



MISSION, TRADITION, AND DATA REVOLUTION

Los Alamos has a rich legacy of leading computing revolutions,

a legacy that began before computers even existed. The elaborate calculations underpinning the Laboratory's original mission often took months, so in the race against time, when every day mattered, new methods of streamlining were continually devised. Those efforts—both mechanical and mathematical—paid off and secured permanent places at the Laboratory for computers and computation, which have evolved in tandem over the decades.

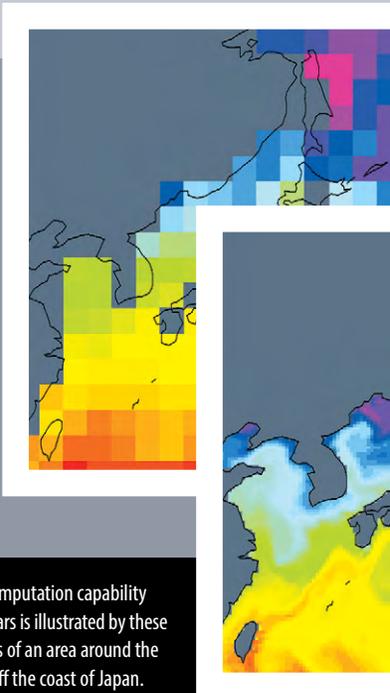
Today the Lab is on the leading edge of a new revolution, born of opportunity. With myriad digital devices now cheaply available, mass quantities of data are being produced, and scientists realized that new ways of managing data are needed and new ways of utilizing data are possible. Thus the field of data science was born. Data science at the Lab falls into two broad categories: pattern recognition-based platforms, such as real-time traffic-navigation assistants or cyber-security software, that evaluate risks, rewards, and characteristic behavior; and physics-based platforms that match models and equations to empirical data, such as how fluids flow through fractures in the earth's subsurface during processes like fracking or underground nuclear detonation.

Presently, Los Alamos data scientists are making advances in machine learning, such that data itself can be the algorithm, instead of a human-coded algorithm. The data come from experiments, for example materials-science experiments geared toward building a better widget.

First, the computer mines the data to figure out what characteristics comprise a better widget, then it explores avenues to arrive at the best widget possible. Human brains are still required to evaluate performance, but the goal is for even this to be automated.

On the other side of the Lab's computing coin lies simulation, a computing revolution born long ago from brute force and necessity. War and defense have long driven human innovation, and as the Lab transitioned from a temporary war effort to a permanent scientific institution, its first electronic computer, MANIAC I, was built to help model thermonuclear processes for new weapons designs. Built in 1952, MANIAC I used von Neumann architecture, an organization scheme envisioned by Manhattan Project scientist John von Neumann. Overseeing MANIAC I was Nicholas Metropolis, who, along with von Neumann and others at Los Alamos, devised the Monte Carlo method—a computational algorithm based on repeated random sampling rather than direct deterministic computation—which spawned a family of methods that remain essential to modern science.

Contemporary with von Neumann and Metropolis were Enrico Fermi, John Pasta, Stanislaw Ulam, and Mary Tsingau, who together are credited with the birth, in 1955 at Los Alamos, of experimental mathematics and nonlinear science. The Fermi-Pasta-Ulam-Tsingau publication (Mary Tsingau, the programmer who coded the first-ever numerical simulation experiments on MANIAC I, was initially excluded from the byline of the publication) describes a paradox in which complicated physical systems exhibit periodic behavior despite predictions



Improvement in computation capability over the past 25 years is illustrated by these climate simulations of an area around the Kuroshio current, off the coast of Japan.

CREDIT: Mat Maltrud/LANL

to the contrary. The scientists initially thought the computer got it wrong, but then they realized it was their thinking that was off, not the computation. It was new physics. It was unexpected and non-intuitive, and it could not have been done without a computer.

