of about 15 cm or greater. Distorted, low-amplitude reflections of the transmitted pulse are picked up by the receiving antenna in the time it takes for light to travel from the MIR to the object and back again.

The operating principle of MIR motion sensors is based on the relatively straightforward principle of range gating. In looking for the return signals, MIR samples only those signals occurring in a narrow time window

after each transmitted pulse, called a range gate. If we choose a delay time after each transmitted pulse corresponding to a range in space, then we can open the receiver "gate" after that delay and close it an instant later. In this way, we avoid receiving unwanted signals.

The MIR receiver has a very fast sampler that measures only one delay time or range gate per transmitted pulse, as shown in Figure 3a. In fact, we use circuitry that is similar to the transmit impulse generator for this range-gated measurement, another unique feature of our device. Only those return pulses within the small range gate—corresponding to a fixed distance from device to target—are measured. The gate width (the sampling time) is always fixed based on the length of the pulse; but the delay time (the range) is adjustable, as is the detection sensitivity. Averaging thousands of pulses improves the signal-to-noise ratio for a single measurement; i.e., noise is reduced, which increases sensitivity. A selected threshold on the averaged signal senses any motion and can trigger a switch, such as an alarm.

Randomized Pulse Repetition

As mentioned earlier, a noise source is intentionally added to the timing circuitry so that the amount of time between pulses varies randomly around 2 MHz. There are three reasons for randomizing the pulse repetition rate and averaging thousands of samples at those random times. First, interference from radio and TV station harmonics can trigger false alarms; but with randomizing, interference is effectively averaged to zero. Second, multiple MIR units can be activated in one vicinity without interfering with each other if the operation of each unit is randomly coded and unique. Each unit creates a pattern recognizable only by the originating MIR. Third, randomizing spreads the sensor's emission spectrum so the MIR signals resemble background noise, which is difficult for other sensors to detect. Emissions from an MIR sensor are virtually undetectable with a conventional radio-frequency receiver and antenna only 3 m away. In other words, randomizing makes the MIR stealthy.

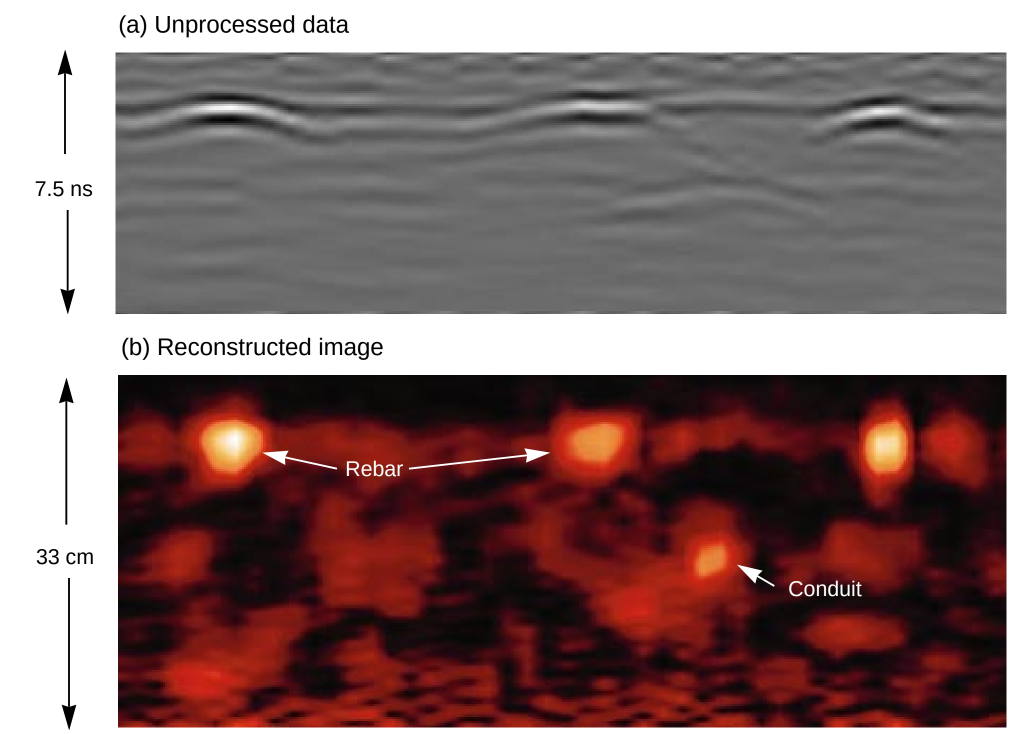


Figure 4. (a) Unprocessed radar information we obtained along a concrete floor in the Nova facility. (b) After applying a specialized image-reconstruction algorithm to the unprocessed MIR data, buried rebar and conduit shown in a cross section become clear.

Equivalent-Time Sampling

More sophisticated MIR sensors, such as our MIR Rangefinder, cycle through many range gates. As shown in Figure 3b, the delay time is swept, or varied, slowly with each received pulse (about 40 sweeps per second) to effectively fill in the detection bubble with a continuous trace of radar information. In essence, we are taking samples at different times, thus different distances, away from the device. The result is an "equivalent-time" record of all return pulses that can be correlated to object distance. The equivalent-time echo pattern exactly matches the original "real-time" pattern, except that it occurs on a time scale slowed by 10^6. We can easily display the equivalent-time echo pattern on an oscilloscope or read the data into a computer. We are applying this sampling technique to many short-range applications, such as lightweight altimeters or reservoir-level measurement, as well as all MIR imaging applications.

Forming Images

With equivalent-time sampling, we can form images by moving the Rangefinder in front of a target area or by using a stationary array of Rangefinders. Figure 4a shows unprocessed radar information we obtained along a concrete floor in the Nova facility. Each vertical trace is a return signal from a different position

Table 1. Some commercial applications of MIR.

Commercial Sector	Application of MIR
Automotive	Parking assistance; backup warning; precollision detection; cruise control; airbag deployment; electronic dipstick for all fluid levels
Security	Home intrusion and motion sensor; keyless locks, automatic doors; child monitoring; vehicle theft alarm; radar trip wire; perimeter surveillance
Appliances	Stud finder; laser tape measure; wireless thermostat; automatic dispenser; automatic tool shutoff; toys, games, and virtual reality
Manufacturing	Fluid-level, proximity, and harsh-environment sensing; robotic sensor; industrial automation

along the floor. When many individual vertical views into the floor are stacked side-by-side, resembling slices of bread making up a loaf, we can reconstruct a cross section of the floor. As expected, features are obscured by the clutter inherent in all radar measurements. To resolve the locations of buried objects, such as rebar and conduit shown in Figure 4b, we apply a specialized image-reconstruction algorithm using diffraction tomography.[2]

Many such slices stacked together form a full 3-D view of the subfloor or other concrete structure (Figure 5). This unique combination of the MIR sensors and imaging software is spurring new, low-cost nondestructive inspection methods.

Summary of Features

As MIR technology has evolved, a unique combination of features resulted. Although certain specifications—signal strength, operating range, and directionality—can vary depending on the type of system and its intended purpose, the following features are common to most units:

- Low cost, using off-the-shelf components.
- Very small size (circuit board is about 4 cm^2).
- Excellent signal penetration through most low-conductivity materials, so it is able to "see through" walls, concrete, and other barriers, including human tissue.
- A sharply defined and adjustable range of operation, which reduces false alarms.
- Long battery life, typically several years, because of micropower operation.
- Simultaneous operation of many units without interference.
- Randomized emissions, making the sensor difficult to detect.

Current MIR prototype units at LLNL are made with low-cost, discrete components. In the planning stages are single chips—application-specific integrated circuits (ASICs)—that will replace most of the discrete parts and result in even lower cost and smaller size.

One limitation is that the penetration of MIR signals through a material decreases as that material's electrical conductivity increases. Thus, the technology cannot see through thick metal, such as a ship's hull, or sea water, but it still can penetrate substances with moderate electrical conductivity, such as the human body.

MIR as a Sensor Technology

MIR technology opens up many possible low-cost sensor systems for motion detection or proximity, distance measurement, microwave image formation, or even communications. For example, in some cases it has advantages over many kinds of conventional proximity and motion sensors, such as passive infrared (heat sensors), active beam-interruption infrared, ultrasound, seismic, and microwave Doppler devices. Many of these sensors are adversely affected by temperature, weather, and other environmental conditions, making them prone to false alarms. Passive infrared sensors can be triggered by light and heat, and their detection range is not well defined. Even a thin sheet of paper blocks both infrared and ultrasound signals. Similarly, ultrasound motion and Doppler microwave sensors interfere with one another when several units are co-located. Without range gates, these sensors can trigger as easily on distant objects as on nearby insects. They can also have limited material penetration, detectable emissions, and expensive components. MIR technology provides an attractive alternative to these devices.

