Advancing computer technology and our continued creativity are key to the further advancement of groundwater modeling at the Laboratory for beneficial use everywhere. It is interesting to note that the personal computers that can be bought off the shelf today are as powerful as the Cray 1 supercomputers of less than 10 years ago. As computers become ever more powerful, our modeling capabilities can only expand for effective global applications.

Key Words: artificial neural network (ANN), genetic algorithm, groundwater contamination, groundwater remediation, hydrostratigraphic analysis, inverse modeling, volatile organic compound (VOC).

References

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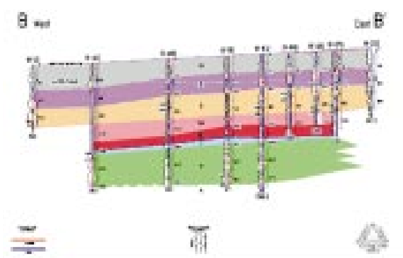
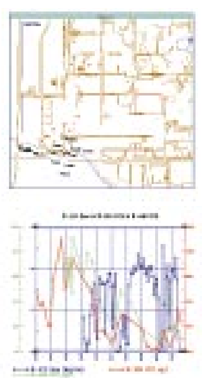
For further information contact Robert J. Gelinas (510) 423-2267 (gelinas1@llnl.gov). Information on flow and transport modeling is also available from Peter McKereghan of Weiss Associates (510) 450-6151. Virginia Johnson (510) 423-2005 (vmjohnson@llnl.gov) is a Laboratory expert on ANNs and genetic algorithm optimization.





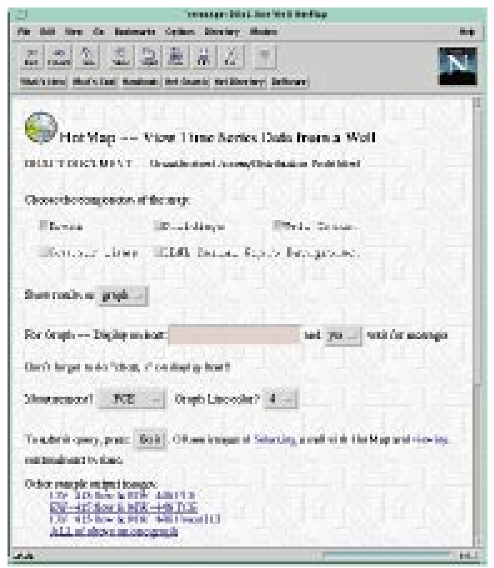


Figure 8. From the HotMap menu, an authorized user is linked to an array of information about the Livermore site.

About the Scientist

ROBERT J. GELINAS joined the Laboratory's Theoretical Physics Division in 1966 as an applied physicist. He received his Ph.D. (1965) and an M.S.E. (1961) in Nuclear Engineering and a B.S.E. (1960) in Chemical Engineering from the University of Michigan. He is currently the Environmental Transport Group Leader in the Environmental Restoration Division of the Environmental Protection Department. His experience includes leading groups of scientists and engineers in energy, defense, environmental, and high-power laser projects at both LLNL and in commercial R&D, where he was principal scientist and manager of the Science Applications International Corporation facility in Pleasanton, California, from 1975 to 1985. Gelinas has published extensively in the fields of reactive fluid flow and transport, with applications to radiative weapons systems, atmospheric and subsurface environments, high-average-power and Nova-class lasers, hydrocarbons, nuclear systems, and nuclear weapons effects.

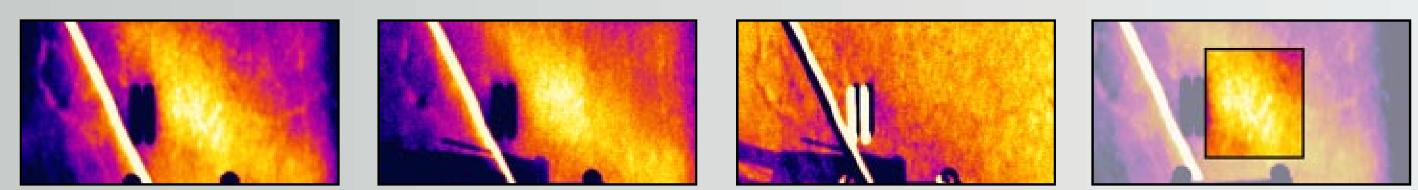
Dual-Band Infrared Computed Tomography: Searching for Hidden Defects

Dual-band infrared computed tomography systems developed at Lawrence Livermore are providing highly sensitive and accurate three-dimensional nondestructive inspection and evaluation of manmade structures in a variety of applications inside and outside the Laboratory.