As long as supercomputers have existed, Los Alamos has been home to the latest and greatest among them. After MANIAC I came the IBM 701, the first electronic *digital* computer, followed by the faster IBM 704, then MANIAC II, then the IBM 7030, or "Stretch," which is often

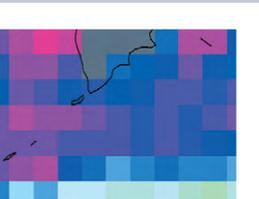
Revolution in computing is a tradition at Los Alamos and is central to the Laboratory's mission.

hailed as the first true supercomputer. Continual innovation in supercomputers over the last six decades has enabled continual innovation in simulation, which, although it began with thermonuclear processes, is now at the heart of many different research efforts at the Lab. For example, numerical models used to predict long-term climate shifts as well as weather (e.g., hurricane trajectories)

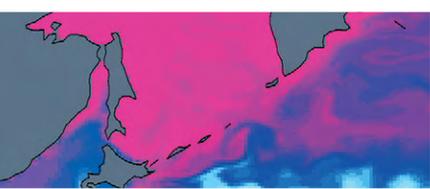
rely on high-performance computing capabilities. Thirty years ago, the best these simulations could do was to parse the weather geographically down to 200-kilometer squares; now they have gotten down to just 10 kilometers.

Although data science and machine learning are the young new arrivals, supercomputing and simulation are the mainstays of the Laboratory's high-performance computing program, and all have their place at the table. By addressing the most complex processes in some of the hardest problems facing science, national labs like Los Alamos are pushing the frontier of science and contributing directly to national security and the global economy. The next milestone on that frontier is exascale computing, the ability to perform a quintillion calculations per second. It's a tall order and a considerable leap from where we are now, but looking back on where we came from, there's every reason to have confidence that Los Alamos will have a leading role in this revolution as well. **LDRD**

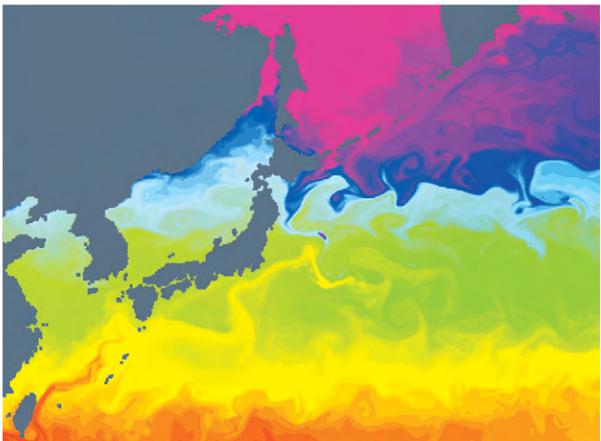
—Eleanor Hutterer



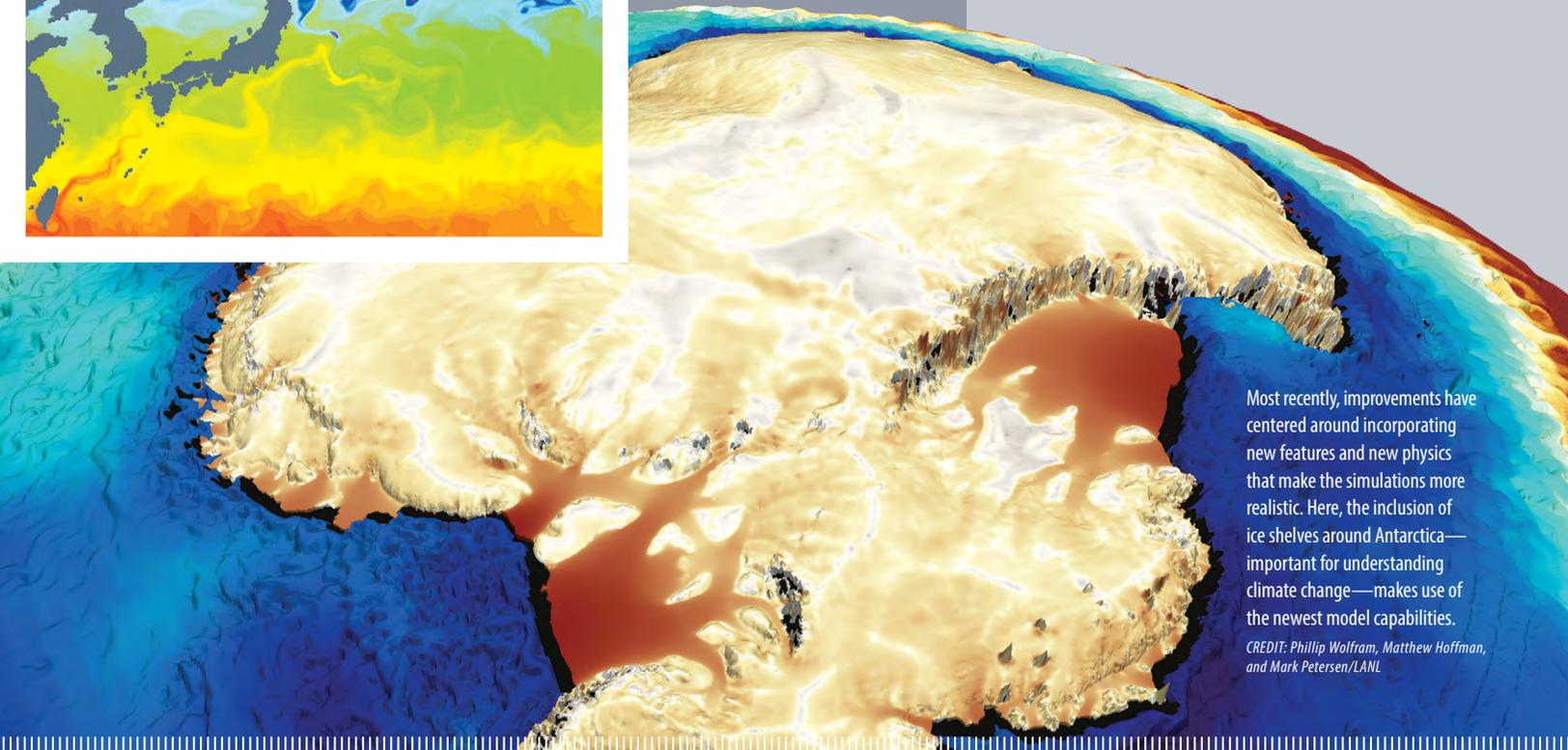
In the 1980s, prior to Los Alamos engaging in climate-simulation research, the best resolution was 2.0 degrees, or about 200-kilometer squares.