We are following two paths in developing and applying MIR technology. For well-developed products, we encourage commercial applications, and we are licensing the technology to qualified manufacturers in the U.S. using a procedure that ensures fairness of opportunity. For ideas that require more research and systems development, we are continuing to explore electronics, antennas, signal processing, and imaging concepts as we develop programs that will apply MIR technology to support Laboratory missions and address problems of national interest.

Commercially Ready MIR

Table 1 lists some of the commercial applications of MIR. One key factor in virtually all commercial markets for MIR is cost. Most of our sensor units can be manufactured at a fraction of the cost of existing technology—indeed, they are typically hundreds of times less expensive. In many cases, there simply is no practical alternative technology on the market that is as robust, accurate, and inexpensive.

Security Systems

Home security systems now on the market can cost thousands of dollars, require regular maintenance, and be disrupted by interference from a neighbor's system. At a projected cost of $20, an MIR sensor (Figure 6), powered by AA batteries, operates without frequency channels or wiring and is simple to install. Motion sensors can be adjusted for sensitivity and range so that a pet, for example, would not trigger an alarm and could roam freely anywhere below a ceiling-mounted MIR sensor. Installations of MIR sensors already exist in the DOE nuclear weapons

MIR Recognition and Awards

- Thirty U.S. patent applications.
- Twelve industry licensees and many more expected.
- *Popular Science,* cover story March 1995 and Best of What's New Award 1994.
- *New Scientist,* cover story August 1995.
- *Electronic Design News,* 100 Hottest Products of 1994.
- Intellectual Property Owners, Distinguished Inventor of 1994.
- Federal Laboratory Consortium Award for Excellence in Technology Transfer 1995.

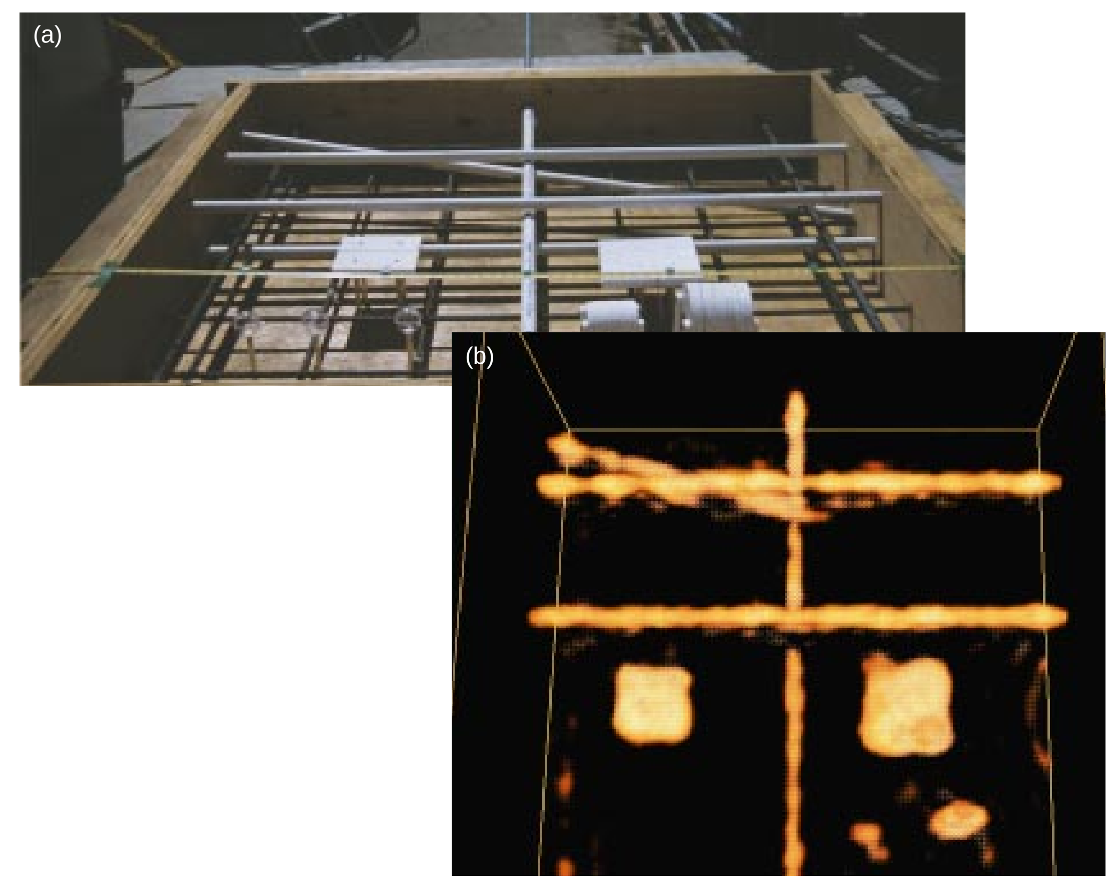
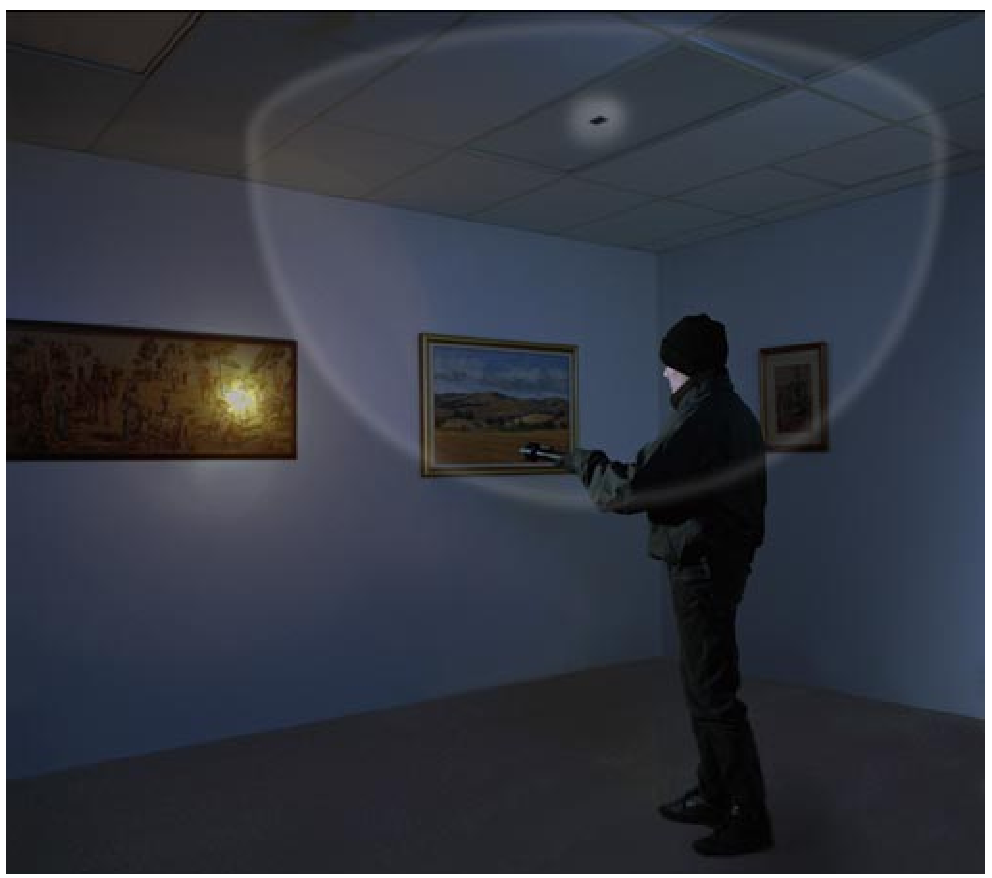


Figure 5. Imaging steel in concrete with MIR. (a) The internal elements of a concrete slab before pouring. (b) Reconstructed 3-D MIR image of the elements embedded in the finished, 30-cm-thick concrete slab.

Figure 6. An MIR concealable intrusion sensor detects intruders at ranges up to 6 m. Units can be mounted on the ceiling, located behind objects, or hidden in shelves, closets, or drawers. The system detects motion by repeatedly monitoring the echo pattern to see if it changes. A change signifies that an intruder has penetrated the invisible radar bubble.



complex, DoD Special Forces, U.S. Border Patrol, and the intelligence community. At Livermore, an MIR security system is now being installed in the lobby of the Nova building.