(Above) The dual-band infrared (DBIR) laboratory that the Federal Highway Administration is currently using for bridge inspection is a converted mobile home. The mobile DBIR laboratory's cameras, mounted about 4 meters (13 ft) above the roadway, scan the reinforced-concrete bridge deck for defects called delaminations. (Below) Delaminations are seen at the center of (a) the 8- to 12-micrometer (μm) longwave thermal infrared image and (b) the 3- to 5-μm shortwave image, both of which also show clutter. Clutter is identified in (c) the spectral difference map and later removed from (a) and (b) to create (d), which clearly shows only the delamination (minus clutter) as the bright yellow area with anomalous heat flow at the center of this image where temperatures are about 2°C warmer at noon and 0.4°C cooler at midnight.

PICTURESQUE bridges such as the recently famous ones in Madison County, Iowa, have secured a fond place in American hearts. But the fact is that many of them and their less attractive fellows are badly in need of repair. Federal highway officials estimate that 20% of the country's half-million two-lane bridges are structurally deficient.

Beginning in April 1996 and continuing through the summer, a converted motor home will roam the highways in several states, testing a system developed at Lawrence Livermore that can pinpoint the flaws in these well-traversed and rapidly aging bridges. Funded by the Federal Highway Administration (FHWA), this dual-band infrared (DBIR) system uses a technique known as dual-band infrared computed tomography (DBIR-CT), which locates defects in materials by sensing time-dependent temperature differences. (See the box on p. 25 and the images below.) Our system promises to make bridge inspections more reliable, faster, and safer. It also has a wide range of nondestructive inspection and evaluation applications, including unmasking metal corrosion in aircraft skins, assessing structural damage in reinforced concrete buildings, analyzing the integrity of containers of radioactive waste, and identifying corrosion in exposed petrochemical pipelines.



(a) (b) (c) (d)

Finding flaws in the bridges' concrete and asphalt roadbeds and repairing them is expensive—an estimated $3 billion annually. In addition to the dollar outlay, there is the emotional cost: the aggravation that motorists endure while highway crews go about the slow, meticulous task of pinpointing problems. Currently, bridge crews must close lanes to traffic while they conduct visual inspections—looking for potholes, rust stains, cracks, or broken pavement. To detect hidden flaws, they manually drag a chain across the deck, listening for auditory differences that indicate areas of possible cracking—it is a little like rapping your knuckles along drywall, hunting for a secure anchor point. The chain technique, however, is slow, disruptive, unreliable, and costly and raises serious safety concerns. Also, it works only with concrete, not asphalt-covered roadways.

Road-Testing the Technology

The Laboratory's DBIR system provides reliable bridge inspections while minimizing lane closures. It is designed to eliminate the need to shut down lanes for routine inspections or have road crews risk possible injury as they dodge traffic. With the mobile unit, highway crews can conduct their examinations as they ride across a bridge. The Laboratory's system also will let inspectors peer beneath a roadbed's surface to hidden trouble spots before they get out of hand. For example, if defects like rebar corrosion are identified before they become serious, maintenance crews could perform less costly repairs. Delaminations (concrete layer separations beneath the surface) can be discovered before they lead to possibly hazardous potholes. The FHWA team will test the prototype DBIR system this summer by using it to examine bridges and then compare the data collected with the defects road crews actually uncover and repair.

Steve Chase, the FHWA engineer in charge of nondestructive evaluation technology, calls the system, which was developed at the Laboratory, "an evolutionary development in bridge deck inspection." While traditional infrared imaging systems work at only one wavelength, the Laboratory's system collects images at two separate ranges of wavelengths (3 to 5 and 8 to 12 micrometers), allowing greater precision in computer calculations of temperatures. The dual-band system compensates for the influence of surface contamination on materials and surface compositional differences, both of which can skew readings in traditional, single-band systems.

The bridge inspection DBIR system taps into the Laboratory's well-honed expertise in nondestructive inspection and evaluation, developed over the years in support of the nation's nuclear weapons program. The system also capitalizes on ideas proposed by the Laboratory for detection of buried land mines during the Gulf War.

In fiscal year 1994, the Laboratory began adapting the DBIR technology to meet the Federal Highway Administration's needs. Feasibility tests were conducted with tower-mounted infrared cameras, which overlooked asphalt-covered and exposed concrete slabs that served as a surrogate bridge deck. (See the illustrations in the box on p. 25.)

