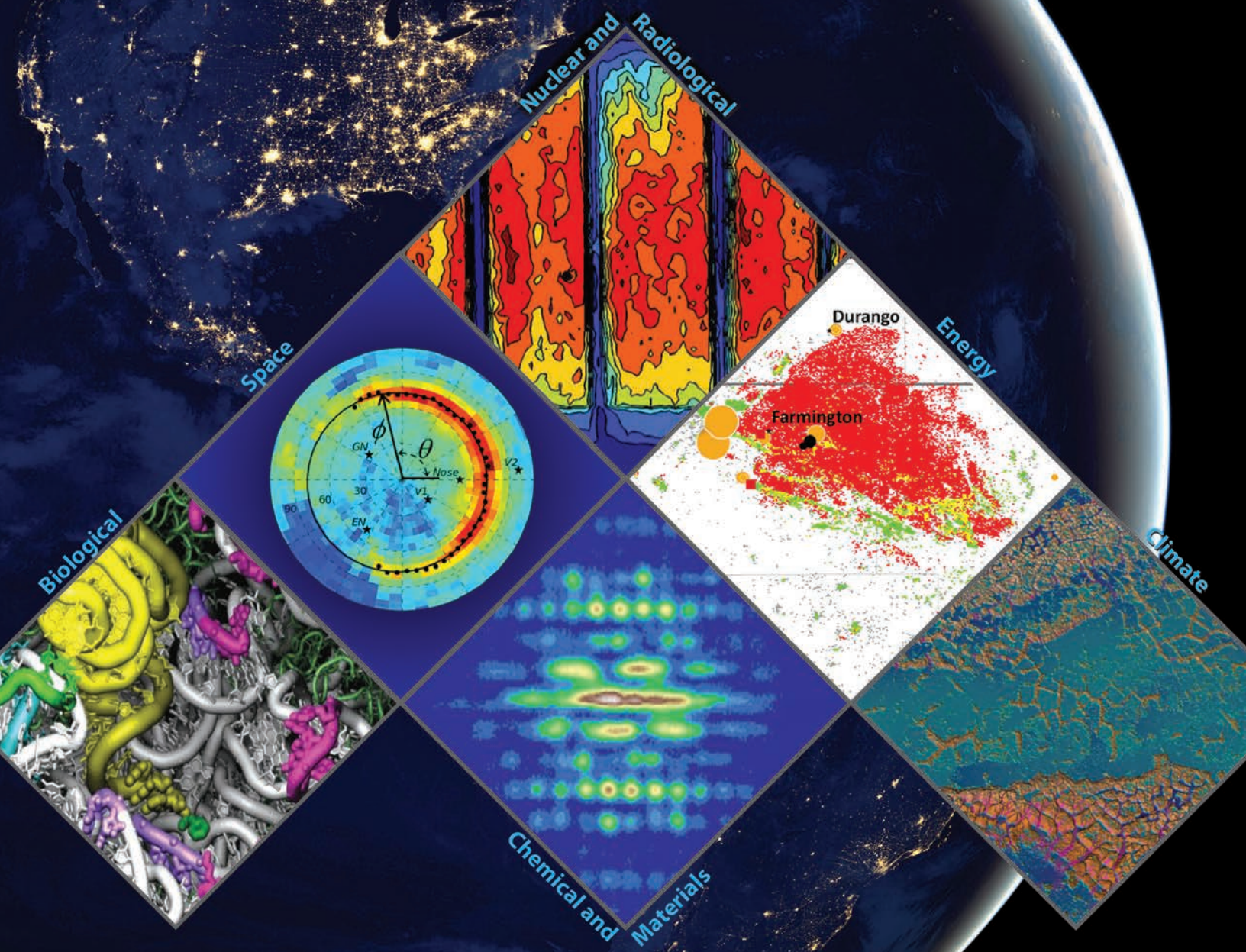
2014 update

Science of Signatures

SoS: A Los Alamos National Laboratory Science Pillar



Los Alamos
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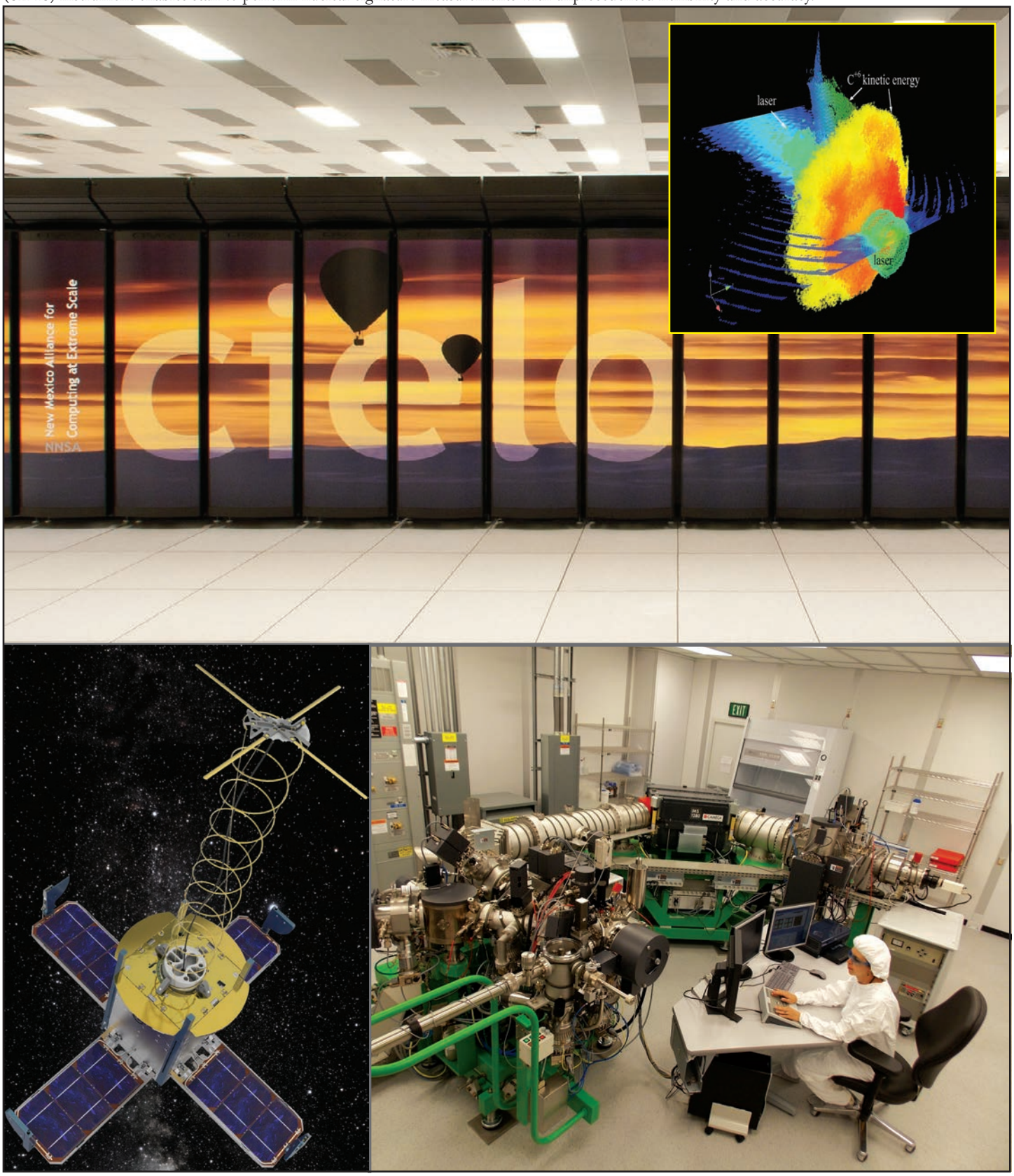
Signatures at Los Alamos National Laboratory

Projects that involve signatures are taking place in every corner of the Laboratory. *Top.* One of the world's most powerful computers, Cielo is a Cray Computing system and a project of ACES, the New Mexico Alliance for Computing at Extreme Scale, a joint project of Sandia and Los Alamos national laboratories. Cielo is the next-generation capability-class platform for the Advanced Simulation and Computing Program, and it allows signature modeling and analysis in unprecedented ways. *Inset.* A simulation of ion acceleration. *Bottom left.* "Cubesats," at 10 cm per side, are satellites small enough to hold in one hand and are in the process of revolutionizing space-based sensing. *Bottom right.* A Cameca secondary ion mass spectrometry (SIMS) instrument enables staff to perform nuclear signature measurements with unprecedented flexibility and accuracy.



Cielo super computer and Cubesat: LANL Image Library. SIMS: Josh Smith.

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About the Cover

Radiological and nuclear: A simulated micro-X-ray fluorescence map of fuel pellets inside zircaloy tubing. This technology is under development to characterize actinides in nuclear fuels and for nuclear forensics. Space: The Interstellar Boundary Explorer (IBEX) mission was a LANL-supported satellite launch that is making a map between the solar system and interstellar space. Chemical and Materials: An Optimal Dynamic Detection (ODD) technique based on shaped laser pulses is developing into the next generation tool for stand-off explosives detection. Show here is a femtosecond shaped laser pulse. Biological: A technique using ribosome simulations is allowing researchers to look for new antibiotics. Climate: Microtopography simulations of surface and subsurface hydrology in permafrost regions will help predict the impact of a thawing arctic on carbon in the atmosphere. Energy: An instrument that gives real-time measurement of gas emissions from a power plant in the 4 Corners region of the USA helps predict the results of energy choices. Background image: NASA's Earth Observatory, nasa.gov.

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Foreword

This 2014 update to the Los Alamos National Laboratory (LANL) Science of Signatures (SoS) strategy represents more than just a "freshening up" of the first version, which was released in 2012. In the past two years, the Science of Signatures has matured significantly, and individual plans for our areas of leadership have been launched. Perhaps even more importantly,the Laboratory's core strategic approach has also evolved, and a new Laboratory plan describing it was released in early 2014. That plan (see page 8) clearly articulates our mission and the roles that the science pillars play in helping to achieve it. What has not changed is the basic importance of signatures to national security and the ways in which we seek to understand them. LANL is often asked to detect and measure the characteristics of complex systems and to use the resulting information to quantify the system's behavior. The SoS pillar is the broad suite of technical expertise and capability that we use to accomplish this task. With it, we discover new signatures, develop new methods to detect and measure signatures, and deploy new detection technologies.

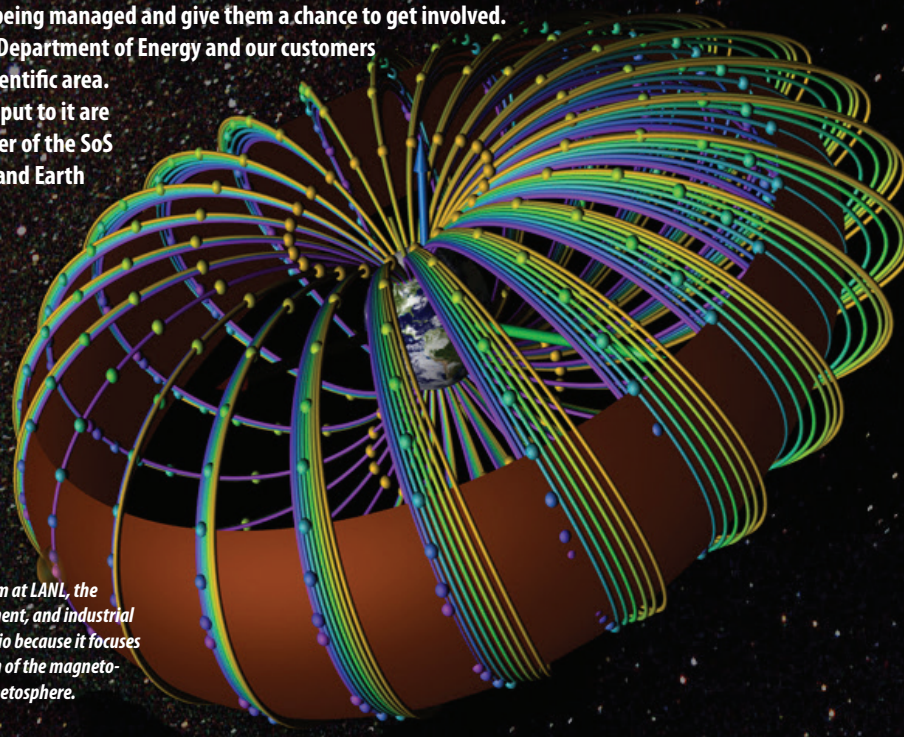
The breadth of work at LANL in SoS is impressive and spans from the initial understanding of nuclear weapon performance during the Manhattan Project, to unraveling the human genome, to deploying laser spectroscopy instrumentation on Mars. Clearly, SoS is a primary science area for LANL and we foresee that as it matures, new regimes of signatures will be discovered and new ways of extracting information from existing data streams will be developed. These advances in turn will drive the development of sensing instrumentation and sensor deployment.