Automotive Sensors

MIR motion sensors placed on the side of vehicles can alert drivers about other cars in blind spots, warn when another vehicle is too close, and activate side air bags. A sensor placed on the rear bumper, for example, provides parking assistance or warns when a curb is very close. In one test, a sensor unit installed in a car's taillight section functioned perfectly even when we smeared mud over the taillight or placed 30 cm of ice in front of the sensor unit. One licensee is expected to equip cars with MIR proximity sensors by the 1997 or 1998 model year. Other automotive uses include security systems, traffic flow sensors, distance and speed indicators, and dipsticks (described below).

Tools to Manufacturing

Do-it-yourself tools based on MIR can locate wooden or steel studs in a wall, steel within concrete (Figure 5), plumbing lines, or electrical wiring. We envision electronic tape measures, automatic thermostats, automatic dispensers, games, and toys that incorporate the new MIR technology. In manufacturing, we are exploring robotic sensors, harsh-environment sensors, and industrial automation equipment based on MIR.

One application in particular, the "electronic dipstick," has the potential to revolutionize the way fluid levels are measured in virtually every industry. The electronic dipstick, a low-cost, solid-state sensor that has no moving parts, is impervious to wetting, corrosion, sludge, and condensation. The device shown in Figure 7 launches a signal along a single metal wire, rather than through air, and measures the transit time of reflected electromagnetic pulses from the top of the dipstick down to a liquid surface. Our tests show that the electronic dipstick can resolve fluid-level changes smaller than a millimeter and is accurate to within 0.1% of its maximum length. The dipstick can detect all fluid levels in a car, measure oil levels in supertankers, and remotely monitor water levels in reservoirs, among many other uses.

Projects in the Works

Some of our ongoing projects include specialized motion sensors, short-range altimeters, radar ocean

imaging, highway and bridge-deck inspection, and hand-held wall surveying. In defense and law enforcement, we are exploring MIR in scenarios such as border control and surveillance systems, mine and ordnance imaging, the imaging of individuals behind walls, and proximity fuses. We also envision potential uses in environmental and medical research.

Many of these applications of national interest are government-sponsored, involving signal processing, computations, and communications expertise along with hardware development, and we draw on Laboratory experts in all those fields. Following are a few areas in which we have already made substantial progress.

Border Surveillance

Border and perimeter surveillance pose serious technical problems for the nation and many industries and agencies, including drug enforcement, land management, and military security. Among many other issues, visible devices such as antennas or cameras are often targets for vandalism or attack. The Laboratory is working with the U.S. Border Patrol to demonstrate an automated, covert surveillance system for international borders as well as for military sites and police boundaries.

By combining an array of concealable MIR units with advanced, low-cost computation and communication technologies, we plan to deploy an automated surveillance method. We can monitor a localized area or establish an unattended, electronic trip-line that would cover a few kilometers and eventually extend across perhaps hundreds of kilometers. MIR modules placed up to 100 m apart would measure human movement—discriminating between people and other sources of motion—and rapidly communicate an intrusion down the chain of modules to the nearest base station. We now have sensor units in place at the Border Patrol station in El Centro, California, at an International Atomic Energy Agency facility, and at Sandia National Laboratories, Albuquerque.

Detecting Mines

Landmine detection is a serious military and humanitarian problem. One thousand people are killed or maimed every week worldwide by mines left from previous wars. MIR can detect both plastic and metallic land mines buried in most soils. Our technology is attractive because its small size and low cost allow either hand-held or vehicle-mounted arrays and because images formed by an array aid in discriminating mines from ground clutter.[3,4] Currently, a laptop computer can reconstruct an image in less than 10 seconds, but much higher speeds are feasible. Field tests at the Nevada Test Site show conclusively that the MIR sensor readily detects buried mines through 2-D imaging, but full 3-D imaging (Figure 8) may be necessary to more reliably discriminate between a mine and other buried features, like rocks of similar size and shape. A linear array of MIR modules mounted on the front of a remote-controlled vehicle, or on a boom extending beyond the vehicle, can detect antitank and antipersonnel mines. Even in areas of rough terrain or dense foliage, portable mine-detection systems operating in the look-ahead mode are feasible with current technology.

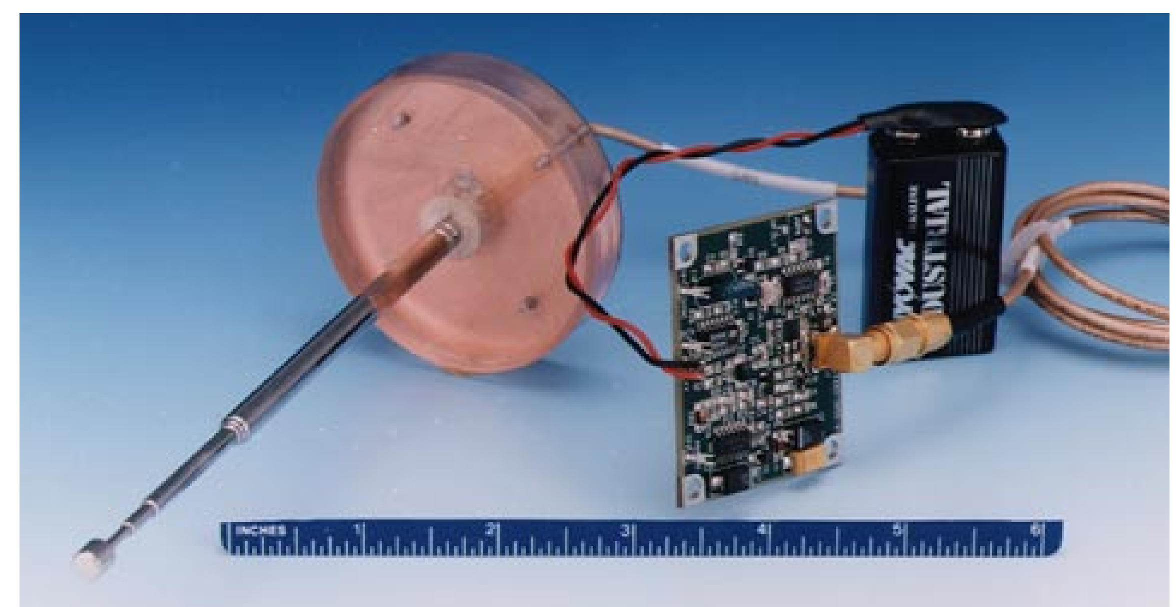
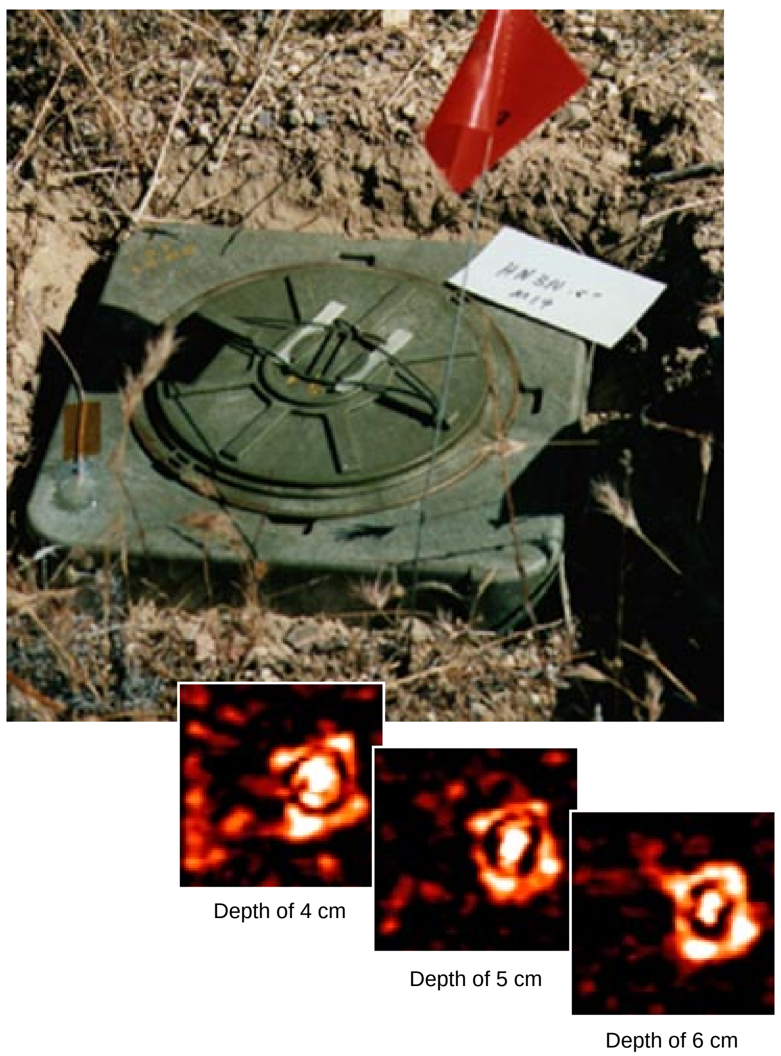


Figure 7. The electronic dipstick is a metal wire connected by cable to an MIR electronic circuit. As a highly accurate fluid-level sensor with no moving parts, this device has myriad applications in manufacturing and is significantly lower in cost than laboratory equipment performing the same task.