The feasibility tests were used to optimize the DBIR system response to thermal differences between normal and defective concrete structures and to clarify interpretation of corrosion in steel reinforcements that causes hidden delaminations. These hidden flaws are typically masked by clutter from oil, grease, paint, patches, shadows, rocks, wood, plastic, metal, or concrete composition variations.

With good results from the feasibility study, the Livermore team last year mounted DBIR cameras on a telescoping mast located at the front of a motor home that had been converted for field tests. The mobile DBIR Bridge Deck Laboratory successfully completed its first road test in November 1995 on the Grass Valley Creek Bridge near the Northern California town of Weaverville. Scientists were able to view 1-meter-long sections of roadbed approximately 1 meter (3 ft) long and one lane (3 meters or 10 ft) wide while traveling at 40 kilometers per hour (25 mph). VIEW computer codes developed at Livermore sped processing and analysis of the images, which had been recorded and stored on a high-speed hard disk.

Livermore researchers are awaiting results of the spring and summer 1996 shakedown tests by the Highway Administration before planning the next phase of their DBIR activities. The FHWA's Chase is optimistic about the technology's future: "If it proves to be a valuable technology, and I think it will," he says, "there's potential for commercialization by a private company."

Aging Aircraft Applications

According to the Laboratory's Nancy Del Grande, a principal scientist for DBIR inspection capabilities development, the technology has numerous applications in addition to FHWA bridge inspections. The technology has applications in Laboratory programs—identifying thermal stress and damage to optical components used for the National Ignition Facility, measuring emissivity and radiative heat transfer for Stockpile Surveillance, and characterizing the thermal efficiency of the uranium

Dual-Band Infrared Computed Tomography: How It Works

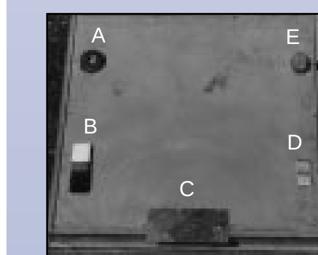
The use of dual-band infrared computed tomography (DBIR-CT) imaging as an inspection tool is based on the knowledge that flawed and corroded areas of a manmade material or structure heat and cool differently than do areas with no defects. DBIR-CT uses two thermal infrared bands to provide time sequences of high-contrast images called temperature maps of naturally or flash-heated materials and structures. When these maps are processed using computer codes developed at LLNL, they unfold the location and amount of hidden defect and corrosion damage. DBIR-CT enables researchers to analyze heat flow patterns at 10 times the sensitivity of single-band systems, to image structural defects in three dimensions, to differentiate surface and subsurface clutter from corrosion damage, and to quantify that damage so that major damage in need of immediate attention can be differentiated from minor defects.

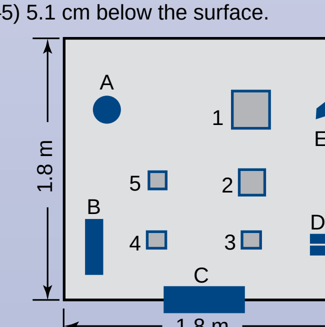
The DBIR inspection and evaluation process works like this (see the figure below): First the material or structure is heated either naturally by the sun or artificially using pulsed lasers, quartz lamps, or flash lamps. Bridge decks, for example, are naturally heated; airplane fuselages are heated by flash lamps. The material or structure is scanned by the DBIR-CT system using two ranges of infrared wavelengths—3 to 5 and 8 to 12 micrometers. The resulting time-sequence temperature maps (Figures c–1 and c–2 below) at each wavelength show heat-flow anomalies that could be caused by defects or corrosion or by clutter such as paint or junk metal on the road surface (in our example below) or subsurface globs of excess epoxy within an airplane skin.

To weed out clutter, the temperature maps are processed using the computed tomography capabilities provided by the VIEW computer code developed at LLNL. The resulting DBIR image-ratio patterns on the temperature map (Figure c–3) showing temperature variations from both surface-only features and from subsurface defects are compared to DBIR image-ratio patterns related to "emissivity noise" (Figure c–4) that show only surface clutter. The clutter from unseen concrete chemical differences stands out clearly on the emissivity-noise map, and when the emissivity-noise patterns are subtracted from the temperature map that shows both emissivity noise and defects, the resulting temperature map (Figure c–5) shows only the flaws—their location, size, shape, depth, and severity.

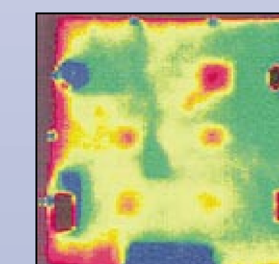
The DBIR system's capabilities shown in the results of laboratory tests (see the figures below) have been confirmed by field tests (see the images bottom of p. 23) and are being put to use in further highway tests by the Federal Highway Administration that began in April 1996.