In the early 1990s, the Connection Machine, a resident supercomputer, helped bring the resolution down to 0.28 degree, or about 30-kilometer squares. This simulation was presented to President Clinton during one of his visits to the Laboratory and also won a Smithsonian Computer World award.



In the 2000s, additional evolution of supercomputer hardware and architecture enabled the resolution to reach 0.1 degree, or 10-kilometer squares.



Most recently, improvements have centered around incorporating new features and new physics that make the simulations more realistic. Here, the inclusion of ice shelves around Antarctica—important for understanding climate change—makes use of the newest model capabilities.

CREDIT: Phillip Wolfram, Matthew Hoffman, and Mark Petersen/LANL

The Laboratory has been home to many Nobel laureates. But in only one instance was the prize-winning work done during the winner's tenure at Los Alamos. That was in 1956, when Fred Reines and Clyde Cowan proved the existence of a new kind of subatomic particle, the neutrino. Since then, neutrino science has continued at the Lab and elsewhere, leading to three more Nobel Prizes. Now, new experiments at Los Alamos are poised on the brink of a new discovery, which looks to be just as exciting as any of them.

In 1930, theoretical physicist Wolfgang Pauli proposed that a new particle—invisible and uncharged—was needed to satisfy the law of conservation of energy during radioactive decay of atomic nuclei. Pauli used the name “neutron,” which was the same name given to another, more massive particle. Pauli's contemporary Enrico Fermi, who would later join the war effort at Los Alamos, resolved the nomenclature problem by giving the less massive particle the Italian diminutive “-ino,” and *viola!* The neutrino.

Scientists now know that neutrinos are among the most abundant particles in the universe—hundreds of trillions of them stream unobtrusively through our bodies every second of every day. So far, three varieties are known: the electron neutrino, the muon neutrino, and the tau neutrino. Neutrinos are almost completely inert, interacting with other particles only by gravity and by the weak nuclear force. In fact, Fermi based his original postulation of the weak nuclear force on Pauli's proposed, and still hypothetical at the time, new particle.

In the early 1950s, as the Laboratory was expanding from a war-time weapons lab to an institution with broader interests, Reines and Cowan, spurred by the general

consensus that it was impossible, set out to capture the elusive neutrino. Because neutrinos are so inert, the likelihood of one interacting with a detector is remote, so a tremendous number of neutrinos is needed to be able to observe just one. The duo initially intended to use an underground nuclear bomb test as the source of this tremendous number of neutrinos, but they quickly determined that a nuclear reactor would be better, so they took their detector—a rig about the size of a modern washing machine—to the reactor at Hanford, Washington.