Figure 8. A typical plastic antitank mine is shown (top) before burial at the Nevada Test Site. MIR technology was used (bottom) to image the mine at three depths, or horizontal "slices."



Inspecting the Infrastructure

More than 40% of the 578,000 highway bridges in the U.S. have structural deficiencies or are obsolete. Corrosion of steel reinforcing bars (rebar), hidden by concrete and asphalt layers, leads to fracturing and delamination, which can result in failure. Visualizing the details of many structures such as bridge decks has required destructive techniques, such as coring.

We are developing MIR devices to nondestructively image bridges and roadbeds, evaluate civil structures, inspect power poles, and locate buried pipes. We received funding from the Federal Highway Administration to build a vehicle for highway and bridge deck inspection. In that project, we have designed a prototype vehicle-mounted inspection system (Figure 9) that acquires data at speeds approaching the normal flow of traffic. Speed is important because a large portion of inspection costs arise from traffic controls. We envision three modes of inspection: a quick mode at the highest vehicle speeds for preliminary assessments, a limited-depth mode for higher-resolution data, and a detailed mode at slower speed to inspect the entire deck thickness (up to 40 cm). Deployment of the full system is scheduled for fall 1996.

Medical Applications

Our radar's average emission level is about a microwatt—about 3 orders of magnitude lower than most international standards for continuous human exposure to microwaves. Thus, MIR is a medically harmless diagnostic tool. In addition, the sensors we are testing remotely measure human vital signs much like the medical tricorder envisioned in Star Trek, without interfering with computers, digital watches, FM radio, or television.

Our MIR heart monitor (Figure 10a) measures muscle contractions (responses of the heart) rather than the electrical impulses (stimuli) measured with an electrocardiogram (EKG). Figure 10b shows the output waveform of a prototype heart monitor compared to that obtained from a standard EKG. The MIR output is complex and rich in detailed information, and we are actively working with physicians to understand its significance.

As a medical monitor, a very small MIR unit built into a single chip could substitute for a stethoscope. The U.S. Army is interested in a portable device that could be worn inside clothing so that a soldier's vital signs can be relayed from the field to a medical command post.

An MIR-based breathing monitor (Figure 11) does not have to make contact with a person's body, and it can operate through a mattress, wall, or other barriers. The detection of breathing motion can be a valuable asset in hospitals and homes, could guard against sudden-infant-death syndrome, and might be used by people with breathing disorders such as sleep apnea, in which the affected individual occasionally stops breathing.

We are exploring the use of MIR for additional medical devices, including speech-sensing devices and a polygraph sensor. Devices for the blind could warn of obstacles and variations in terrain and help to train individuals in using canes. We are initiating clinical studies to optimize medical radars for heart, respiration, and speech applications. The potential payoffs are enormous not only in financial terms but also in benefits to society.

Rescue Operations

Cameras, dogs, and acoustic equipment tuned to signs of life currently help rescuers to find survivors buried after an earthquake, avalanche, or other disaster. Soon, wall- and rubble-penetrating portable MIR devices could assist in search-and-rescue operations. We have tested units that detect respiration and heartbeats at a range of about 3 m. In the midst of wreckage too unstable to support rescuers, miniature radar devices could be tossed into the debris from a safe distance and signal personnel when physiological signs are detected. We are working with the U.S. Army Corps of Engineers Earthquake Preparedness Center (San Francisco) and with the NASA Disaster Response Team (Ames) to develop such devices.

Figure 9. Vehicle-mounted radar imaging for bridge-deck inspection. Arrays of MIR modules mounted on the front and rear allow the vehicle to cover a 2-m-wide swath with each pass. Radar images are reconstructed and processed at an on-board workstation.

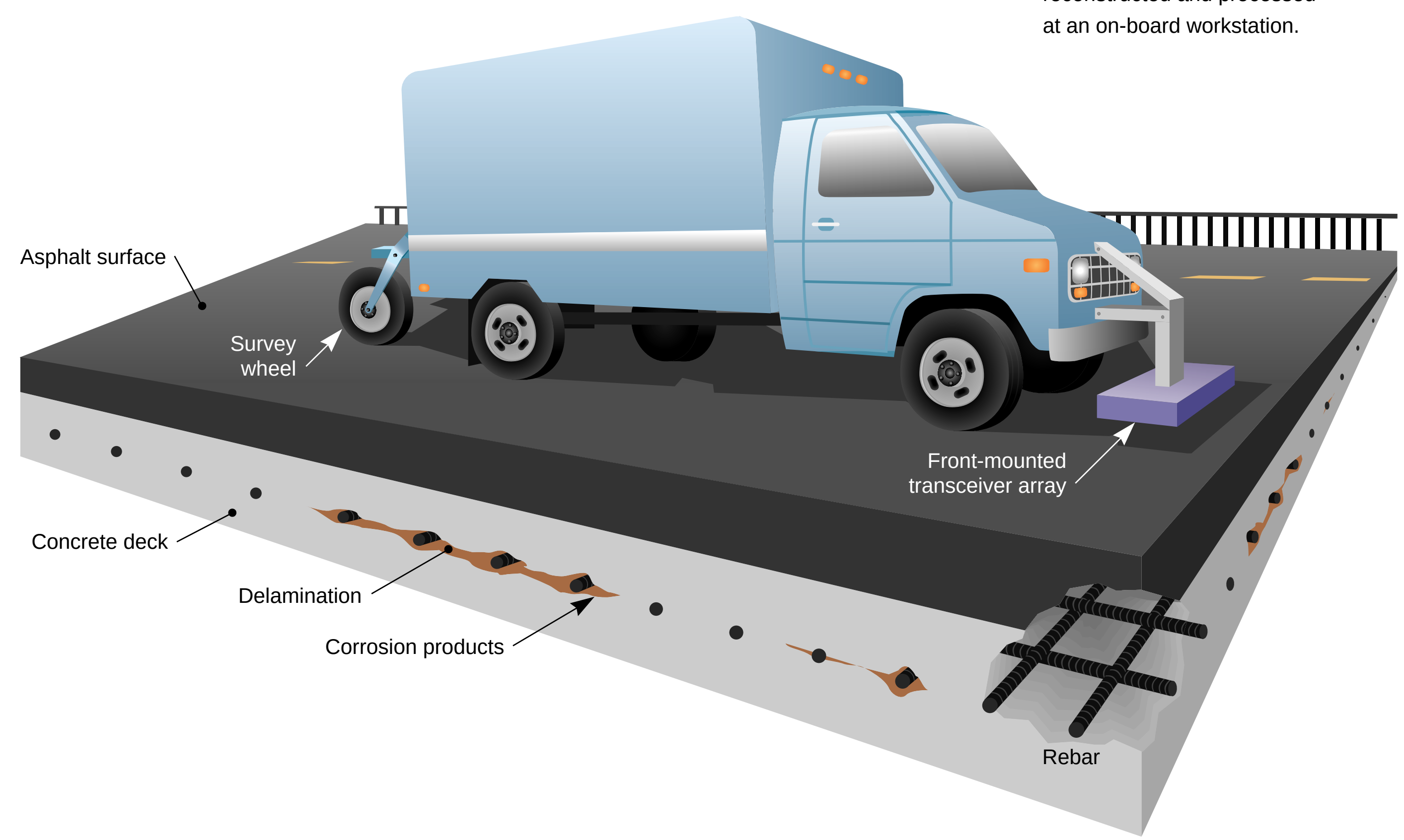
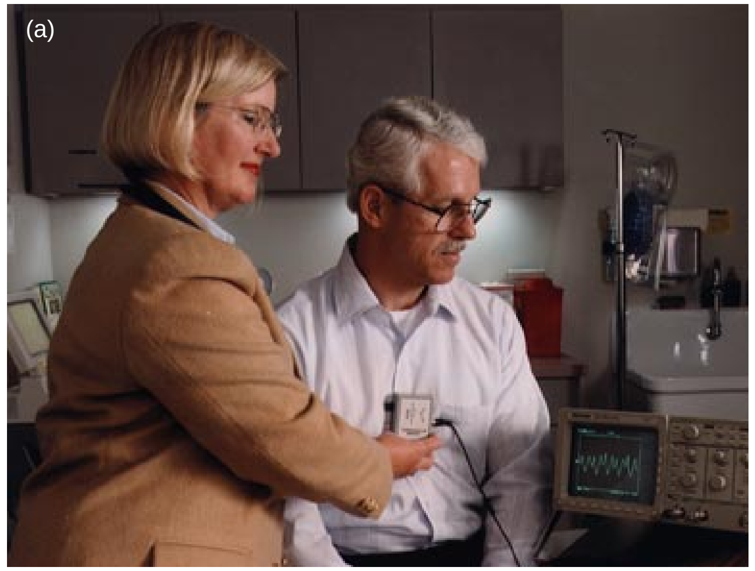
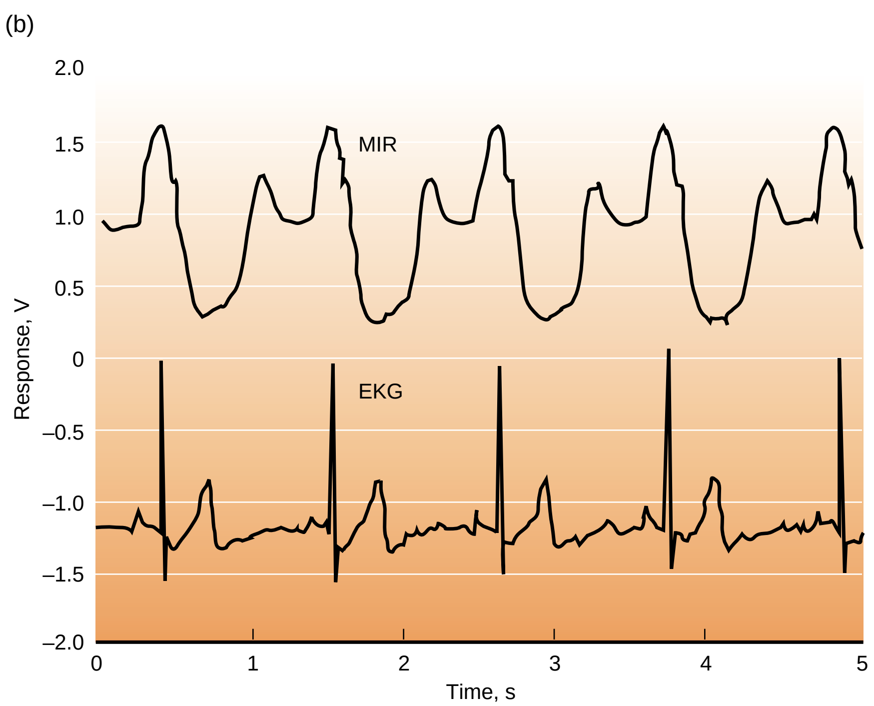