The Science of Signatures is one of four science pillars championed by the Laboratory and is vital to supporting our status as a leading research institution. As with the other pillars (Materials for the Future, Nuclear and Particle Futures, and Information Science and Technology for Predictive Science), SoS relies on the integration of technical disciplines and the multidisciplinary science and engineering that is our hallmark to tackle the most difficult national security challenges. The pillar really began in 2012 when a team of science leaders from across the Laboratory worked to develop a SoS strategy that positions us for the future. Although the crafting of this strategy has been championed by LANL's Chemistry, Life, and Earth Sciences Directorate, SoS is truly an Laboratory-wide effort. As the list of participants on the inside cover shows, the pillar has engagement from science organizations across LANL. This process tapped the insight and imagination of many LANL staff and managers and resulted in a strategy that focuses on our strengths while recognizing that SoS is dynamic.

The following pages highlight the interdependence between SoS, advances in materials science, advances in nuclear and particle science, and advances in information technology. The intent is that SoS shape and inform Los Alamos investments in nuclear forensics, nuclear diagnostics, climate, space, energy, and biosurveillance; the areas of leadership that you will read about in this strategy document.

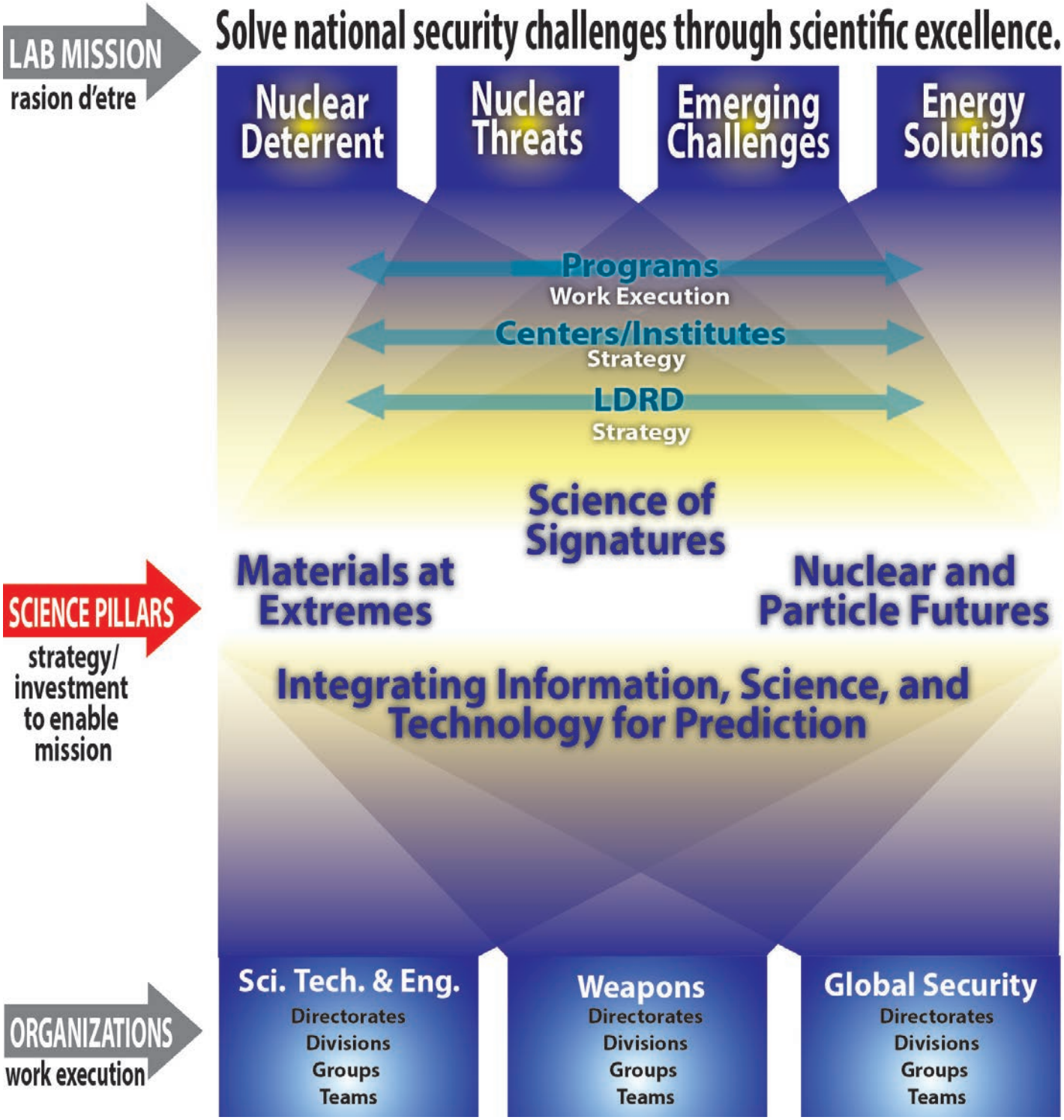
The Science of Signatures is still a relatively new strategic direction for the Laboratory. The primary purpose of this document is tell Laboratory staff how SoS is being managed and give them a chance to get involved. A second important purpose is to inform the Department of Energy and our customers of our capability growth in this important scientific area. Questions concerning the SoS strategy and input to it are welcomed and may be directed to any member of the SoS Leadership Council or to the Chemistry, Life, and Earth Sciences Directorate Office.

– Nancy Sauer, Associate Director for Chemistry, Life, and Earth Sciences



Originally developed under the Laboratory-Directed Research and Development (LDRD) program at LANL, the Dynamic Radiation Environment Assimilation Model (DREAM) now includes academic, government, and industrial collaborators. DREAM represents an important part of the space situational-awareness portfolio because it focuses on assimilating disparate, sparse data streams to provide space weather in almost any location of the magnetosphere, as well as providing predictions based on solar-wind input and its coupling to the magnetosphere.

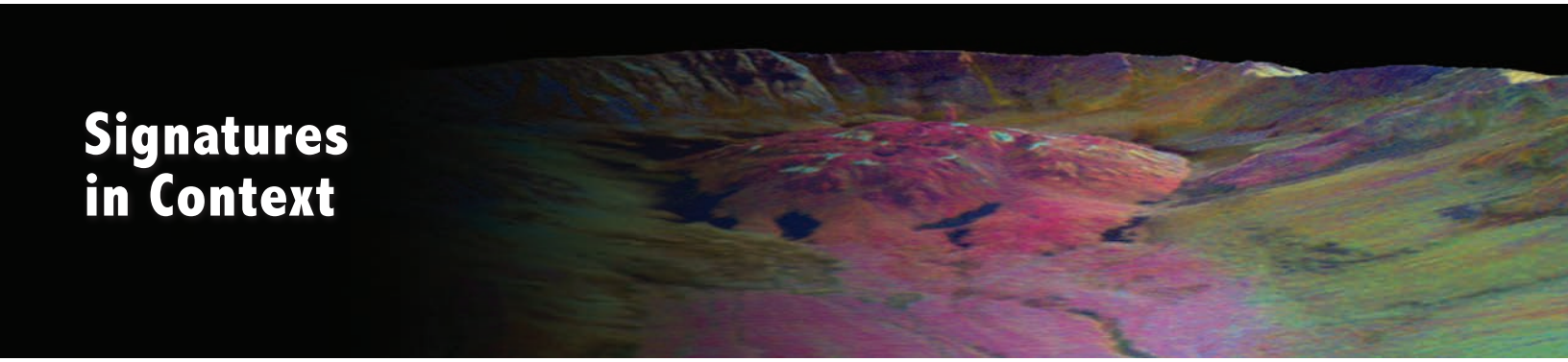
How LANL Plans for the Future



Directorates, divisions, groups, and teams are organized into the three major areas of Science, Technology and Engineering; Weapons; and Global Security (our principal associate directorates, or PADs). The science pillars are a conceptual framework that enhances and organize science activities that cross-cut these areas. They do so by forming the basis for our investments in equipment, facilities, and people. Additionally they are the framework for structuring our other major strategic tools: LDRD, and the Laboratory institutes and centers. The end goal of the pillars, then, is to enhance our ability to meet the major components of our mission now and in the future. Page 8 of this document has additional information on how we plan for the future.

In its broadest and simplest sense, a "signature" is any information that is unique, recognizable, and useful. A handwritten mark as a means of demonstrating authorship and authenticity is a familiar example, as is

Signatures in Context



the pattern-recognition skill that allows us to distinguish spinach from poison ivy. Phrased differently, signatures come from both raw signals and from information that can then be translated into knowledge.

By this definition, signatures are the way we interpret our world, and we have used them throughout history to guide our decisions. Today, advanced science and technology enables us to access unprecedented volumes of data related to previously inaccessible aspects of our environment. An accurate interpretation of this data allows us to perceive, predict, comprehend, and react appropriately to changing situations in the world around us. Given that the problems facing us today are among the most challenging in the history of our nation (perhaps of our species), understanding signatures is an important part of preserving our present and securing our future.

At Los Alamos, the Science of Signatures (SoS) is the application of our complete technological toolbox to intransigent problems in system identification and characterization for global security, nuclear defense, energy, and health. The vision of SoS is to use our tools to achieve meaningful measurement and generate useful knowledge in complex environments. Examples with sweeping benefits range from observing and understanding the triggers and implications of climate change, to identifying the illicit manufacture or transportation of nuclear devices, to recognizing the onset and progress of disease.

Making significant headway against problems of this scope requires using a highly integrated, multidisciplinary approach that draws on all the traditional strengths of the Laboratory. In addition to the Science of Signatures, these strengths are gathered under the headings of the other three science pillars; Materials for the Future (Materials); Integrating Information, Science, and Technology for Prediction (IS&T); and Nuclear and Particle Futures (NPF).

The Materials and IS&T pillars are tightly integrated with the SoS pillar; new materials and new instruments are required as new signature types and requirements are identified, and advances in information science are needed to extract meaningful information out of increasingly complex backgrounds. This relationship is described in greater detail in the following pages.

At Los Alamos, the Science of Signatures is the application of our complete technological toolbox to intransigent problems in system identification and characterization for global security, nuclear defense, energy, and health.

At Los Alamos, we believe that the biggest science breakthroughs will come as we work across boundaries and approach difficult problems in revolutionary ways. To solve specific problems, we draw upon physicists, biologists, computer scientists, chemists, materials scientists, earth scientists, space scientists, decision scientists, engineers, and numerous other disciplines as required.

The advantage of the four pillars approach is that it gives these experts a framework for applying their skills across traditional boundaries. The case studies in this strategy document describe some of the innovations that have already been achieved using this approach. Going forward, our challenge will be to nurture and grow the Science of Signatures and the other three pillars in ways that allow us to build on that history of innovation and achieve our mission with unprecedented excellence.

Unprecedented in History

We can trace the roots of the Science of Signatures concept back to the Manhattan Project and the inception of the Laboratory. One of the science challenges during that time was to understand how a nuclear device performed. Although the theoretical underpinnings of performance were understood, there remained pressing questions. How did that theoretical understanding conform to the experimental reality of a nuclear explosion? What were the observables of value, or "signatures," that would verify and validate the theory? What were the prompt diagnostics (measurements in extreme conditions) that would give us information that would advance our ability to computationally model how the nuclear device worked? What were the radiochemical diagnostics (first air samples from atmospheric testing and then soil samples from underground testing) that would advance our understanding of the nuclear processes that occurred during a nuclear weapon explosion? How did those nuclear processes contribute to device performance? What isotopic tracers could we add to the device that would provide information, in addition to the information developed from the nuclear materials?