After preliminary work at Hanford, the team decided to build a bigger and better detector at the brand new reactor in Savannah River, South Carolina. It was there that they finally and conclusively observed the electron antineutrino—the antiparticle of the electron neutrino, whose very existence proved the existence of the other. Reines and Cowan sent a jubilant telegram to Pauli in Switzerland informing him of their success. Clyde Cowan died in 1974, and Fred Reines alone was awarded the Nobel Prize in 1995 for their work.

Nowadays most neutrino detectors are much, much larger. Usually they are international collaborations involving thousands of tons of liquid in enormous vessels thousands of feet below the surface of the earth. But the latest neutrino detector at Los Alamos, though larger than the first, is still quite small, just three meters tall, and shaped like a pressure cooker.

Reines and Cowan relied on brute force and brilliance, but this latest Los Alamos neutrino detector has the benefit of serendipity as well. It turns out that the proton beam at the Los Alamos Neutron Science Center—established in 1972 to study the short-lived subatomic



Fred Reines (left) and Clyde Cowan inspect their neutrino detector in 1955, a predecessor to the one they used in 1956 to prove the existence of the elusive neutrino. Forty years later and 21 years after Cowan's death, Reines alone was awarded the 1995 Nobel Prize in Physics for their shared discovery.

CREDIT: LANL photo archive



BRINGING NEUTRINOS BACK TO LOS ALAMOS



Bill Louis (left) and Richard Van de Water inspect their neutrino detector, CAPTAIN-Mills (“CAPTAIN” for Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos, and “Mills” in honor of their colleague and friend, Geoff Mills, who passed away in 2017).

CREDIT: Michael Pierce/LANL

Los Alamos scientists were the first to detect neutrinos. Now a new batch of scientists is going after a new kind of neutrino, even harder to find than the first one.

particles known as pions—is an abundant source of neutrinos, which are a natural byproduct of charged pion decay. Also, the three-meter-tall pressure cooker, which was built by a different group in 2014 for an unrelated experiment, was no longer needed and was up for grabs. In 2017, Richard Van de Water and Bill Louis acquired it and are now in the process of converting it into a liquid argon-based detector to prove the existence of an as-yet hypothetical neutrino variant: the sterile neutrino.

Whereas regular neutrinos are *almost* inert, interacting only by the weak force and gravity, sterile neutrinos, if they exist, have to be *completely* inert, interacting by none of the known forces of particle physics, only gravity. For a decade, Louis and collaborators ran the Liquid Scintillator Neutrino Detector experiment at Los Alamos, which, via the same reaction picked up by Reines and Cowan, led to the first experimental evidence of sterile neutrinos. Presently, Louis and Van de Water collaborate on the Mini Booster Neutrino Experiment at the Fermi National Accelerator Laboratory near Chicago, which, by way of a different reaction, has produced even more convincing evidence for sterile neutrinos. The pressure-cooker detector is designed to detect sterile neutrinos in yet a third way: by the oscillation of muon neutrinos into sterile neutrinos, which will look like muon neutrinos disappearing.

Many scientists thought neutrinos could be important to resolving the dark matter conundrum—i.e., what it is and how it works—but the mystery persists. Now the idea of sterile neutrinos is tantalizing as a possible portal to the dark sector. If sterile neutrinos really do exist, it will be the biggest thing in subatomic physics since the quark. If not, it will still be a big deal, because whatever Louis and Van de Water are measuring, it's not nothing. It's definitely something.

There is a shared sense among physicists that there is not-yet-discovered physics at hand, and everyone is drilling in a different place to find it. Louis and Van de Water are drilling at the place where medium-energy muon neutrinos can transform into sterile neutrinos. They've seen it with two different experiments so far, and they're going for a hat trick.

Some say it can't be done. That it's impossible. But then, they've said that before. **LDRD**

—Eleanor Hutterer



FROM TRASH TO 100-TESLA TREASURE

Inside a strange building with five-foot-thick concrete walls

and six-foot-diameter portholes resides a family of magnets unlike any others in the world. This is the Pulsed-Field Facility (PFF) at Los Alamos, a paragon of ingenuity and one of three facilities that comprise the National High Magnetic Field Laboratory, (the Magnet Lab). The building itself was inherited from another project, hence the anachronistic portholes. So too was the enormous motor-generator that powers the magnets from the more conventional building next door. This generator, once dormant and destined to be scrapped, is what makes the record-setting magnetic fields at this world-class research facility possible, though it was never intended for this purpose.