Figure 10. (a) An MIR cardiac monitor. (b) Its output (upper trace) is distinctly different from that obtained by a conventional EKG (lower trace). We are working with physicians to correlate the radar signals with physiological functions.





Looking to the Future

We continue to develop MIR for a variety of applications, and we are exploring ways to increase its performance in difficult situations. Even though the new radar technology performs very well, we still need to address issues such as reduced clutter, enhanced resolution and contrast, electromagnetic attenuation by different media, multiple scattering, shadowing, dispersion, real-time operation, and full 3-D imaging speed.

For some applications, we want to extend MIR from the centimeter-wave region into the higher-frequency, millimeter-wave region. Higher-frequency MIR will provide better resolution and give greater signal directionality with divergence of only a few degrees. Higher frequency will also mean that MIR could detect smaller objects of 2 cm or smaller diameter, such as concealed weapons or bullets, and even tiny asteroids approaching a spacecraft. MIR using millimeter waves could replace ultrasound motion sensors, such as those used for automatic door openers.

The current maximum range for MIR is about 100 m using high-gain antennas. Our intent is to extend the range to about half a kilometer. Longer range will require an improved signal-to-noise ratio. We are looking at higher-power systems and improved antenna designs to extend the range and at better signal and image processing to reduce noise.

Key Words: electronic dipstick; micropower impulse radar (MIR); radar heart monitor; ultrawide-band radar, radar imaging, microwave sensors.

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For licensing and MIR partnering information contact (510) 422-6935 (mir@llnl.gov). Also see our homepage (http://www-lasers.llnl.gov/ lasers/idp/mir/mir.html).

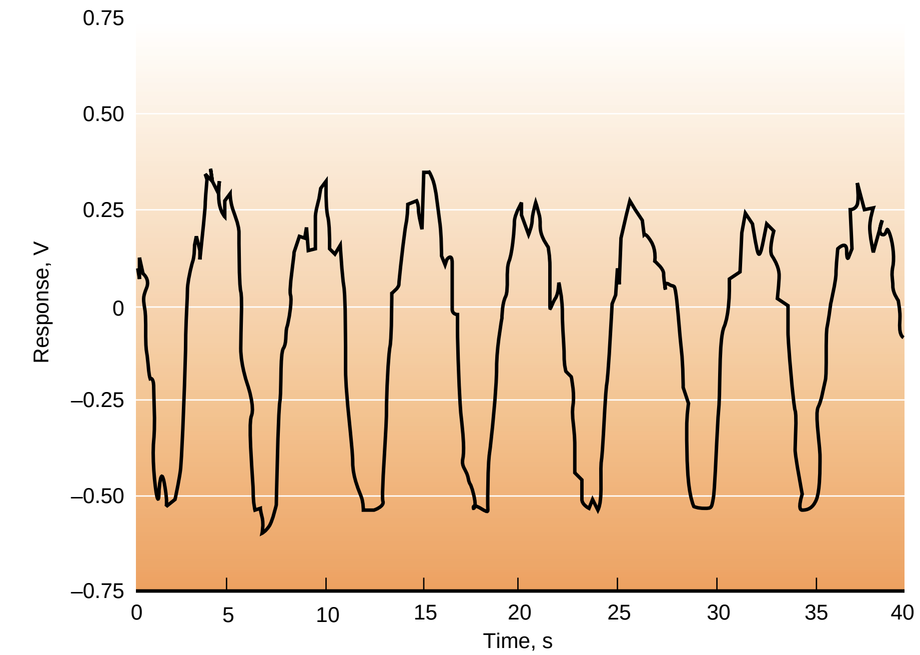
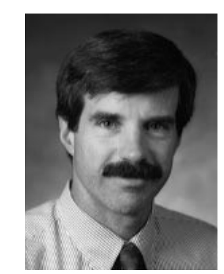


Figure 11. An MIR breathing monitor detects the respiratory cycle through a 10-cm-thick chair back. The higher-frequency waveforms are cardiac activity.

About the Researchers



STEPHEN AZEVEDO, currently the Program Group Leader of the Microradar Project in the Laser Programs Directorate, has a background in digital signal and image processing. Concentrating in electrical engineering, he received a B.S. (1977) from the University of California at Berkeley; an M.S. (1978) from Carnegie-Mellon University; and a Ph.D. (1991) from the University of California at Davis. Azevedo joined LLNL in 1979 and since has been a principal investigator in computed tomography research and radar remote sensing; he also has done work in signal processing, modal analysis, x-ray inspection, nondestructive evaluation, and imaging. He is the author or coauthor of over 40 publications on these subjects.

THOMAS E. McEWAN has been a member of the Laser Programs Directorate in the Imaging and Detection Program since joining the Laboratory in 1990. His accomplishments here include inventing the micropower impulse radar (MIR) and developing the world's fastest solid-state transient digitizer and a palm-size impulse generator. He received his B.S. (1970) and M.S. (1971) degrees from the University of Illinois (Chicago Campus) in electrical engineering. From 1970 to 1985, he was a design engineer at Nanofast Inc. From 1986 to 1989, McEwan led the design of high-speed microelectronics at Northrop Corporation, where he supported programs in radar jamming, electronic countermeasures, and computer-chip development. In addition to the MIR recognitions listed on p. 23, he has six patents in wideband electronics.