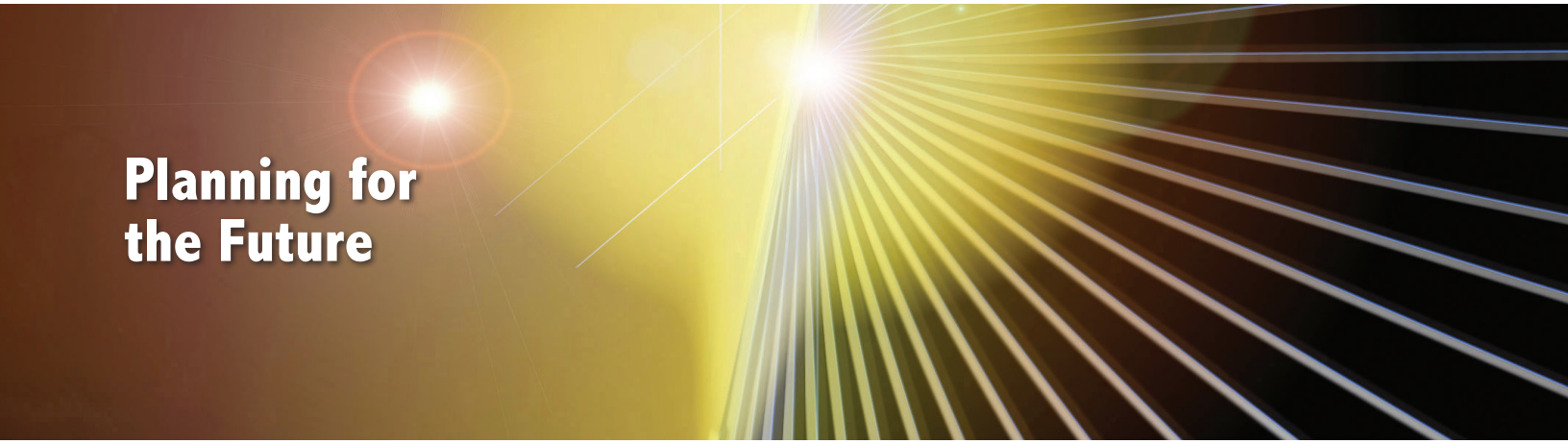
Robert Oppenheimer (left) with General Leslie Groves (right) at the Trinity Site, location of the first nuclear explosion, which took place on July 16, 1945.

These questions spurred the development of a completely new area of science–nuclear signatures. It evolved from first principles directed at developing the tools required to understand nuclear weapon performance, first in atmospheric testing and subsequently in the subsurface environment of the underground testing program. Many of today's recognized nuclear signature techniques directly tie to the science that was developed during that time.

The body of scientific knowledge that grew from these origins is foundational today to our stockpile stewardship mission of understanding nuclear weapons performance without testing. It is equally as important to our capabilities in nuclear and radiological forensics that have been and will be applied to understanding future nuclear events, such as reactor accidents, rogue state nuclear activities, and terrorist attacks. This history and current mission scope give us unique breadth and depth of knowledge applicable to understanding these types of nuclear events.

The Trinity Site from the air.

In 2014, Los Alamos National Laboratory (LANL) published the document *Proud Legacy, Bold Future* to codify our scientific strategy. This document describes our core mission areas and the four science pillars that



Planning for the Future

underpin our service to the nation. We

- Provide a safe, secure, and effective stockpile;
- Protect against nuclear threats;
- Counter emerging threats and create new opportunities; and
- Provide solutions for energy security.

These missions require a robust and flexible science base that we manage and develop using our Science Pillars.

- Materials for the Future (Materials)
- Science of Signatures (SoS)
- Nuclear and Particle Futures (NPF)
- Integrating Information, Science, and Technology (IS&T) for prediction.

The Science Pillars, along with our Laboratory Directed Research and Development strategy (LDRD), our innovation strategy (guided by the Feynman Center for Innovation), and our user facilities comprise our plan for success.

Our vision for SoS is expansive because the capabilities and tools we use are applicable to a broad range of national security issues and emerging national challenges. These challenges include nuclear forensics (a traditional strength), as well as global climate change, signatures of energy production and utilization for understanding environmental impacts, and global biosurveillance for infectious disease progression or other pathogen impacts. Equally important to armed forces and public security are the problems of detecting and mitigating chemical threat agents, and of detecting and characterizing explosives. The science challenges presented by these application areas validate the decision to establish the Science of Signatures as a key component our Laboratory's science and technology base. To meet these challenges, we draw on our extensive experience in remote sensing and space signatures; in nuclear, chemical, biological, earth, and materials science; and in modeling and high-performance computing.

The pillar concept is a primary tool the Laboratory uses to plan for how we will accomplish both current and future missions. The graphic to the right shows how application needs (in blue) can be addressed using the SoS approach. National security/defense encompasses traditional core areas of strength, and energy and climate are areas of pressing national need. "Health" is included under the traditional LANL mission area of "emerging needs" and is called out explicitly because it is clear that many of the critical science challenges of the 21st century will come from this direction.

Science Theme Descriptors

There are three science themes (next page) that guide the development of application in the areas of national security/defense, energy/climate, and health.

SoS Vision

Achieve meaningful measures and knowledge generation in complex environments.

SoS Mission

Characterize measures, signals, and properties in or of complex systems. Detect or attribute change and predict behavior and impact across scales of space (subatomic to astronomic) and time (femtosecond to geologic).

1. Discover signatures

Identify signatures of chemical, biological, radiological, nuclear, and explosives threats. Do the same for climate, energy, and health impacts. Determine those measurable phenomena that uniquely identify and characterize threats or impacts in complex environments.

2. Revolutionize measurements

Develop new measurement technologies, methodologies, or strategies or develop transformational advances in the current state-of-the-art for threat/impact-specific signatures. Make sensitive and specific measurements in entirely new ways and/or measure new phenomena (signatures).

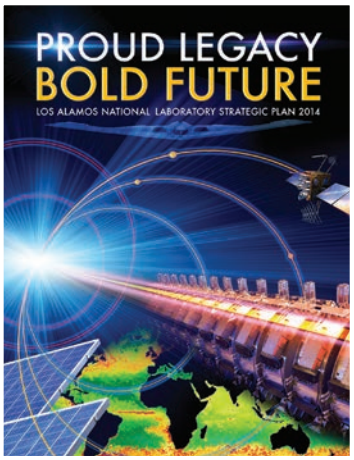
3. Forward technology deployment

Move measurement technologies and methodologies forward through engineering. Forward deployment includes prototyping of sensors and instruments for field deployment and systems integration of sensor networks. Bring science advances to public and private sectors in a way that provides feedback into signature discovery and/or revolutionary measurement technologies.

SoS and the Other Pillars

Each of the science pillars is distinct and has discrete science goals fundamental to the Laboratory's future science and technology base. However, they also overlap, and interfaces among the three pillars must be understood and leveraged for the benefit of all four. Within the Science of Signatures, each thrust within all six areas of leadership (described below) requires support from and advances in the Information Science and Technology pillar. For example, essential to signature discovery are data mining, data analysis, data fusion, information management, pattern recognition, uncertainty quantification, and many other IS&T capabilities. Data manipulation and analysis are key components to revolutionizing measurements, and IS&T is critical for real-time processing, compression, and communication during deployment of measurement technologies.

There is also significant interdependency between the SoS science thrusts and the Materials thrusts of emergent phenomena, materials in extremes, and defects and interfaces. Revolutionary measurements will require revolutionary materials. Examples where this interface is playing out range from advanced scintillators for nuclear detection, to biomimetic materials for pathogen detection, to new materials and approaches for making measurements in extreme environments. The Nuclear and Particle Futures focus on the R&D associated with the nuclear component of threat reduction and is synergistic with the SoS nuclear forensics area of leadership. Special emphasis is placed on high-energy physics, nuclear physics, and fusion energy science, advances in which are fundamental to SoS.



The Laboratory strategic plan was published in spring 2014, and the SoS plan maps directly to it.

Following are two case studies that illustrate the ways in which signature science helps us achieve our national security mission. Both are taken from one of our core strengths: nuclear science. The first describes a program in explosion monitoring that extends from basic science and first-principles to mature, field-deployed sensing equipment. It is intended to showcase how advances cross-cut applications. The second describes an applied program in nuclear forensics that falls at the opposite end of the development scale. Together, they cover the sweep of discovering new signatures, revolutionizing measurements, and deploying technology.

Case Study

Looking at Nuclear Events from Ground and Space

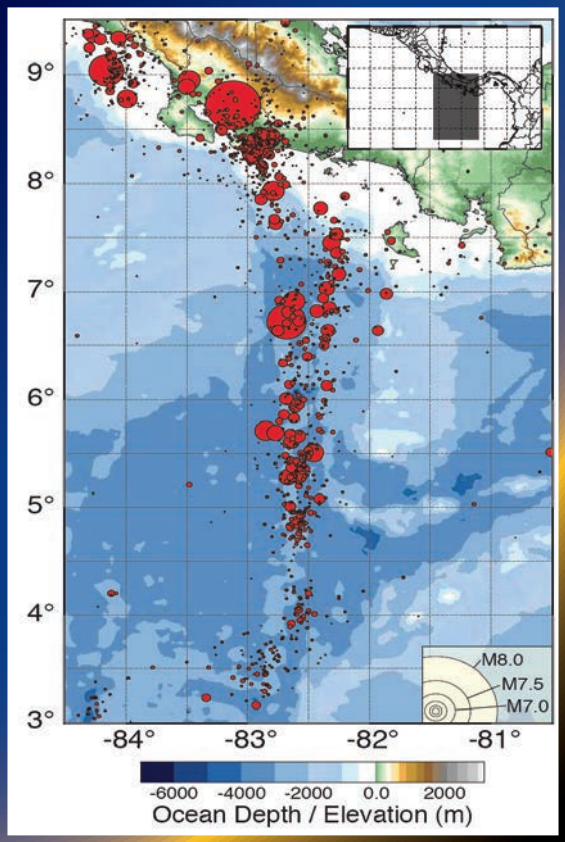
Nuclear weapon test monitoring via remote sensing from both ground and space is a vital DOE national security interest. Los Alamos is a national leader in research to integrate ground and space technologies in support of global nuclear weapon test treaties. The Ground-based Nuclear Detonation Detection (GNDD) and Space-based Nuclear Detonation Detection (SNDD) Programs develop and deploy measurement and analysis systems for global nuclear event monitoring in direct support of the DOE's treaty verification mission (e.g., the Limited Test-Ban Treaty, Threshold Test-Ban Treaty and the current testing moratorium under the Comprehensive Nuclear-Test-Ban Treaty). The integrated GNDD/SNDD research programs fall largely under the Science of Signatures.

Ground-based Nuclear Detonation Detection. During the 1970s, LANL began studying subsurface containment of nuclear tests at the Nevada Test Site, which required a detailed understanding of the underlying geology and the ability to predict subsurface reaction to the explosive shock of a nuclear blast. That capability has developed into a significant program in underground test diagnostics, nuclear explosion monitoring, and nuclear weapon test treaty verification. It is also a major contributor to environmental programs across the DOE complex.

The explosion monitoring mission of the GNDD program and its underlying science are a major research area for SoS. The mission of the GNDD program is to develop, demonstrate, and deliver transformationa technologies and systems to operational monitoring agencies (such as the DOE), as well as to provide event analysis and assessment to fully enable US monitoring requirements and policies for detecting and characterizing nuclear explosions.

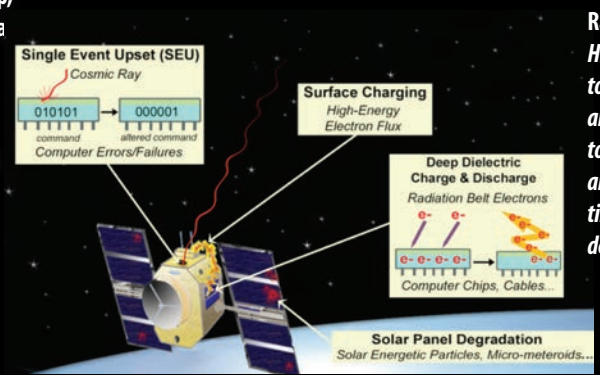
Space based nuclear detonation detection.
Since the launch of the first Vela spacecraft in 1963, the Lab's space-related capabilities have followed a science, engineering, and technology spiral tightly aligned with the needs of the SNDD program. Because understanding natural backgrounds within measurements of an event is critical for event detection and assessment, a vigorous scientific research portfolio has been developed to study these backgrounds. Core science, technology, and engineering capabilities:

- Nuclear detection (x-rays, γ-rays, neutrons),
- Electromagnetic pulse (EMP) detection (kHz-MHz),-
  Background environment of space (energetic particles, plasma),
- Transient event capture (fast *in situ* processing, efficient in situ data-to-information),
- Remote imaging and geolocation of events, and
- Extreme engineering, autonomous operation.