(a) 1.8-m (6-ft) square concrete test slab 18.4 cm (7.5 in.) thick with (b) five surface clutter sites (A–E) along the perimeter and five Styrofoam delamination sites (1–5) 5.1 cm below the surface.

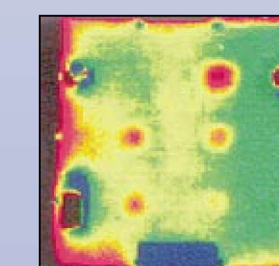




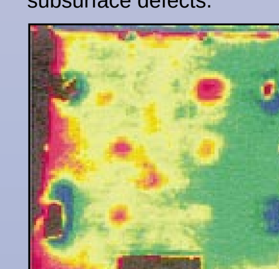
(c–1) 8- to 12-µm long-wavelength temperature map.



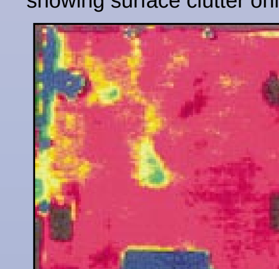
(c–2) 3- to 5-µm short-wavelength temperature map.



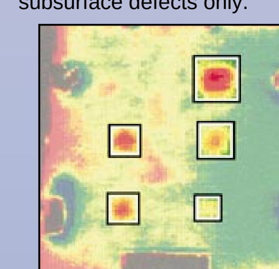
(c–3) Temperature map showing surface clutter and subsurface defects.



(c–4) Emissivity-noise map showing surface clutter only.



(c–5) Temperature map showing subsurface defects only.



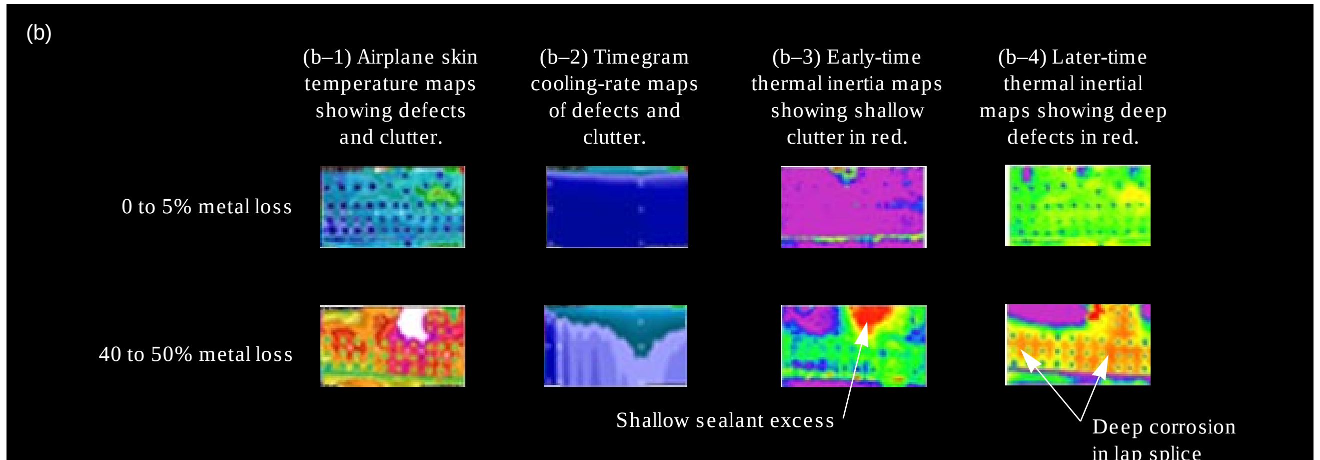
spin-forming process for our Advanced Development and Production Technology. Applications in areas outside Lawrence Livermore programs include detecting corrosive thinning and pitting within exposed petrochemical pipelines, assessing structural damage in reinforced concrete buildings, and analyzing the steel wall thickness and integrity of radioactive waste containers. Since early 1992, Del Grande and her associates have developed DBIR to quantify metal corrosion in aircraft fuselages, with funding from the Federal Aviation Administration's Technical Center.

Currently, aircraft inspectors use visual, ultrasound, and electronic

(a)

Figure 1. (a) Phil Durbin uses the DBIR system scanner, flashlamp, and spectral hood to look for metal loss from corrosion within the skin of an airplane. (b) What the DBIR system sees over time after flashlamp heating. Early- and late-time thermal inertia, temperature, and cooling-rate maps distinguish, through the power of computed tomography, subsurface clutter (shallow sealant excess) from deep corrosion (metal loss) in lapped metal splices.