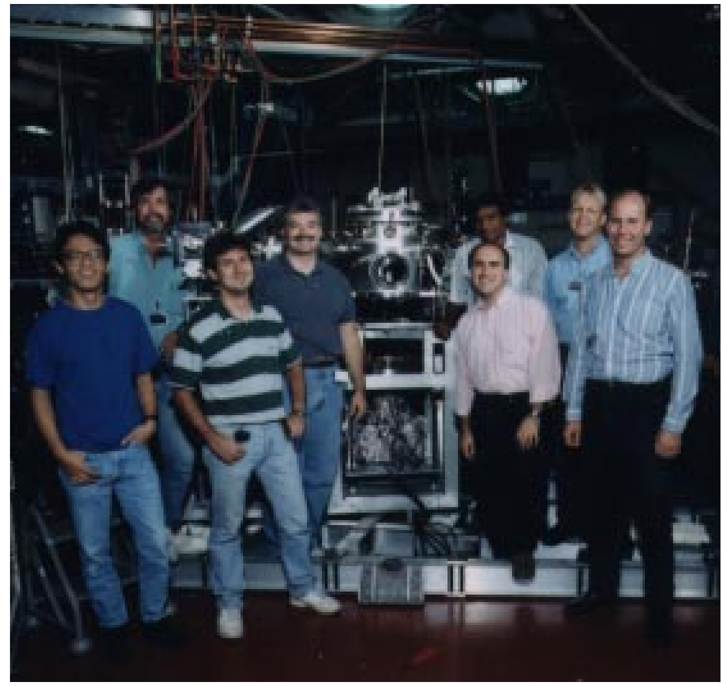
Probing with Synchrotron-Radiation-Based Spectroscopies

MAKING things smaller isn't as easy as it looks! Using novel materials to manufacture atomic-scale microelectronic, electro-optic, and other devices requires a clear understanding of the materials' atomic, electronic, and bonding structures. Through studies they are conducting at the Advanced Light Source (ALS), a $100-million synchrotron-radiation user facility, researchers from Lawrence Livermore National Laboratory are helping to provide that understanding.

Headed by Lou Terminello of the Chemistry and Materials Science Directorate, the Livermore group is part of a large research team. It includes researchers from IBM, the University of Wisconsin, the University of Tennessee, Tulane University, and the Lawrence Berkeley National Laboratory, where the two-year-old ALS is housed. The team was formed to pool resources to build and operate a state-of-the-art, soft x-ray and vacuum ultraviolet beamline at the ALS. The 33-m-long beamline—called Beamline 8.0—was designed especially to provide the brightest and highest resolution photon flux in an energy range from 40 to 1,500 eV.

Using techniques such as photoemission, photoabsorption, soft x-ray fluorescence (SXF) spectroscopy, and photoelectron holography, the researchers conduct their experiments to essentially "capture" atomic-level images from the material sample they are probing.

This Livermore team of researchers helped to build and begin operation of Beamline 8.0, a soft x-ray and vacuum ultraviolet beamline, at Lawrence Berkeley National Laboratory's Advanced Light Source.



Enhanced SXF

The initial experiments demonstrated the unique capability of the Advanced Light Source to enhance SXF spectroscopy in order to probe systems that are difficult if not impossible using other techniques. Last year, the Beamline 8.0 team became the first of the ALS users to publish its experimental results in refereed journals, with papers in *Physical Review Letters,*[1] *Review of Scientific Instruments*,[2] and *Applied Physics Letters.*[3] The reports focused on results using SXF spectroscopy to reach deep into the interior of materials to look at the atomic and electronic structures of graphite and titanium oxide. Resulting images showed dispersive features in fluorescence spectra.

While the collaborators share a technical affinity in advancing new characterization techniques, each affiliated organization has its own specific interest. For example, Tulane and the University of Tennessee are chiefly focused on SXF to examine the electronic structures of solids. On the other hand, IBM, which provided most of the funding for construction of the shared beamline, is interested in basic and applied research on microelectronic materials and on characterizing material interfaces.

Robust Interfaces

Interfaces are also a central thrust for the Livermore team's research. With funding from the Department of Energy's Office of Basic Energy Sciences, the team is studying the structure of heterogeneous interfaces, an important aspect of microelectronics or other advanced materials. Explains Terminello, "Because microelectronic devices are getting smaller and smaller, an interface is becoming a more important constituent of the overall device. Let's say you join dissimilar materials and want to traverse the interface with electrons for your electronic device. The interface very definitely has an impact on how, and whether, the device performs."

The team's materials science work at the ALS has involved making interfaces as well as characterizing them. In one experiment, the researchers grew oxides on silicon using nitrous oxide. "We found we could get a robust interface using that growth method because we are essentially growing a thin nitride film right at the interface," said Terminello. "That makes the interface less susceptible to breakdown when high-voltage fields are applied to very small devices."

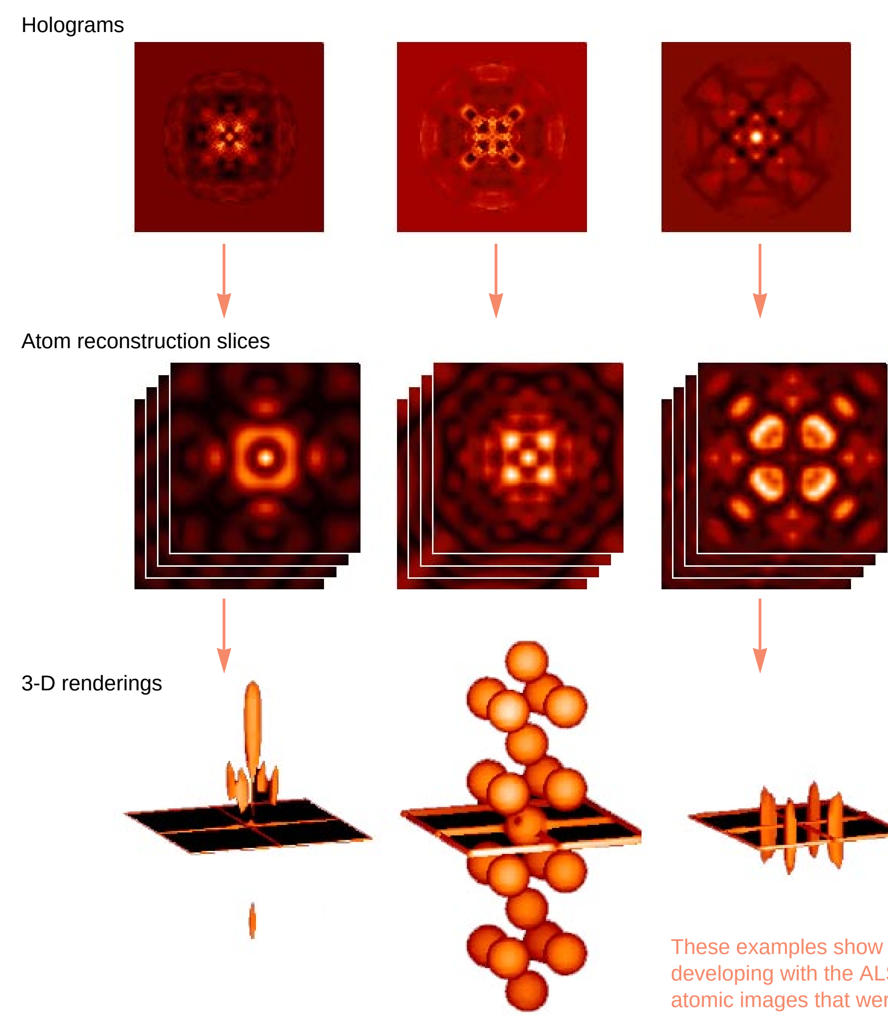
Livermore's ALS researchers are seeking to understand on an atomic scale the structure of materials such as thin films, multilayers, diamond films, novel semiconductors, and epitaxial overlays on single-crystal substrates, and then relate that knowledge to the properties that would govern the materials' performance in a variety of applications.

Seeing the Theory

The ALS experimentalists have been closely coupling their atomic-level measurements to work done by Livermore's theoretical scientists, who are forging new pathways in the computational study of novel materials and their interactions (see *Energy & Technology Review*, August–September 1994). Part of the structural information gathered by the ALS group, can be compared directly to elements of theoretical models that groups such as Livermore's H-Division have developed. Says Terminello, "What that comparison does is allow us to have greater confidence in the theoretical models for use in predicting the structure and behavior of new materials— so in the future we can achieve 'materials by design.'"