Above: Being able to distinguish between natural earthquakes and anthropogenic events is a key element of ground based detonation detection. In this series of measurements, LANL scientists used surface waves to estimate precise relative locations and source properties of natural seismic events along a fracture zone near Panama. Similar methods can applied for any seismic source, including potential underground nuclear explosions.

(Wessel, P., and W. H. F. Smith (1998), New, improved version of Generic Mapping Tools released, EOS, Trans. Amer. Geophys. U., 79, 579.)



Radiation Damage to Satellites:
High altitude nuclear explosions have the ability to cripple satellite resources by creating an artificial radiation belt. Los Alamos is working to understand the structure and impact of such an artificial belt in both short and long term time frames using advanced models under develoment with collaborators.

Case Study

National Technical Nuclear Forensics

The U.S. National Technical Nuclear Forensics (TNF) program has three components:

1) Interdicted Materials,
2) Interdicted Devices, and
3) Post-detonation.

For each, nuclear and radiological analysis can provide critical information concerning nuclear material type, place of origin, process history, or system performance. These data in turn help authorities determine the "what, where, when, and how" associated with the event.

Technical nuclear forensic conclusions are an essential component of the broader process of attribution, which involves integration of nuclear with traditional forensics data. This, together with information from various other sources, can help identify those responsible for a planned or actual attack. In addition to attribution, nuclear forensics contributes strongly to deterrence and prevention and promotes the concept of nuclear accountability.

The National Technical Nuclear Forensics Center (NTNFC), by Presidential mandate, is tasked to develop and maintain national guidance for TNF issues. The overall NTNF program is implemented by a variety of governmental agencies that include the Department of Justice (DOJ)/Federal Bureau of Investigation (FBI), the Departments of Defense (DoD), Energy (DOE), State (DOS), Office of the Director of National Intelligence (ODNI), and the Department of Homeland Security (DHS). LANL and seven other DOE national laboratories contribute to NTNF as well.

Los Alamos is unique in that we support the breadth of the NTF programs, from collections to final analysis. One of LANL's strengths within the TNF arena is that the Laboratory leverages its broad technical disciplines to address TNF problems (fundamental signatures science) that include

- radiological, chemical, and material analyses;
- materials and safeguards expertise;
- data evaluation and assessment,
- atmospheric and dispersion modeling;
- pre- and post-detonation field collections and analyses, and
- fundamental R&D for signature development.

Nuclear Forensic Analysis Center Expands ISO 17025 Accreditation.

In 2013, five groups in the Chemistry, Quality, Materials, and Nuclear Engineering divisions collaborated to achieve an expanded scope of accreditation for bulk nuclear material analysis, in accordance with the recognized International Standard ISO/IEC 17025:2005 General Requirements for the Competence of Testing and Calibration Laboratories.

The expanded accreditation scope now also includes methods for plutonium and uranium assay and isotopic composition, neptunium and americium content, and chemical form and density, for a total of thirteen analytical chemistry processes and two sample preparation processes.

Maintaining and extending LANL's scope of accreditation is key to sustaining the Laboratory's role as one of two FBI "hub" laboratories for analysis of bulk special nuclear material.

Ongoing field exercises.

As part of the Laboratory's role as a hub, we send experts in field collection and analysis to exercises organized by the Department of Homeland Security.

These exercises can be wholly domestic, or can involve international partners such as the United Kingdom.

Top: A team collects simulated "debris samples" from the hood of a vehicle during a NTNF field exercise called Trinity Oak at Fort Gordon, Georgia. Bottom: LANL staff analyze samples as part of field analytical operations.

Sponsored by the U.S. Department of Homeland Security

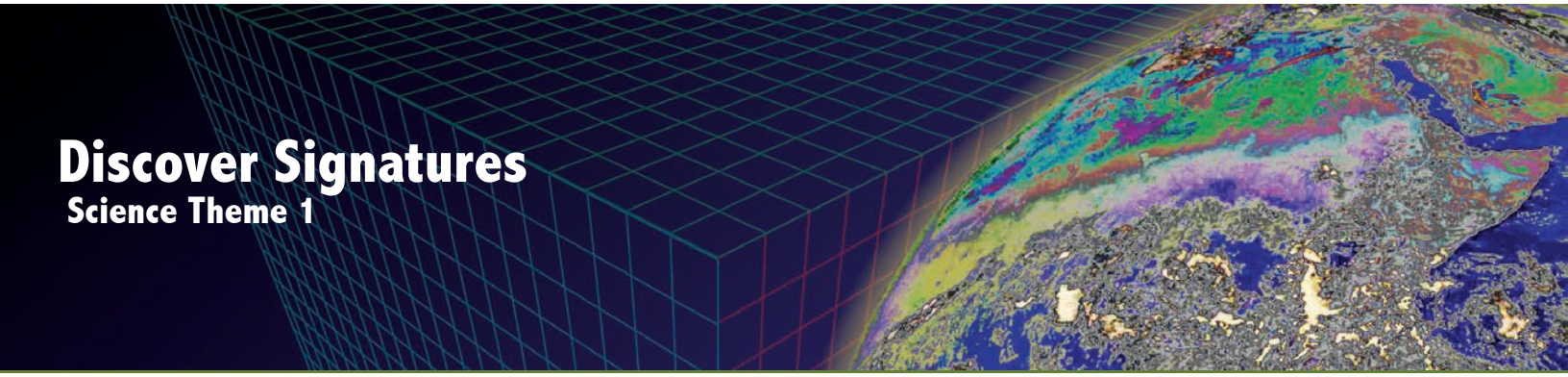
Nuclear Forensics Undergraduate Summer School 2014

The Lab contracts with the Department of Homeland Security to run a summer school that will ensue a future workforce of qualified nuclear forensics personnel. The school provides hands-on training in topics essential to nuclear forensics as a means of interesting students in pursuing graduate studies in related fields. Students are trained in nuclear decay, atomic and nuclear structure, nuclear material processes and uses, the nuclear fuel cycle, radiation detection, standard analytical methods, and more. The 2014 school was held at the University of Missouri.

"An international approach to develop nuclear forensics capabilities and train experts strengthens nuclear security cooperation, builds confidence among states, and contributes to the global efforts to prevent nuclear and radiological smuggling."

- Anne Harrington,
NNSA Deputy Administrator for Defense Nuclear Nonproliferation

The discovery theme seeks what is unique about a threat or impact. It involves extracting signatures needed to detect and characterize chemical, biological, radiological, nuclear, and explosives threats; as well as addressing challenges in climate, energy, and health.



Discover Signatures

Science Theme 1

The objective of discovery is to find and measure phenomena that identify national security threats, relevant energy/climate signatures, or health impacts of interest, as well as provide information and knowledge about them.

Signature discovery also draws on predictive information science and technology for a model-based understanding of complex systems. In a nutshell, what can you measure, how is what you measure affected by backgrounds, and what does that measurement mean? Difficulties lie in extracting relevant information out of a complex environment cluttered with numerous irrelevant phenomena that obscure meaningful signatures or in mining new information from existing data or instrument signals. Cyber signatures, for example, can arise from subtle differences in information signals, or new technical capability may bring out a cyber signature from what was previously background.

Technical advances come from data fusion and analysis techniques that can extract useful signatures that lead to new knowledge about the complex environment under study. Further IS&T capabilities can lead to coupling of multiple signatures that in turn lead to other knowledge not available from individual signatures. The ultimate end state is for forward technology deployment of measurement capabilities (theme 3) that when coupled with expert guidance can adapt to the environment and feed back into the discovery of entirely new signatures.

This theme looks at how the threat or impact is uniquely identified and if surrogate signals or indicator signatures can be used. Specificity is attained when signatures are identified within natural or anthropogenic backgrounds, or are differentiated from related but benign signatures. New composite signatures may also be discovered by combining multiple distinct signals that must be analyzed together to generate knowledge or to increase precision or specificity to a meaningful level. Practical advances must take into account that signatures can change over time through exposure to environmental conditions, movement within the system being measured, and other physical, chemical, and biological effects.

Science Challenges

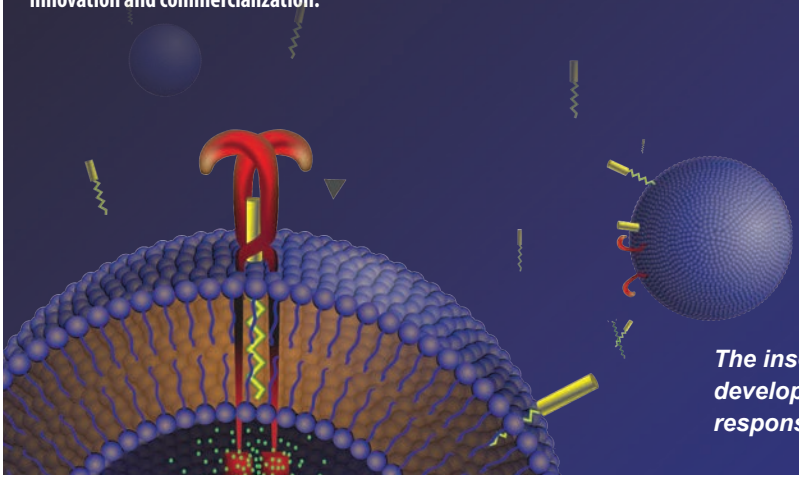
This theme has two key challenges: (1) signatures can change and (2) accurate threat characterization can require multimodal signature discovery. In the first, signatures (chemical, biological, infrastructure, cyber, and others) either evolve with time, or they change by virtue of their interaction with the complex system for which they are characteristic. In each case, complete knowledge of change within the context of the system must be understood in order to guide signature identity and measurement.

The second challenge arises because a threat can rarely be characterized by the measurement of a single signature. Characterization sometimes requires multiple signatures, often of very different signature types that, in turn, require distinctly different sensing materials and signal transducers. By way of example, characterization of a potential illicit production facility (chemical/nuclear/biological) may require information on electrical use, acoustic signatures, and waste chemicals. Thus, this challenge focuses on multiplexed signal transduction in which differing or orthogonal signal types are integrated for subsequent analysis.

Signatures of Human Health and Disease

Mortality associated with disease can be decreased with early diagnosis. However, current technologies for early detection are inadequate, creating a need for rapid, sensitive and specific detection methods. The Los Alamos Biosensor Team is developing new biosensor technologies capable of detecting signature biological molecules such as proteins, carbohydrates, and intact pathogens using sensitive, specific, and responsive biological agents. Applications span from detecting national security threats such as anthrax or botulism, to medically important organisms and conditions such as influenza, breast cancer, and tuberculosis. One novel approach uses planar optical waveguides as a platform for protein and ligonucleotide detection.

This project requires the participation of chemists, biologists, engineers, and materials experts alike. Such an integrated effort is possible because of extensive collaboration, both amongst scientists at LANL and with external organizations. This Science of Signatures technology has won numerous awards for scientific innovation and commercialization.



The inset image shows an experimental apparatus developed to mimic the natural cellular recognition responses triggered in cells (background image).