In the mid 1980s scientists at Los Alamos were planning a new facility, the Confinement Physics Research Facility, to study nuclear fusion. The project required strong magnetic fields, which in turn required a very large power source for the intended electromagnets. Unlike permanent magnets, electromagnets are transient and are only magnetic when powered by electricity. After scouring the country, the scientists happened upon a giant sleeping in a Tennessee field, near the banks of the Cumberland River.

The behemoth lay in pieces inside a warehouse, its life seemingly over before it had begun. The nearly 700-ton Swiss-made steam turbine generator was one of several that had been purchased new a decade earlier by the Tennessee Valley Authority for the planned, and then abruptly canceled, Hartsville Nuclear Plant. Never even assembled, it was sold to Los Alamos for little more than the price of scrap.

The 1200-mile journey west began in 1987 and required numerous feats of engineering, as the generator, weighing about the same as four large blue whales, was the heaviest single load ever to travel on New Mexico roads. First, the stator and the rotor, the two largest pieces of the generator, were repacked into their original crates and loaded onto a barge, which traveled down the Cumberland River to the Ohio River, then by way of the Mississippi River to the Arkansas River

roads, and used special temporary bridges and load spreaders for the 17 bridge and culvert crossings along the way.

Bizarrely, no sooner was the enormous generator finally installed in its brand new building, than the plasma confinement project, like the nuclear power plant, was abruptly canceled. It was late 1990 and the rotor had been turning for one week.

Meanwhile, elsewhere on the Hill, discussions were under way about Los Alamos joining a National Science



and into Catoosa, Oklahoma. Next, the crates were loaded onto special train cars custom built for the second leg of the voyage, a convoluted rail route dictated by bridge weight restrictions, to Lamy, New Mexico. Finally, in the spring of 1988, the generator completed its journey with much fanfare, traversing the 65 miles from Lamy to Los Alamos by road, in a slow-moving convoy that drew crowds, closed

The nearly abandoned and still new motor generator leaves Tennessee on a barge, headed for the big-time at a new plasma-confinement facility in New Mexico. *CREDIT: MagLab photo archive*

Foundation collaboration, as the site of a new pulsed-field facility for the Magnet Lab. One aim of this proposal was to build the first long-pulse 60-tesla magnet. (A tesla is a large unit of magnetic field strength; even a hospital MRI usually



The Pulsed-Field Facility draws scientists from around the world to Los Alamos.

Despite the plasma-confinement gig falling through, the motor generator has indeed found fame and glory as the source of power for world-record-setting magnets at the National High Magnetic Field Laboratory's Pulsed-Field Facility. CREDIT: Michael Pierce/LANL

operates at only 3 tesla). Among the Laboratory's assets were an essentially new generator, recently orphaned and ready to power the proposed 60-tesla magnet, and a robust body of expertise in explosives-generated high magnetic fields and capacitor banks. And so Los Alamos was chosen as the home of the PFF.

This time the project didn't fold, and over the past 28 years the generator has powered the PFF to new limits and world records. In 1997 the facility achieved the original goal of generating the first 60-tesla pulse to last longer than 100 milliseconds. And in 2012, facility scientists set a world record for the highest non-destructive magnetic field with their "100-tesla shot," a heart-stopping moment during which the facility's largest magnet surpassed 100 tesla for a thousandth of a second. That magnet, the crown jewel of the facility's user program, now routinely provides 95 tesla for scientists from around the world.

The machine behind the magnets alternates between motor and generator. First it's a motor, spooling up to store electrical energy from the grid. Then it's switched into generator mode and dumps this energy as a short but incredibly powerful burst—the generator itself is capable of a staggering 1.4 gigawatts—into the waiting electromagnets. All that power can raise a large magnet's temperature from -200°C to room temperature in a second or two. Between the heat from the current and the force from the magnetic

field itself, these extreme electromagnets can only be used in quick pulses, lest they melt or blow themselves to bits.

The PFF boasts the most reproducible high-field magnets in the world. Scientists studying the physical properties of metals or superconductors, for example, need many pulses to really learn anything useful. A tiny sample of the material of interest is placed in the bore of the magnet, the magnet is turned on, measurements are made, the magnet is turned off, and the whole thing is reset to go again. On any given day, multiple teams of scientists from around the world may be running experiments; during the 100-tesla shot, experiments on eight different materials were performed simultaneously.