One of the Livermore team's principal tools to characterize interfaces is a specially developed electron spectrometer, based on a design originally created at IBM in the early 1980s. While an electron energy analyzer is a fairly common piece of research equipment, the device built for the ALS beamline permits more detailed and streamlined analysis of atomic and electronic structures. For example, it records how many electrons are being emitted from interface atoms in the sample under examination, and it simultaneously preserves the electron trajectories as they are emitted from the surface. Furthermore, the device collects all the angular information at one shot. The bottom line is that the unit allows researchers to efficiently do the angle mapping required to get the complete picture of the physics governing the emitted electrons.

The unit recorded its first photoemission in October 1994 and has been in use ever since. The device's angle-resolving capabilities became operational in July 1995. Terminello predicts that the analyzer will develop into a "workhorse" in the coming months as the team continues its nanoscale look at the fundamental properties of a variety of novel materials and observing the phenomena that are taking place within them.



These examples show the atom-imaging technique that the Livermore team is developing with the ALS. Top row: photoelectron holograms. Middle row: real-space atomic images that were recovered from holograms above. Bottom row: 3-D renderings made from above images (center one is an ideal model of the atoms).

Key Words: synchrotron radiation, spectroscopy, Advanced Light Source, Beamline 8.0, material interfaces.

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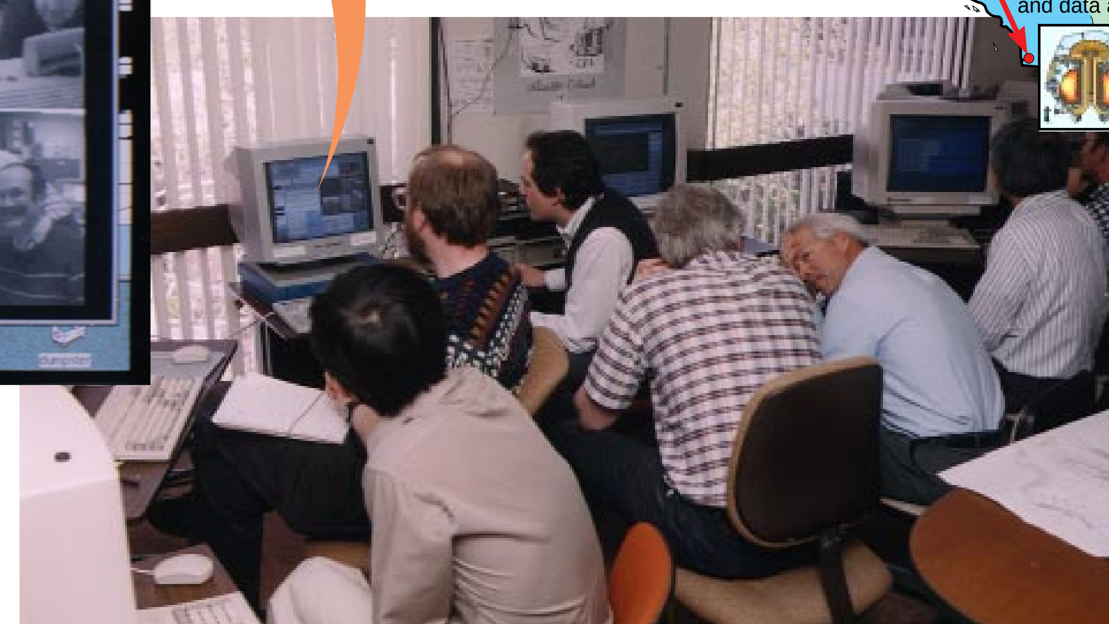
Operating a Tokamak from Across the Country

PHYSICISTS often share the use of large, expensive, experimental facilities to study the actions and reactions of minute particles. But demands upon existing facilities are high. Lawrence Livermore National Laboratory is pioneering the development of technology for remotely conducting magnetic fusion experiments as a way to maximize the use of experimental tokamak facilities. Fusion experts live all over the world, so their ability to conduct experiments from multiple locations will enable many new scientific collaborations.

Real-time data crosses the country within a tenth of a second via the Internet.

Split-second flash of light from inside the tokamak at MIT indicates a plasma has formed and the shot is successful.

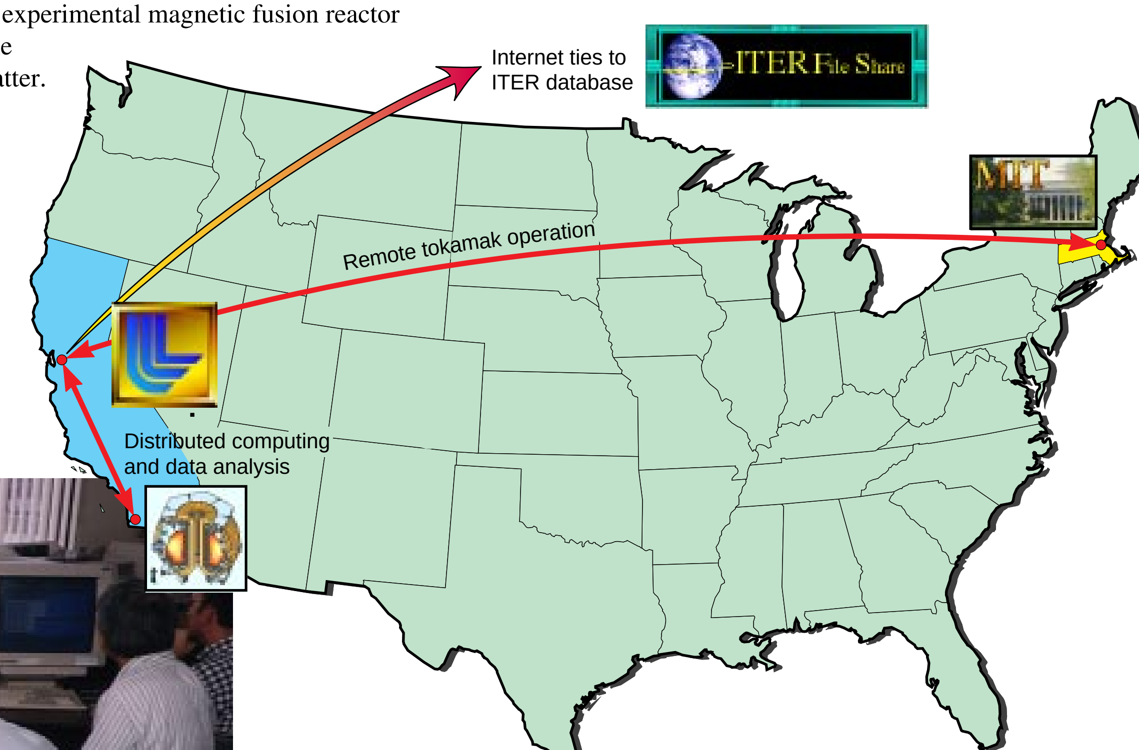
Real-time video of researchers in the control room at MIT



From this control room in Livermore, a team of LLNL and MIT researchers successfully tested the technology for controlling fusion experiments from a distance via the Internet—in this case, from 3,000 miles across the country. During the first full day of the demonstration, 21 of 35 “shots” on the tokamak at MIT were controlled from computers in Livermore.

Greater demand also is being made for more efficient use of funds to construct and use such facilities. Like other electronic operations, remotely operating experiments will also significantly cut the time and cost of travel to these facilities as well. Scientists at one laboratory could control all phases of a physics experiment on a device at another location, while simultaneously conferring with colleagues at other laboratories and universities who are obtaining real-time data from the experiments in process.

While remote control of machines is nothing new, remote operation of a complex, experimental magnetic fusion reactor from the other side of the country is a different matter. LLNL researchers are finding that success requires not only real-time access to controls and diagnostic equipment but also direct access through sound and visuals to scientists and technicians resident at the experiment. The recent explosive growth of high-speed, wide-area computer networks like the Internet is making remote operation possible.



Working Toward Remote Operation

Since 1991, scientists at Livermore have been developing capabilities for remote operation of a tokamak. In a collaboration with General Atomics in San Diego, the Livermore project

How Magnetic Fusion Works

Magnetic fusion scientists use a tokamak (the word is a Russian acronym) to duplicate the Sun's process of creating energy through fusion. The goal is to create a commercially viable energy source without contributing to global warming or acid rain and without producing toxic wastes.

In the doughnut-shaped tokamak, powerful magnets are used to confine plasma—a highly ionized gas like the material at the Sun's surface. Enough energy must be used to heat the plasma to a temperature sufficient to produce ion velocities high enough to react and fuse—at temperatures in the range of 20 million to 100 million degrees kelvin. Current tokamaks create plasma in bursts a few seconds long, but scientists are working toward steady-state operation, which is more advantageous for power generation and easier on the materials in the system.