Signatures of Drought and Tree Mortality

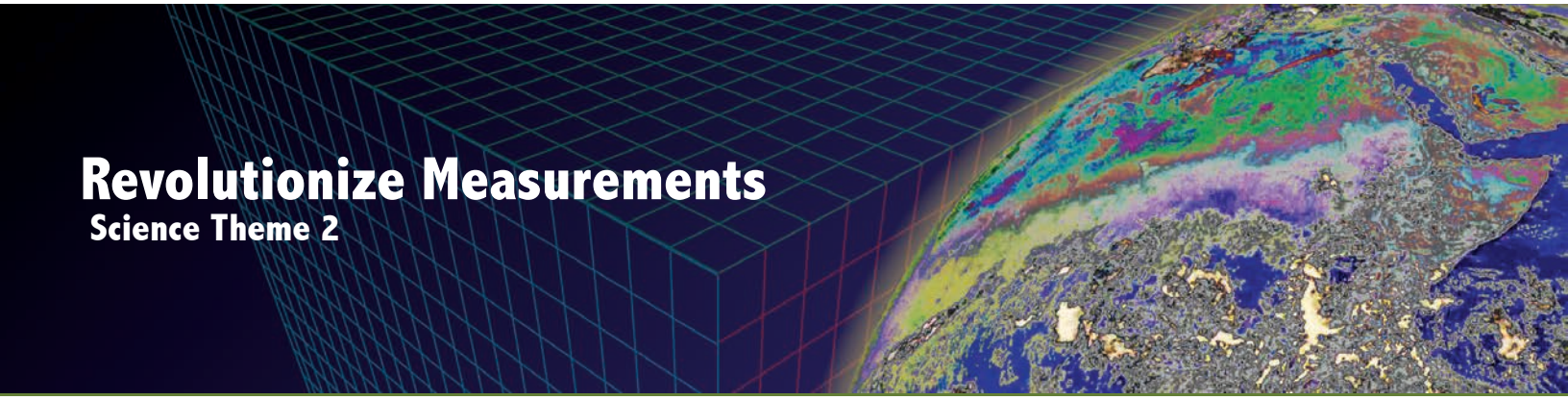
A technology originally designed to detect national security threats has been adapted to advance understanding of the mechanisms of plant mortality.

A team of physicists, biologists, and plant scientists has shown that water content can be monitored noninvasively and unobtrusively in intact trees using ultra-low-field nuclear magnetic resonance (NMR). The scientists' goal is to provide basic insights into questions such as how plants die, especially during drought. Understanding the mechanisms of mortality, especially the tipping points, will provide important input to forecasts of future climate because current models cannot simulate vegetation change and related climate effects. The LANL research represents a first step towards fieldable, non-invasive monitoring to answer these fundamental questions.

Ultra-low field NMR instruments can be made so that they are easy to operate, portable, and adapt noninvasively to the tree. The work demonstrates that the combination of LANL's unique abilities in ultra-low-frequency magnetic resonance imaging and climate-driven vegetation mortality research can provide an understanding of plant function and mortality.

Tree mortality is a global phenomenon with important feedbacks to climate and eco-system sustainability. Nuclear magnetic resonance and other measurements of tree function are essential to understanding the relative importance of cavitation, carbon starvation, and insect infestation during drought events. At right, other signatures of drought stress are measured in a unique large-scale field experiment that uses HVAC units to simulate variable climate conditions.

The focus of this theme is radically improving sensitivity and selectivity in existing measurements and developing new and transformational measurement technologies, methodologies, and strategies.



Revolutionize Measurements

Science Theme 2

Such increased specificity and sensitivity enable the gathering of new information and knowledge of substantially higher fidelity than is currently possible. One example is extracting a weak signature from masking backgrounds; another example is spatial/temporal domain measurement of dynamic phenomena that can lead to new or radically improved understanding of processes. Challenges come from developing measurement methods for fundamentally new phenomena associated with existing and emerging threats (creating revolutionary sensors).

This goal draws on the IS&T pillar to move data and information processing into the sensor (or instrument) and on the Materials pillar for new sensor materials. In essence, this theme seeks to answer the following question: How can measurements be made in entirely new ways and/or how can new phenomena be measured? Are there detectors and sensors that can be combined to produce a valuable signature? Can high-throughput tools measure the signatures? What isotopic or species attributes can be used to directly or indirectly detect the signature? Can conventional separations be replaced by faster methods or separations that can discover a signature for the analyte? Can remote, field-deployable, multi-scale detection methods be developed?

To find answers, we must develop methods and technologies that measure fundamentally new signatures or uniquely identify sparse signatures in cluttered environments. Revolutionary advances in elements such as sensitivity, required sample size, speed of measurement, and spectral resolution are required, as is the ability to quantify and uniquely remove background from primary measurement of targeted threat signature. Measurements must span in situ and remote sensing, with some emphasis on enabling measurements of activities or events in locations of denied access. Time and space must be considered, including networked sensing, sensor arrays, perimeter monitoring, and space-based coverage.

Science Challenges

Key challenges in this area are to quantitate specific, actionable signatures in a noisy background of nonspecific signatures and to implement unattended and remote sensing. Specific desirable signatures are often weak and obscured by stronger undesired signatures. In other instances, undesired signatures mimic desired signatures and give rise to false positives. An example is biological pathogens in an environment where nearly identical non-pathogenic organisms predominate. Such cases require the ability to sensitively measure multiple signatures simultaneously and necessitate advances in sensors and sensor networks.

Additional enduring technology gaps come from remote signal measurement (e.g., detecting greenhouse gases in the atmosphere) and measurement at excluded/denied sites (e.g., sites of illicit production). Passive and active electromagnetic interrogation can be used to remotely detect some threats, but others (e.g., biological threats) have no specific spectral signatures. In such cases, novel sample collection strategies have great potential. Moreover, even for those threats that have specific spectral/optical signatures, improved standoff distance for detection and robustness and fidelity of the signal require revolutionary improvement.

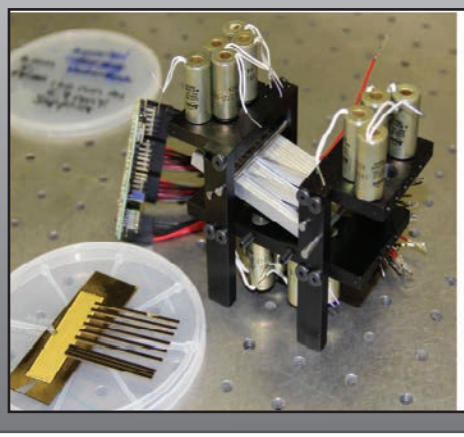
Hyperspectral Imaging for Forensic and Atmospheric Monitoring

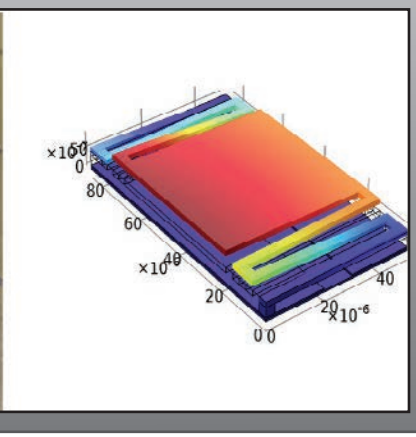
Hyperspectral imaging in development at LANL holds the potential to provide real-time continuous monitoring for a wide variety of applications, from detection of chemical sources to tracking of greenhouse gases for treaty verification.

Adaptive spectral imaging sensors combine broadband context imagery with programmable, multi-band spectral imagery for real-time monitoring. The technology allows tuned detection filters to be loaded to monitor multiple species of interest. These programmable spectral sensors can augment satellite imagery at regional scales and local scales and customize alternative spectral band sets for specific monitoring applications.

In the research described below, scientists have identified a new technique to use spatial light modulation devices such as micro-mirror arrays to apply programmable spectral filtering to the entire 2-D image simultaneously. The resulting programmable, high-resolution, multi-band spectral filter provides complete control over the spectral content of the image.

Left, Microelectromechanical (MEMS) based adaptive hyperspectral imaging can be rapidly deployed in the field. Right: MEMS mirror arrays are designed to optimize performance across a wide range of wavelengths as required for specific applications.



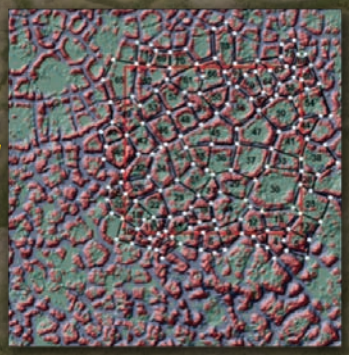


Measuring Effects of Permafrost Degradation in the Arctic

LANL researchers are making remote and in situ measurements as part of the Next Generation Ecosystem Experiments: Arctic (NGEE), which is a DOE Office of Science project investigating feedbacks of permafrost degradation on climate.

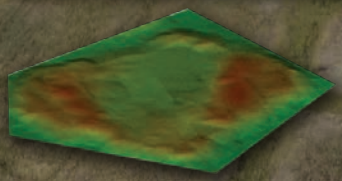
Passive diffusion cells are used to measure fine scale geochemical gradients in the thaw zone to understand potentials for greenhouse gas production and solute transport.

High resolution light detection and ranging (LIDAR) measurements



Polygonal ground is common in the Arctic, and an innovative suite of measurements is being made to characterize polygonal ground geomorphology, hydrology, and isotope chemistry.

Accurate polygon models



Dynamic models of thawing ice wedges and ground ice

LIDAR measurements at 0.25-m resolution are used to build accurate geomorphological representations to simulate permafrost dynamics

The focus of this theme is to use engineering to advance the practical application of measurement technologies and methodologies. It broadly includes the prototyping of sensors and instruments for field

Forward Technology Deployment

Science Theme 3

deployment and the development and deployment of integrated sensor networks. Deployment scenarios include extreme environments (space, other planets, the Arctic, nuclear reactors) and extreme operational conditions (unattended operation for extended periods; continuous, real-time data streams). Sensors must be made within extreme size, weight, power, and cost constraints (unmanned aerial vehicles, aircraft, small satellites, sensor-in-a-cellphone), and within a complex framework of other sensors (DoD deployment, sensor networks and arrays). Measurements demonstrated in controlled environments must also be possible in exotic, diverse, and noisy environments.

Data fusion, analysis, and learning algorithms are key components to extracting information and knowledge about the environment being sampled. Adaptive sampling and measuring technologies will be needed to address changing conditions. IS&T is critical for real-time processing, compression, and communication, where as Materials promises new lightweight components and power sources.

In essence, this theme explores how we bring innovative measurement to the real world and how we learn about complex environments in a way that provides feedback into new signature discovery and/or new revolutionary measurement technologies. It explores whether signatures detected in complex environments can be attributed to a specific source for a given magnitude, natural background, or anthropogenic noise.

To be effective, we must identify relevant, sparse information within enormous data volumes. We must also have sufficient confidence in our conclusions that they can serve as a basis for attribution and subsequent action/response. Achieving sufficient confidence requires new ways to process raw data streams to directly convert data to information, new models for interpreting data, and new methods for deriving information.

Science Challenges

The key challenge in forward technology deployment is delivering novel engineered systems underpinned by advances in both signature discovery and signature measurement. Prototype sensors and sensing systems must be designed, built, and demonstrated based upon the adaptation of measurement technologies to relevant field applications. ChemCam is an excellent example of where the Laboratory did this well (see facing page).

Success will require advancing essential engineering capabilities, as well as employing new product realization strategies to address the deployment challenge. In particular, evolving benchtop proof-of-concept devices through the component and field validation processes will require specific fundamental attention. Essential engineering capabilities that require investment include

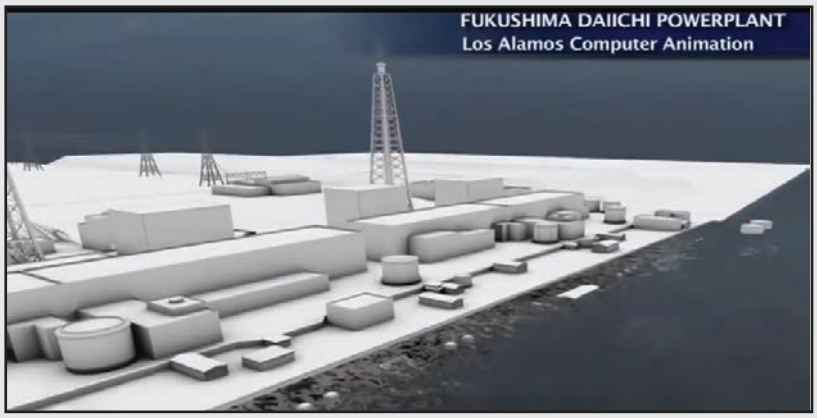
- miniaturization (micro and nanofabrication);
- ruggedness (thermal, vibration, radiation);
- onboard energy harvesting and storage;
- sensor reliability, including diagnostics and self-healing response;
- sensor networking;
- robust, optimal sensor system design; and
- adaptable, tunable, and reconfigurable sensing systems.