The PFF at Los Alamos embodies a coalescence of capabilities: very high magnetic fields, unique magnet designs and pulse shapes, exquisite temperature control, and innovative probes and measurement technologies. These capabilities, in concert, keep the facility at the forefront of the institutional, national, and global materials-research communities.

Sometimes it takes the very large—like a football-field-sized facility—to understand the very small—like the subatomic properties of semiconductors. And sometimes it takes three tries for a gigantic generator to find its fate.

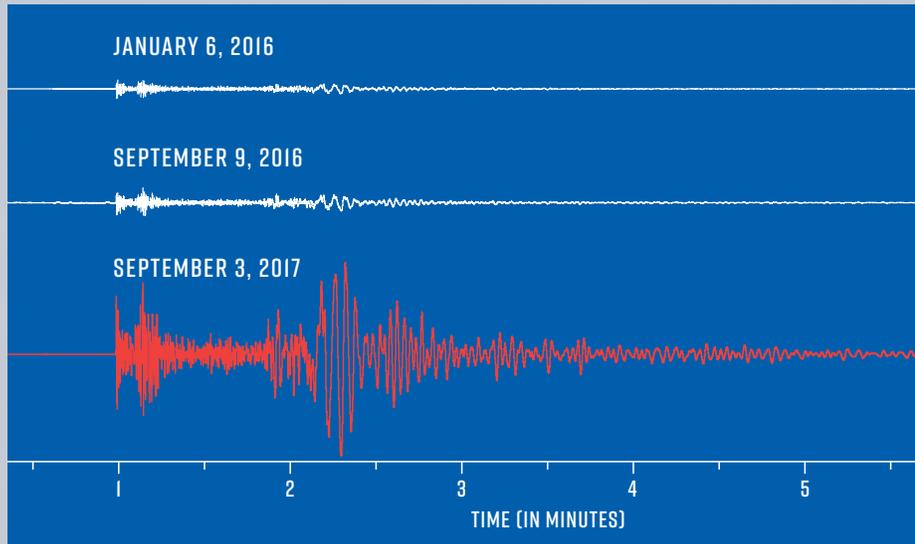
—Eleanor Hutterer

Nuclear weapons have existed for

73 years. And for 73 years, scientists have been monitoring nuclear detonations from afar by the vibrations they send through the ground beneath our feet. But nuclear explosions aren't the only events that produce tremors in the earth; earthquakes, volcanic eruptions, mining operations, and chemical explosions all produce seismic signals. In keeping with the Laboratory's national security mission, when something sizeable makes the ground shake, Los Alamos scientists need to be able to say, with certainty, what it was.

The first nuclear detonation—the Trinity test—took place at 5:29 a.m. on Monday, July 16, 1945, near Alamogordo, New Mexico. Numerous seismometers (some incidental, having been permanently deployed by universities, observatories, or other agencies, and some temporary, having been set out specifically for the test) were located at various distances from ground zero. Most of the temporary devices registered virtually no activity, but at least three of the permanent devices did pick up something. At a U.S. Coast and Geodetic Survey station in Tucson, Arizona, 270 miles away from Alamogordo, at approximately 5:30 that morning, a seismometer needle suddenly began to move, swinging rapidly up and down across the slowly rolling paper for about three minutes. The survey-station scientists didn't know it at the time, but they had just seismically detected, for the first time, a nuclear detonation.

For the first two decades of the nuclear age, as different countries developed their own weapons, tests were usually conducted above ground, so monitoring technology focused on signatures in the air. In 1963, the Limited Test Ban Treaty forced nuclear testing to move underground and, as a result, seismology became a national security research priority. Throughout the Cold War years, seismology was used to help discriminate explosions—both chemical and



nuclear—from earthquakes whenever and wherever they occurred in the world.

More recently, however, smaller-magnitude events have made the challenge of detection and characterization more complex. The information about these smaller, suspect events is embedded in a noisy background of nuisance events, occurrences in our busy world that produce seismic signals. So as the real signals are getting smaller, the background noise is not, and distinguishing between the two presents a formidable technical challenge.