Fusion energy has not found its way into our electrical sockets because confining and heating the plasma are very difficult. However, recent experiments give every indication that ignition for controlled fusion power applications will be achieved in the next 10 to 15 years.

staff has developed software to remotely access General Atomics' DIII-D tokamak. Today, when experiments are in process, researchers in Livermore can control diagnostic equipment, operate data acquisition systems, and obtain and view results. They have access to all computer-based information at the DIII-D. They also have created integrated, network-based, high-performance computing and data storage facilities. However, the main controls for actual remote operation of the DIII-D are not on the network.

Unlike the DIII-D, the Alcator C-Mod tokamak at Massachusetts Institute of Technology's Plasma Fusion Center, the newest tokamak in the U.S., was designed with network-based control and data acquisition systems. Although the Alcator C-Mod hardware was not designed specifically for remote operation, its systems are compatible with this option. Until recently, however, only a few instruments had been operated remotely.

In March 1995, scientists in Livermore conducted fusion experiments on the Alcator C-Mod device in Cambridge, Massachusetts, in the first transcontinental operation of a tokamak. The Livermore team and MIT researchers worked together to operate the tokamak using a part of the Internet called the Energy Sciences Network, or ESNet, which is managed by Livermore. The plasma shape, the particle fueling source, the radio frequency heating, and a reciprocating probe were all controlled in real time from Livermore over ESNet.

Scientists also exchanged a variety of data between Livermore and Cambridge: video images, experimental data from the diagnostic equipment inside the tokamak, and video and audio communications between researchers at each end (see figure pp. 32–33). Data and signals crossed the country in about 100 milliseconds. Multiple video cameras captured images of the control room in Cambridge, of the exterior and interior of the tokamak, and of researchers in Livermore. A flash of light inside the tokamak indicated each successful pulse, or shot. These real-time visuals of the people and equipment at Cambridge helped bring the experiment to the scientists in Livermore.

The ability to control the tokamak's systems from Livermore did not eliminate the need for a local staff at Cambridge. Engineers on site at the tokamak monitored all systems to assure the safety of the equipment and local personnel.

This demonstration was the definitive test for controlling a large, complex physics experiment from a remote location, and MIT and Livermore scientists learned much about the possibilities for remote collaboration. They also learned that work remains to be done to make the remote researcher more a part of the experiment.

Bringing Remote Operation Fully On Line

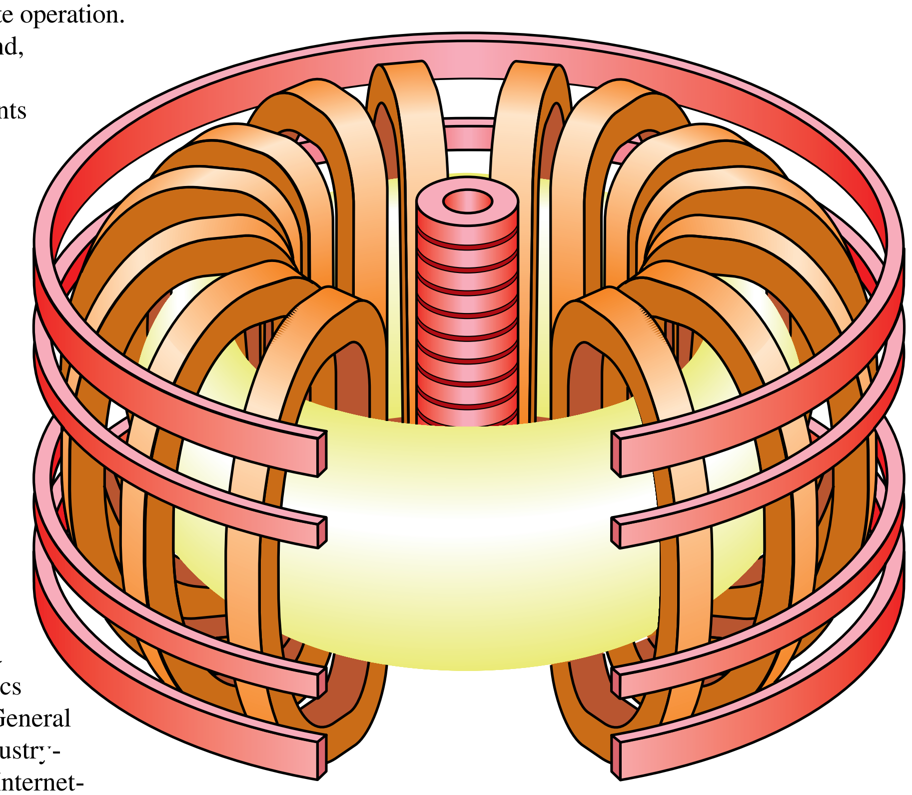
Remote operation is an integral part of the design of the huge International Thermonuclear Experimental Reactor (ITER), a magnetic fusion collaboration among the European Community, Japan, the Russian Federation, and the U.S. ITER is planned to operate in steady state with controlled ignition and steady burn. Design is under way at several international sites, although a location for the reactor itself has not yet been determined. Current planning includes a network of control room facilities in each of the partners' countries. ITER may be operating as early as 2007, by which time the participants expect to implement full remote operation.

With both a domestic tokamak and ITER in mind, Livermore recently began work on a DOE-funded Distributed, Collaboratory Experiment Environments Program to develop remote operation capabilities further. This two-year project involves eight national laboratories and universities working in four groups to develop testbeds for remote access to various kinds of expensive, hard-to-duplicate physics facilities—from an electron microscope to Lawrence Berkeley National Laboratory's Advanced Light Source to a tokamak. By building these testbeds and using them for real-world experiments, the groups are studying the technical and interactive aspects of controlling apparatus, taking data, and interacting with colleagues over wide-area networks. The goal is more than an incremental change in today's use of computers and local-area networks; rather, it is the introduction of a new realm.

Livermore is leading one of the four groups in a collaboration that includes Princeton Plasma Physics Laboratory, Oak Ridge National Laboratory, and General Atomics. This group is working to integrate an industry-standard distributed computing environment with Internet-based audio-visual communications to enhance remote collaborations on General Atomics' DIII-D tokamak. The project demands real-time synchronization and exchange of data among multiple computer networks, as well as the presentation of enough auditory and visual information associated with the control room environment so that remote staff are fully integrated in operations.

The vision is for a scientist thousands of kilometers away to get the same sense of presence and control as at the experiment site. The end result of this project should be distributed environments that provide location-independent access to instruments, data handling and analysis resources, and fellow collaborators. This merging of computers and electronic communications will bring substantially increased effectiveness to doing science and spur applications far beyond operating a physics experiment—to environmental monitoring, engineering design, medical triage, and remote diagnosis.

Tokamaks use magnetic fields from variously shaped magnets (orange, red) to contain a plasma (yellow) of hot gases.



Key Words: Magnetic fusion, remote operation, distributed computing.

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Groundwater Cleanup with Hydrostratigraphic Analysis

The Lawrence Livermore National Laboratory’s groundwater cleanup program has made dramatic strides in removing contaminants underneath the Laboratory and nearby area. Individual contaminant plumes are effectively targeted for hydraulic capture and cleanup by a Livermore team of researchers. Their use of hydrostratigraphic analysis integrates chemical hydraulic, geologic, and geophysical data, which results in a three-dimensional model of the subsurface area. The resulting hydrostratigraphic framework developed at Livermore is proving to be a highly useful management tool to plan, budget, implement, and monitor the groundwater cleanup effort. Researchers expect to transfer their knowledge to other remediation sites. Dollar savings so far have been in optimally placing extraction wells, thereby maximizing contaminant removal and saving time.

■ *Contact:*
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Micropower Impulse Radar

Invented and developed at Lawrence Livermore National Laboratory is an inexpensive and highly sensitive, low-power radar system that produces and samples extremely short pulses of energy at the rate of 2 million per second. Called micropower impulse radar (MIR), it can detect objects at a greater variety of distances with greater sensitivity than conventional radar. Its origins in the Laboratory’s Laser Directorate stem from Nova’s transient digitizer. The MIR’s extraordinary range of applications include security, search and rescue, life support, nondestructive evaluation, and transportation.

■ *Contact:*
Stephen Azevedo (510) 422-8538 (azevedo3@llnl.gov). For licensing and MIR partnering information (510) 422-6935 (mir@llnl.gov) or our homepage (http://www-lasers.llnl.gov/lasers/idp/mir/mir.html).

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