Muon Tomography for Nuclear Materials

Muon scattering tomography is a subset of muon tomography and was developed at LANL in 2003. It has since been turned into an important new class of imaging technology. Muons are elementary particles similar to electrons but with a mass about 200 times greater. They are created when cosmic rays interact with matter and can be used to create a three dimensional image of an object as they pass through it . They can penetrate much more deeply than x-rays and do not damage the object being imaged.

The technique measures the muons both entering and exiting an object by placing a pair of muon detectors in front of and behind it and measuring the muon trajectories and the way they change as they pass through. This difference can be used to reconstruct the interior of the object. Because the muon scattering angle increases with atomic number, the technology is ideal for imaging nuclear materials and other so-called "high-Z" materials. This ability makes the technology applicable to both global security applications and diagnostic applications involving nuclear materials. For example, the technique is being adapted for reactor analysis and shows tremendous promise for pinpointing the exact location of materials within the Fukushima reactor buildings because the SNM within a reactor shows up more clearly than the surrounding containment building, plumbing, and other objects.

A muon tracking detector invented by LANL scientists and manufactured and sold by Decision Sciences Corporation uses natural cosmic rays to detect smuggled nuclear material in vehicles.



Los Alamos will assist Toshiba in developing a muon tracker for use at the Fukushima plant. Los Alamos researchers began working on an improved method for muon radiography within weeks of the 2011 earthquake and tsunami that damaged the Fukushima reactor complex.

Space Signatures

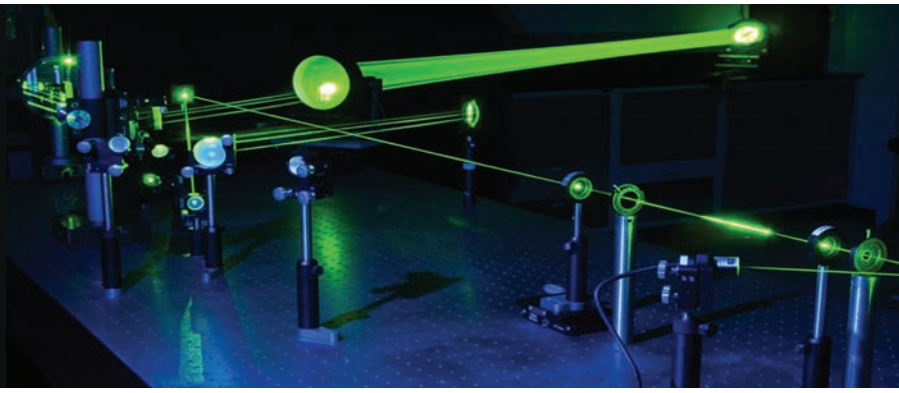
The Mars Science Laboratory launched by NASA in 2012 uses houses an instrument originally developed at Los Alamos called ChemCam, which uses a laser to probe Mars' surface. The ChemCam laser pulse vaporizes an area the size of a pinhead. The system's telescope examines the glowing plasma created by the vaporized material, then records the colors of light contained within it. Colors are analyzed by a spectrometer, which yields the elemental composition of the vaporized material. ChemCam is designed to look for lighter elements such as carbon, nitrogen, and oxygen, all of which are crucial for life. The system can provide immediate, unambiguous detection of carbon or water from frost or other sources on the planet's surface. ChemCam has the ability to detect any element on the periodic table and can zap an area about 23 feet away from the rover vehicle. Because of the great success of ChemCam, an updated version has been selected for the Mars 2020 mission as well.

The system relies on a technology primarily developed at Los Alamos called laser-induced breakdown spectroscopy (LIBS). At the heart of the technology is an infrared laser that focuses more than a million watts of power onto a tiny area for five-billionths of a second. LIBS has been used on Earth to determine the composition of objects within extreme environments such as inside nuclear reactors and on the sea floor. Other applications for LIBS include cancer detection and environmental monitoring. The Mars Science Laboratory is the technology's first extraterrestrial use, and it has been highly successful. LANL leads the overall investigation for this instrument.

Two members of the LANL ChemCam team testing the instrument in a clean room.

The key to success in SoS is to identify discrete areas where the Laboratory can lead nationally and internationally within the context of the three SoS science themes. These are our Areas of Leadership.

Areas of Leadership
Strategic Goals



These areas were selected by a combination of SoS leadership council (see page 3) activities and broad-based engagement during workshops attended by hundreds of staff. They connect directly to the Laboratory's mission and are flexible enough to anticipate future mission space. The selection involved evaluating the scope of LANL's activities as a national security science laboratory and balancing that against a realistic assessment of funding and staffing. These leadership areas are

- Radiological and Nuclear,
- Chemistry and Materials (Including explosives)
- Biological,
- Climate,
- Energy, and
- Space.

Some of these (Radiological and Nuclear, Chemistry and Materials, and Space) encompass traditional strengths and enduring national security missions. Others (Energy, Climate, and Biological) are developing or nascent strengths required to meet emerging missions. We are aware that these areas may at first glance appear orthogonal to the traditional Department of Defense/Intelligence Community definition of signature type (signals intelligence/SIGINT, etc.), but we feel that the melding of our scientific strengths with the SoS science themes of discover signatures, revolutionize measurements, and forward technology deployment is in fact a practical and innovative way to approach and meet emerging signature needs of these traditional sponsor bases.

The planning process has resulted in a focused strategy consistent with our identity as a national security science laboratory and can be presented coherently both internally at the Laboratory and to our external stakeholders.

Our planning efforts look forward over a ten-year time horizon, and our goals set a high bar in terms of revolutionizing the state of-the-art. These are stretch goals, but not unrealistic because scientific advances in materials, chemistry, miniaturized and distributed sensing, and in other areas create unprecedented opportunities to advance the Science of Signatures. The strategic challenge faced by the Laboratory is to select specific projects to pursue that directly mesh with LANL strengths and support the LANL mission.

Each of the following summaries describes why we believe the area of leadership is appropriate for LANL and how we believe it ties directly to our mission. For each, we also briefly describe how we selected the goals we did from the myriad possibilities.

Some Los Alamos Strengths

- Weapons design expertise enables the characterization and understanding of nuclear threats.
- Isotope and nuclear materials handling expertise does the same.
- Energetic materials expertise enables detection and understanding of explosive threats.
- Chemical, materials, and bioscience expertise facilitates the detection, characterization, and understanding of chemical and biological threats.
  - Capabilities enable understanding of signature transformations in the environment.
- National security science requires innovative instruments and measures.
  - Open National User Facilities are available for national security science.
- Experience deploying instruments/diagnostics in extreme environments (e.g., space, a bomb) enables development of unique and robust detection and sensing capabilities.
- The extent of our theoretical, computational, and simulation expertise facilitates the prediction of complex system behavior and impacts.
  - Enables global-scale security science.
- Secure space and a cleared workforce enable national security science.
- Extraordinarily broad, multidisciplinary science and engineering teaming.

Overarching Challenges

There are science challenges that crosscut all areas of leadership:

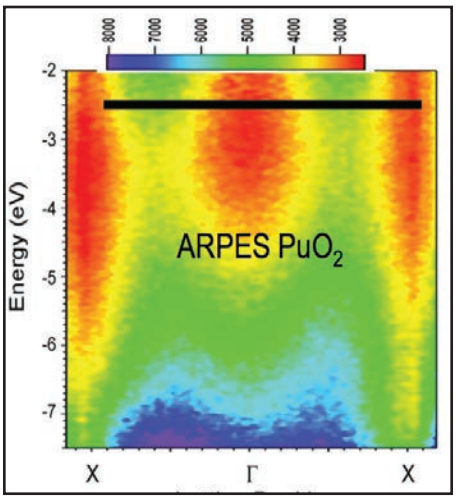
- Science over wide-ranging scales of length and time.
- Signature evolution in space and time.
- Signal-to-noise discrimination in measurement technologies.
- Processing at the sensor head.
- Uncertainty quantification.
- Bridging the technology maturation "valley of death" during deployment of young technologies.
- Distribution and networking.
- Realizing fieldable devices.

The list is not all-inclusive, but nearly the complete set of challenges listed above will apply to, and be addressed in, the detailed strategy for the individual areas of leadership. The following summaries were extracted from detailed workshop reports.

Nuclear and Radiological Signatures

Nuclear detection, nuclear and radiological material characterization, and weapons reconstruction are leadership areas for Los Alamos National Laboratory. Specific themes are nuclear event detection and characterization, nuclear device and material detection and render safe/emergency response, debris collections and diagnostics, nuclear and radiological material (bulk and particle) analysis, nuclear material production and characterization, device reconstruction, and nuclear/radiological material and device risk assessment and performance modeling.

Our strengths in the nuclear and radiological area arise from a demonstrated capability and proficiency of over 70 years of analysis and characterization of both bulk and particle radiological materials as well as ground and space-based sensing. Los Alamos works end-to-end, across the nuclear defense spectrum and has significant programs and missions in deter-dissuade, detect, interdict, render safe, consequence management, and recovery for materials, device, and debris operational and R&D science. We receive, analyze and process femtogram to kilogram quantities of special nuclear materials over a nuclear science complex composed of 15 facilities ranging from ultra-clean to industrial scale analytical and processing laboratories.



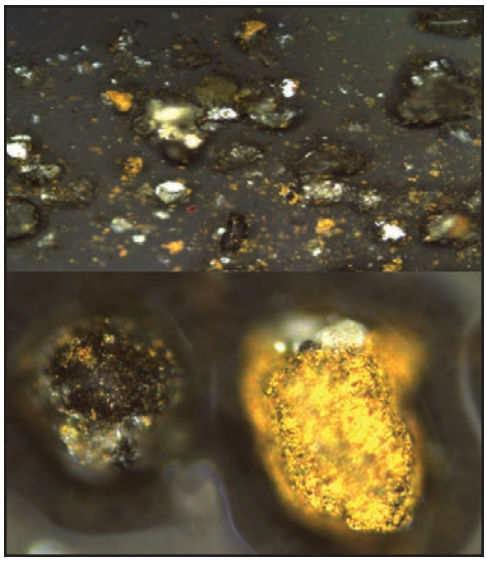
Angle-resolved photoemission from plutonium oxide films is one tool used to develop a first principles predictive tool to describe the electronic structure and behavior of strongly correlated actinide materials. This basic knowledge is needed for research in threat reduction, fuels, weapons, and much more.

We also have ground and space-based assets that have the ability to detect and characterize event and post-event signatures. Additionally, remote and urban prompt research is underway in a multitude of sponsor areas. National and international research for DOE, NNSA, DoD, DHS, DOS, ODNI missions are the staple for our nuclear and radiological efforts.

Because a significant portion of the activities and science associated with radiological and nuclear work is classified, the goal descriptions included here are less specific than for those areas in which classification is not an issue. Each goal has an associated action plan, and more details are included therein.

Nuclear Detection/Nuclear and Radiological Materials Characterization: An important part of the nuclear and radiological detection mission in the United States is the interception and tracing of unknown nuclear materials. These materials might be discovered at border crossings or during international inspections. Shutting down the pathways that lead to their production and distribution is the key to international nuclear security. Radiological and nuclear materials characterization work emphasizes field deployment of personnel and techniques with extremely rapid turnaround. In 2010, the NA-45 Office of National Technical Nuclear Forensics announced the selection of Los Alamos National Laboratory as one of

The LANL plutonium facility, center, has the capability of receiving large quantities of nuclear material and provides a unique opportunity for nuclear signature testing.



Nuclear forensics can be accomplished with a wide variety of analytical techniques, including light microscopy. Shown here are particles of uranium analyzed during a training exercise. The physical particle characteristics give information about the origin of the sample.

two "hub" laboratories for analysis of bulk special nuclear material to support the national predetonation nuclear forensics program. Our chosen goals mesh with this mission space.

Goal 1: Achieve standoff detection of structures that yields valuable/actionable information about radiological and nuclear materials that we wish to observe but cannot access.

Goal 2: Create a suite of capabilities that enable process characterization and monitoring of special nuclear materials production facilities for a variety of applications.