During the Cold War, ground-based nuclear-detonation detection was comparable to studying an aerial image and asking, "Is there a city there or not?" Now, because scientists are looking for finely detailed signals in an overwhelmingly noisy background, the analogous query would be, "Is there a vehicle parked on a particular corner, and if so, is it a car or a truck?"

Seismically, small explosions look more like earthquakes than large explosions do. To distinguish between explosions and earthquakes, scientists need to understand the effects that surface topography, local geology, and subsurface structure have on

Modern seismograms are computer generated, allowing for finer and more detailed analysis. These three traces were produced by a detector located in China and record the most recent announced nuclear-weapons tests conducted in the Democratic People's Republic of Korea (North Korea), which publicly claimed that the last one was a thermonuclear weapon, also known as a hydrogen bomb.



READING RUMBLINGS IN THE EARTH

the signals they receive. There are regional differences in the way seismic signals propagate through the subsurface, depending on the unique geology of each region. In the 1990s, Los Alamos, in coordination with several other national labs and federal entities, began the Ground-based Nuclear Detonation Detection program. The goal was to leverage decades' worth of underground nuclear test data to create new systems for monitoring and characterizing potential nuclear explosions around the world.

Gone are the days of pen-to-paper seismographs—modern seismology is conducted with computers. And seismology at Los Alamos is conducted with supercomputers. Large computational experiments help scientists understand how seismic waves propagate from a single source through the earth and into the atmosphere. This understanding, in turn, helps scientists discern different types of man-made explosions as well as natural disturbances.

As the Laboratory develops machine-learning techniques to help meet challenges across many fields, the Ground-based Nuclear Detonation Detection program is leveraging these capabilities to help solve the signal-to-noise discrimination problem. The program is building a reliable, predictive computer-modeling framework that uses multiple signatures. Rather than relying on a single signature, this approach to explosion monitoring combines ground-based

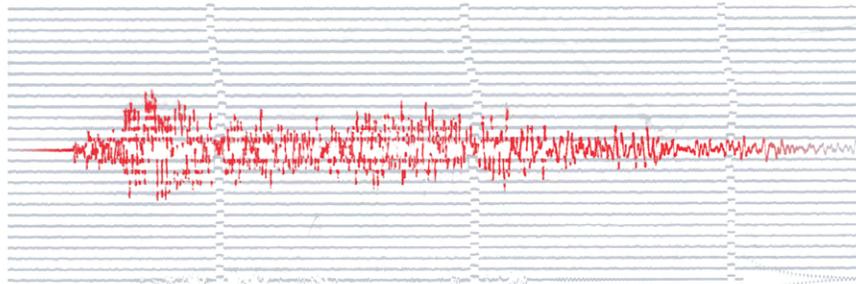
seismic and acoustic data with chemical, satellite, and ocean data into a comprehensive explosion monitoring system.

With a combination of supercomputer simulations, newly developed analytical techniques, and expanded data sets available for monitoring activity across the globe, the new system will build on the Laboratory's confidence in its detonation-detection and evaluation abilities.

The national labs take on the hardest scientific problems, and the toughest technical tasks, all in support of the nation's security. At its inception, the Laboratory was tasked with building the bomb, and the capabilities that have evolved from that first charge continue to serve the Laboratory's mission, 75 years later. Los Alamos achieves the tasks of monitoring nuclear programs, ensuring treaty adherence, and continuing stockpile stewardship through the most rigorous and robust scientific capabilities.

So when something makes the ground shake, somewhere in the world, scientists here at Los Alamos are primed and ready to determine what, where, and how big it was.

—Eleanor Hutterer



The first-ever nuclear-weapon test, the Trinity test, is recorded on this seismogram, from July 15 and 16, 1945, from a seismometer located in Tucson, Arizona, as part of the U.S. Coast and Geodetic Survey. At approximately 5:30 a.m. on the 16th, a seismic disturbance lasting about three minutes was recorded, which, though not known at the time by survey scientists, was caused by Trinity, 270 miles away.

CREDIT: This image was scanned from a microfilm that was produced in the course of the Historical Seismogram Filming Project of the 1980s (<http://ds.iris.edu/seismo-archives/info/publications/Lee1988.pdf>). The U.S. Geological Survey in Denver, Colorado, holds both the microfilm and the original document. Digital scan courtesy of Jim Dewey/USGS.

Whether a seismic disturbance came from an earthquake, an industrial accident, or a nuclear weapon, scientists need to know.