(b)



Temperature maps (left to right) compare (b–1) airplane skin temperatures at two locations, (b–2) timegram cooling rates at those same locations, (b–3) early-time thermal inertias (0.1 to 0.5 seconds) after flash heating at the locations, and (b–4) late-time thermal inertias (1 to 3 seconds after heating) for (top row) noncorroded or barely corroded (0 to 5% metal loss) aircraft skins and (bottom row) heavily corroded (40 to 50% metal loss).

techniques to look for fuselage defects. However, in order to determine the extent of corrosion damage, the fuselage must be taken apart.

Livermore's DBIR detection methods do not require aircraft disassembly. When applied to aircraft studies, DBIR can show the extent of metal corrosion near the aircraft skin's surface or deep within it. (Figure 1.) It can characterize the type of defects involved—such as gaps or areas with poor adhesive bonds with or without metal loss from corrosion. Also, it can differentiate between corrosion and conditions that may be mistaken for corrosion, such as fabrication ripples, surface roughness, and uneven sealant in a lap joint.

While the DBIR system for bridge inspections relies on natural heat sources, the system for aircraft inspections uses flashlamps and thus relies more on the computed tomography (CT) aspects of the technology than do DBIR bridge inspections. The metal skin is heated with uniform thermal pulses each lasting a few milliseconds. The resulting surface temperature changes, which vary with location and time, are then imaged by the dual-band scanner for analysis by computer. Hotter readings indicate areas of potential corrosion. A patent on the Laboratory's active (flash-heated) and passive (diurnally-heated) DBIR processes for imaging anomalous structural heat flows was issued in August 1995.

Livermore researchers have conducted several DBIR-CT tests on commercial aircraft. A demonstration at Boeing in early 1995 used a uniform pulsed-heat source to stimulate infrared images of hidden defects in an aircraft fuselage. The DBIR camera and image processing system produced temperature, thermal inertia, and cooling-rate maps. In combination, these maps characterized the defect site, size, depth, thickness, and type. LLNL researchers are able to quantify the percent metal loss from corrosion above a threshold of 5%, with overall uncertainties of 3%.

The Laboratory team's goal is to produce a single corrosion defect map that eliminates clutter from excess sealants, ripples, and surface features. Such a map could be incorporated in a commercial DBIR scanner, making it easier to assess damage. The Laboratory has worked out a Cooperative Research and Development Agreement with Bales Scientific Incorporated to commercialize DBIR corrosion inspection technology.

A recent round-robin investigation of nondestructive investigation equipment used to detect hidden corrosion on U.S. Air Force aircraft indicated that false detection of corrosion results in costly, unnecessary, and destructive exploratory maintenance, said Del Grande. "We expect our technology to cut the cost of destructive exploratory maintenance in half by eliminating clutter," she said.

Key Words: dual-band infrared computed tomography, nondestructive inspection and evaluation.

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Other key Laboratory researchers on the DBIR projects are Phil Durbin, Project Manager, Federal Highway Administration project (510) 422-7940 (durbin2@llnl.gov) and Ken Dolan, project manager, Federal Aviation Administration project (510) 422-7971 (dolan2@llnl.gov).

About the Scientist

NANCY DEL GRANDE (née Kerr) received her A.B. in physics from Mount Holyoke College in 1955 and her M.S. in physics from Stanford University in 1957. She joined the Laboratory's Test Program in 1959. She became the first woman to design and conduct an experiment using x-ray spectroscopy to measure the temperatures of nuclear devices stored underground at the Nevada Test Site. She pioneered the technology transfer of x-ray temperature methods for nuclear device diagnostics to the dual-band infrared (DBIR) precise airborne temperature measurement method for detecting underground objects and applied it to depict deep aquifers at the Long Valley, California, geothermal resource area and to locate buried land mines at the Yuma Proving Grounds.

In 1992, she transferred to the Nondestructive Evaluation Section of the Laboratory's Engineering Sciences Division where she has been principal investigator and principal scientist for DBIR imaging projects to detect corrosion in aging aircraft (1992–1995) and delaminations in bridge decks (1993–present). She is the author or co-author of over 50 publications on x-ray spectroscopy and infrared physics and has been issued two patents, one for a technology to identify anomalous terrestrial heat flows from buried and obscured objects, and another a system to image anomalous structural heat flows from corrosion within aircraft skins and bridge decks.