Goal 3: Field novel methods or quantum improvements in actinide analysis for safeguards applications.

Goal 4: Discover, design, and deliver the next generation of monitors and algorithms to detect special nuclear materials or weapons of mass effect when they are in movement.

Nuclear Event Characterization: Currently, with the exception of goal 8, nuclear event characterization analysis concentrates more on laboratory techniques with a longer relative time frame than does our predetonation work. In the future, it will be important to shorten the time to achieve results and ideally move the analytical tools to the event. This is a decadal challenge.

The Los Alamos Counting Room has a comprehensive suite of radiation detection instruments and is a unique resource for nuclear material and event characterization.

Goal 5: Drive next-generation material measurements to generate actionable data, directed by interpretation goals while meeting specific time and quality goals.

Goal 6: Provide the technical basis for predicting and interpreting all energy outputs by integrating expertise, models, and measurement systems.

Goal 7: Provide forefront modeling capabilities to guide decision making, as well as to turn data and signatures into knowledge.

Goal 8: Advance space-based and ground-based signatures and detection technologies for nuclear detonation detection.

Los Alamos houses some of the best and most well trained weapons scientists in the world. The infrastructure, scientists, and expertise built up by the weapons programs is leveraged into global security and science missions. Specifically, nuclear device detection, nuclear forensics, event and device reconstruction have all benefited from the weapons program at Los Alamos.

Chemical and Materials Signatures (including explosives)

The chemical and materials sciences are traditional strengths of the Laboratory. Taken together, they represent about 25% of the Laboratory's budget. Specific strengths are in state-of-the-art materials and analytical characterization tools that are used in R&D that is relevant to Science of Signatures. There are also national user facilities such as the Center for Integrated Nanotechnologies and the National High Magnetic Field Laboratory that are applied to chemical and materials signature science.

Having these open user facilities reside alongside specialized classified facilities creates a unique opportunity to apply the Science of Signatures to national security. The goals we have chosen to pursue reflect the opportunities created by that interface.

Goal 1: Discover the next generation of chemical signatures, models, and detection platforms for chemical weapons identification and forensics.

Goal 2: Engineer and model the next generation of materials for sensing.

Goal 3: Build an enduring capability to predict/address emerging threats relevant to explosives detection, forensics, and attribution.

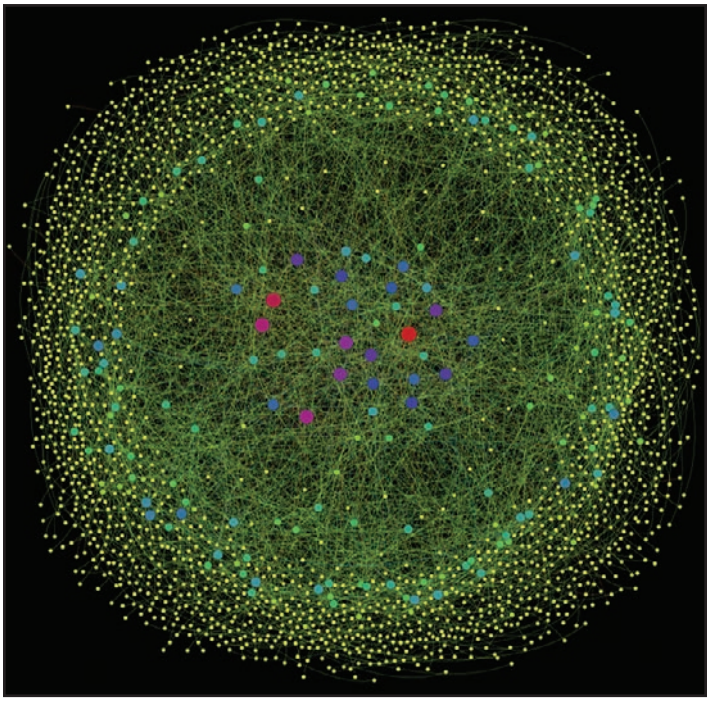
Goal 4: Create the next generation of signatures, models, and detection platforms to characterize nonradiological materials of interest for national security concerns including emerging capabilities in additive manufacturing.

One of the many challenges in this area is to develop a science-based understanding of materials and their interactions to identify changes in the aging stockpile for performance, reliability, or safety.

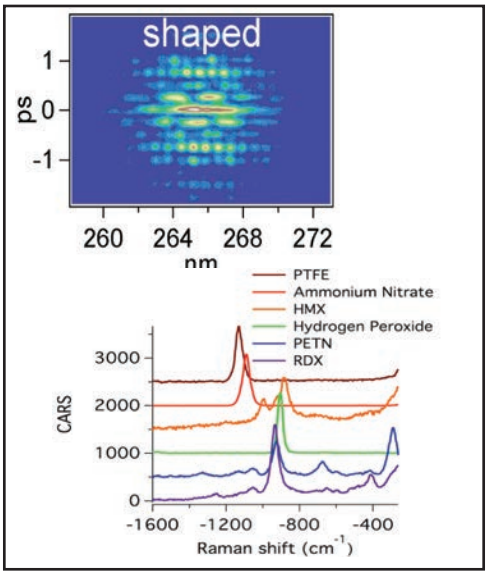
Biological Signatures

The SoS Leadership Team sees biosurveillance, in the areas of both biothreat and public health, as primary national security concerns in the coming decades. The Laboratory's historical and current strengths in bioscience and related technologies resident in a national security science laboratory place it in a unique position to make contributions to biosurveillance.

The biological and related sciences are undergoing revolutionary changes driven by factors such as availability of high-content/high-throughput bioanalytical systems yielding vast amounts of inexpensive data, computational power to manage that data, mathematical/statistical tools for analyzing the data, computational models for organizing information into functional systems, and communication systems for data exchange and access. Equally revolutionary advances in fields such as materials science and chemistry are providing new opportunities to develop bioscience research tools and applications.



Forecasting disease spread requires an understanding of human behavior, since disease requires contact. This image shows a model of the social contact network of southern California. The nodes are colored and sized by degree; red = high degree, blue = medium degree, and yellow = low degree.



LANL's Optimal Dynamic Detection of Explosives (ODDEx) *technology uses a femtosecond laser with shaped pulses to rapidly detect a wide range of explosives at trace concentrations.*

Historical Laboratory strengths in the development of assay systems, wet chemistry, surveillance networks, IS&T, and epidemiological modeling provided the remainder of the context.

The planning effort identified classes of disease with common surveillance needs and used those to bound their strategic recommendations. The diseases themselves and the specific technological advances required are described in the workshop output report.

Goal 1: Diagnostics. Identify and detect pathogens quickly, accurately, and inexpensively using signature validation, molecular assays, detection platforms and sensor networks with the intent of informing epidemiology.

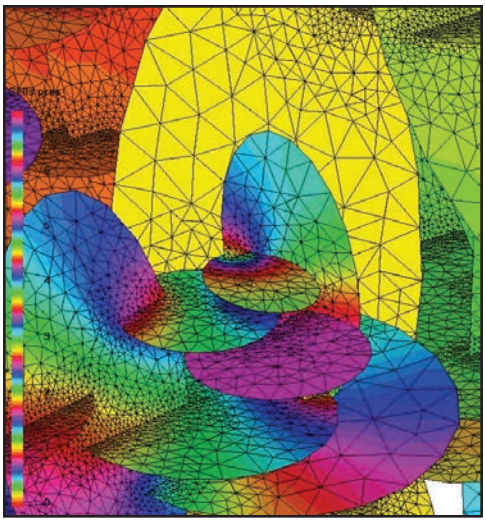
Goal 2: Modeling. Develop new tools for epidemiology and disease modeling that enable us to predict disease progression and transmission by determining pathogen lifecycles, mechanisms of disease onset and progression, and mechanisms of transmission.

Goal 3: Data analysis. Enable disease management and response with knowledge-based decision tools that describe the characteristics of primary disease scenarios, analyze approaches and possible actions, and integrate data streams and modeling to predict outcomes.

Energy Signatures

Energy security is one of the core mission areas of the Laboratory, thus making it important that we pursue it as an SoS area of leadership. There are currently numerous active energy-security-related efforts underway at Los Alamos. These efforts focus on identifying critical national needs, maintenance, enhancement of capabilities, and on developing new programs. The SoS strategy in this area is coherent with the Laboratory's energy security strategy, which states that we will help the nation meet energy challenges through fundamental scientific discovery, harnessing our unique experimental and modeling facilities, and partnering to accelerate commercial implementation of clean, safe, and secure energy solutions.

To that end, energy research at Los Alamos is grouped into three general categories. (1) *Sustainable Nuclear Energy*: America currently derives 20% of its electricity from nuclear power, a number that is likely to rise as nuclear technologies evolve and as new plants come online. (2) *Materials and concepts for clean energy*: Innovation is required to sustain and economically generate, store, transmit, and use the massive amounts of additional energy we will require in the future. (3) *Mitigating impacts of global energy demand*: Anticipated growth in global energy demand will put increasing pressure on the environment, foster global competition for energy resources, and drive massive infrastructure growth in developing nations. The SoS goals address these categories.

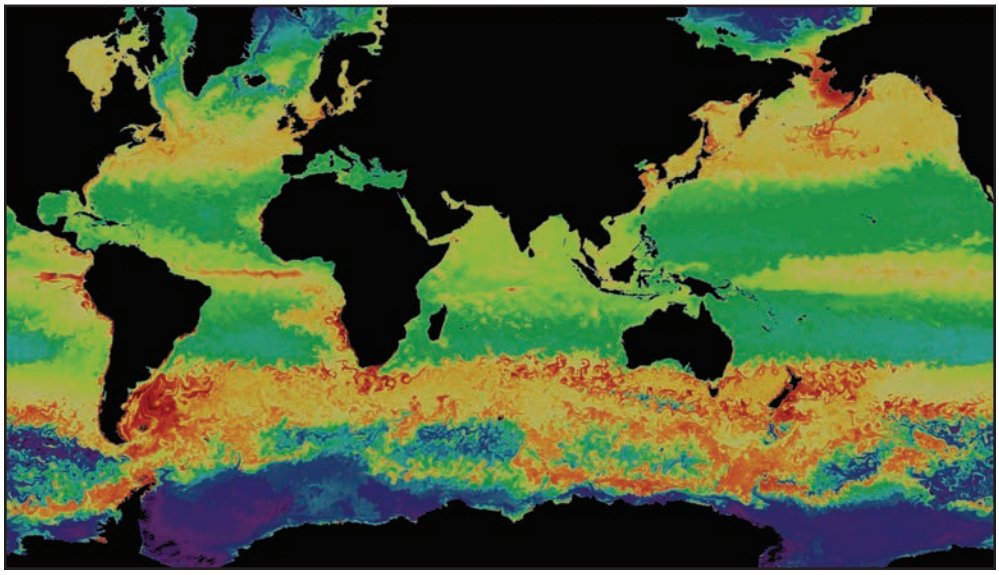


The LANL subsurface flow and transport team has developed fracture network models (shown here) as part of the Spent Fuel Disposition Program. The team is also involved in the development of unconventional sources of fossil fuels, including oil shale and tar sands.

Goal 1: Pioneer new approaches to extracting/attributing signatures of energy from living organisms, geological environments, or man-made systems under conditions that are remote, inaccessible, and/or extreme

Goal 2: Develop materials for energy and environmental systems that respond and/or report back on signature-induced stimuli.

Goal 3: Integrate sensing, modeling, and analysis science and technology to support decisions and investments, protect systems and anticipate risks/degradation, and respond to disruptions, impacts, and consequences.



This image shows chlorophyll concentrations in a high-resolution, eddy-resolving Community Earth System Model ocean with a full ecosystem model. Such simulations can help scientists explore natural emissions and discover sinks of carbon and sulfur for sequestration.

Climate Signatures

In 2013, 35 federal agencies including DOE released their Sustainability Performance Plans (SSPPs), which for the first time included a climate change component intended to help federal agencies reach climate change resilience goals. This climate plan follows on the heels of the 2009 DOE climate change plan which stated that, "...improving the scientific understanding of climate change is a priority for the U.S. Department of Energy."

The broad recognition that climate science is and will continue to be a national priority for scientific research, when combined with the fact that it is an area of historical strength at Los Alamos, dictated that it be pursued as an SoS area of leadership.

Our areas of expertise span from science-based national decision support and assessment for policy makers, to understanding and predicting the impacts of changing energy sources on climate, climate uncertainty quantification, infrastructure assessment and planning, and climate measurements & models. The 2014 U.S. National Climate Assessment Report highlighted that climate change effects are already being expressed, which demonstrates the significance of each of the SoS Climate goals described below.

Goal 1: Become the leader in those signatures of greatest value to climate science by developing computational and analytical techniques applicable to multi-variable data sets and by developing signal detection systems that span software to hardware (prototype to mature).

Goal 2: Achieve excellence in integrating observational data sets with analytic and computational models and use these models to develop new observations and signatures that increase the accuracy of climate predictions.

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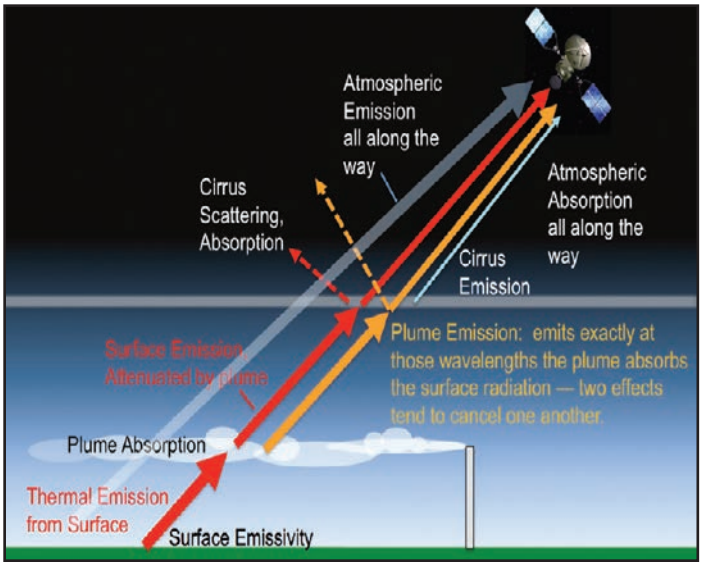
Space Signatures

For 50 years, LANL has flown missions in space to globally detect and assess nuclear detonations and to understand the natural space environment and its effects on radiation detection instruments. This historic treaty-monitoring mission has expanded to two additional areas: space situational awareness (comprehensive understanding of existing and emerging threats, both natural and man-made, to the national space infrastructure) and space-based remote sensing of weapons of mass destruction development and proliferation, primarily nuclear. An emerging area of national security importance is global monitoring of greenhouse gases relevant to global climate change. Key signatures for these programs include radiation detection (n^o, γ-rays, x-rays), plasma and high energy charged particles, and photons (from radio waves to optical). Physics-based models are routinely developed, validated, and applied, for example, to understand instrument performance, signature generation, signature transport (from source to measurement), event geolocation, and space weather.

To develop the expertise, tools, and innovation in support of the Laboratory's national security mission performed in space, a robust research base spans multiple disciplines, including plasma science, astrophysics, space physics, planetary physics, earth sciences, chemistry, and space systems engineering. Current signature discovery and analysis research includes high-altitude lightning phenomena, gamma-ray burst dynamics, radiation belt energization, supernova shock propagation, chemistry and mineralogy of Mars's surface, and solar wind microstructure.



Measuring greenhouse gases from a satellite is a difficult task. Complications arise as light moves from the surface to the satellites, which requires instruments that have maximum possible sensitivity.

2014 Science Magazine cover. Thinking telescopes are being developed for space situational awareness and as a discovery-science platform to answer fundamental questions about transient astrophysical events such as gamma-ray bursts.

Launches of LANL scientific instruments in 2012 include NASA's Mars Science Laboratory and Radiation Belt Storm Probes missions. The robust scientific portfolio additionally enhances the necessary expertise and tools to distinguish national security signatures from background signatures associated with natural benign man-made phenomena.

Goal 1: Develop and demonstrate next-generation technologies and methods for emerging basic science and civilian space opportunities.

Goal 2: Develop and demonstrate next-generation technologies, methods, and capabilities for nuclear detonation detection and nuclear non-proliferation from and in space.

Goal 3: Develop and demonstrate next-generation technologies, methods, and capabilities for emerging opportunities in work-for-others/military space programs.

Crosscutting Los Alamos Goals

Because of the somewhat unconventional nature of the framework, SoS will need extra attention and sustained commitment from the Laboratory if it is to thrive as a science pillar. It will be the ongoing responsibility of the SoS Leadership Team to ensure that these needs are addressed as SoS continues to evolve.

- Formalize the ongoing role of the SoS Leadership Team in ensuring the longevity and vitality of the SoS effort. This effort includes weaving SoS into the existing structures and science strategies for the following institutes and centers.
    - Feynman Center for Innovation,
    - Engineering Institute,
    - Information Science & Technology Institute,
    - Materials Science Institute,
    - Institute of Geophysics, Planetary Physics, and Signatures, and
    - Seaborg Institute.
- Continue to nurture the LDRD-DR SoS focus area to ensure ongoing innovation.
- Integrate SoS planning formally and on an ongoing basis with IS&T, Nuclear and Particle Futures, and Materials planning. Give quarterly cooperative briefs to the LANL Team.
- Explore ways to share information and high-value resources related to SoS. These might include an internal database of equipment and expertise or the integration of SoS into the planning of the LANL capability reviews.
- Manage the ongoing Laboratory investment strategy and process to purchase capital equipment of importance to the Science of Signatures.
- Explore the options for SoS infrastructure: a micro-fab facility that has a joint SoS/Materials focus.
- Consistently employ systems engineering to more efficiently move sensing devices from the bench to the field.
- Ensure that some portion of Laboratory engineering investments support the SoS forward-deployment thrust.
- Partner with industry to enable forward deployment of signature systems.

Conclusions and Next Steps

The key integrating factor across the six Science of Signatures focus areas is the SoS mission statement: "Characterize measures, signals and properties in/of complex systems to detect/attribute change and predict behavior and impact across scales of space (subatomic to astronomic) and time (femtosecond to geologic)." This science

challenge is general and is shared by all six areas of leadership. Similarly, the three science themes for SoS (Discover Signatures, Revolutionize Measurements, and Forward Technology Deployment) cut across the six focus areas and provide a unifying framework for understanding the key science challenges in each focus area.

The key science challenges in each science theme also relate across the six focus areas of the strategy. Science goals in each focus area are framed as capability maintenance and development statements and represent the desired state of evolution of each capability in the focus area over a ten year time horizon. Over the six focus areas, there are 20 science goals that we aspire to achieve. This would be a daunting task for a ten-year time period, but we recognize that the Science of Signatures pillar must endure well beyond the scope of a single decade. It must be managed actively for the next 30 to 50 years, similar to how we plan for and manage the Materials, Nuclear, and IS&T pillars currently (and in consonance with them). With that scope of commitment, we are confident that we can realize our vision and goals for the SoS pillar.

However, our science strategy is only achievable if we have comparable enabling strategies for facilities and infrastructure and for workforce development. We expect that the complete Science of Signatures strategy will help the Laboratory leadership continue to manage the following types of investments:

- **Major Los Alamos Science Investments**
  - Laboratory Directed Research and Development–Directed Research Investments (LDRD-DR)
  - Laboratory Directed Research and Development–Exploratory Research Investments (LDRD-ER)

- **Major Institutional Capital Equipment Investments**.

- **Major Institutional Facility Investments**.
  - Facility modernization, e.g., Biological science laboratory (level 3), radiological facility modernization at TA-48.
  - Radiological Laboratory/Utility/Office Building use
  - TA-46 Chemical Security Initiative Laboratory

- **External Programmatic Requests**
  - New facilities investments
  - Capital equipment
  - Strategic programs and operations

The National Security Sciences Building at LANL.

SoS Strategy at a Glance

Nuclear and Radiological Signatures

Nuclear Detection/Nuclear and Radiological Materials Characterization

Goal 1: Achieve standoff detection of structures that yields valuable/actionable information about radiological and nuclear materials that we wish to observe but cannot access.

Goal 2: Create a suite of capabilities that enable process characterization and monitoring of special nuclear materials production facilities for a variety of applications.

Goal 3: Field novel methods or quantum improvements in actinide analysis for safeguards applications.

Goal 4: Discover, design, and deliver the next generation of monitors and algorithms to detect special nuclear materials or weapons of mass effect when they are in movement.

Nuclear Event Characterization

Goal 5: Drive next-generation material measurements to generate actionable data, directed by interpretation goals while meeting specific time and quality goals.

Goal 6: Provide the technical basis for predicting and interpreting all energy outputs by integrating expertise, models, and measurement systems.

Goal 7: Provide forefront modeling capabilities to guide decision making, as well as to turn data and signatures into knowledge.

Goal 8: Advance space-based and ground-based signatures and detection technologies for nuclear detonation detection.

Chemical and Materials Signatures (including explosives)

Goal 1: Discover the next generation of chemical signatures, models, and detection platforms for chemical weapons identification and forensics.

Goal 2: Engineer and model the next generation of materials for sensing.

Goal 3: Build an enduring capability to predict/address emerging threats relevant to explosives detection, forensics, and attribution.

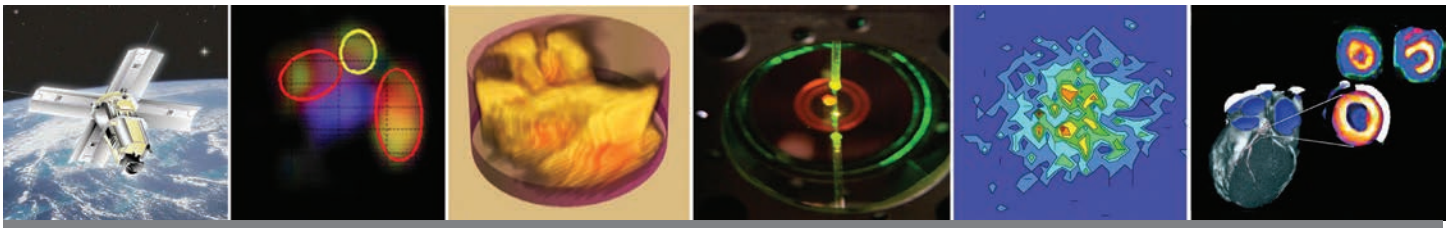
Goal 4: Create the next generation of signatures, models, and detection platforms to characterize nonradiological materials of interest for national security concerns including emerging capabilities in additive manufacturing.

Biological Signatures

Goal 1: Identify and detect pathogens quickly, accurately, and inexpensively using signature validation, molecular assays, detection platforms, and sensor networks with the intent of informing epidemiology.

Goal 2: Develop new tools for epidemiology and disease modeling that enable us to predict disease progression and transmission by determining pathogen lifecycles, mechanisms of disease onset and progression, and mechanisms of transmission.

Goal 3: Enable disease management and response with knowledge-based decision tools that describe the characteristics of primary disease scenarios, analyze approaches and possible actions, and integrate data streams and modeling to predict outcomes.



Energy Signatures

Goal 1: Pioneer new approaches to extracting/attributing signatures of energy from living organisms, geological environments, or man-made systems under conditions that are remote, inaccessible, and/or extreme

Goal 2: Develop materials for energy and environmental systems that respond and/or report back on signature-induced stimuli.

Goal 3: Integrate sensing, modeling, and analysis science and technology to support decisions and investments, protect systems and anticipate risks/degradation, and respond to disruptions, impacts, and consequences.

Climate Signatures

Goal 1: Become the leader in those signatures of greatest value to climate science by developing computational and analytical techniques applicable to multi-variable data sets and by developing signal detection systems that span software to hardware (prototype to mature).

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Space Signatures

Goal 1: Use signatures to understand, assess, quantify, and predict natural and man-made threats to the U.S. space infrastructure.

Goal 2: Field advanced detection technologies on space and airborne payloads or other platforms that have restrictions on mass, power, and volume.

Goal 3: Create smart sensors and sensor systems that are configured for space and that use autonomous measurement strategies for onboard conversion of data to information.

Crosscutting Institutional Goals

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View from Los Alamos, looking East. Photo by Josh Smith.

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NNSA National Nuclear Security Administration