USGS Lidar Science Strategy: Mapping the Technology to the Science

By Jason M. Stoker, John C. Brock, Christopher E. Soulard, Kernell G. Ries, Larry J. Sugarbaker, Wesley E. Newton, Patricia K. Haggerty, Kathy E. Lee, and John A. Young

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Conversion Factors

International System of Units to Inch/Pound

Multiply	By	To obtain
meter (m)	3.281	foot (ft)

Abbreviations

1D	one dimensional
2D	two dimensional
3D	three dimensional
4D	four dimensional
3DEP	3D Elevation Program
CLU	Climate and Land Use Change
CONUS	conterminous United States
CSS	Core Science Systems
DEM	digital elevation model
DOI	U.S. Department of the Interior
DSM	digital surface model
ifsar	interferometric synthetic aperture radar
insar	interferometric synthetic aperture radar
lidar	light detection and ranging
NDEP	National Digital Elevation Program
NED	National Elevation Dataset
NEEA	National Enhanced Elevation Assessment
NGDA	National Geospatial Data Asset
NGP	National Geospatial Program (USGS)
NHD	National Hydrography Dataset
NOAA	National Oceanic and Atmospheric Administration
NVEWS	National Volcano Early Warning System Implementation Plan
OMB	U.S. Office of Management and Budget
TLS	terrestrial laser scanning
UAS	Unmanned Aerial System
ULSPT	USGS Lidar Science Planning Team
USGS	U.S. Geological Survey
WBD	Watershed Boundaries Dataset

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Executive Summary

The U.S. Geological Survey (USGS) utilizes light detection and ranging (lidar) and enabling technologies to support many science research activities. Lidar-derived metrics and products have become a fundamental input to complex hydrologic and hydraulic models, flood inundation models, fault detection and geologic mapping, topographic and land-surface mapping, landslide and volcano hazards mapping and monitoring, forest canopy and habitat characterization, coastal and fluvial erosion mapping, and a host of other research and operational activities. This report documents the types of lidar being used by the USGS, discusses how lidar technology facilitates the achievement of individual mission area goals within the USGS, and offers recommendations and suggested changes in direction in terms of how a mission area could direct work using lidar as it relates to the mission area goals that have already been established.

Introduction

The U.S. Geological Survey (USGS) utilizes light detection and ranging (lidar) and enabling technologies to support many science research activities. Lidar-derived metrics and products have become a fundamental input to complex hydrologic and hydraulic models, flood inundation models, fault detection and geologic mapping, topographic and land-surface mapping, landslide and volcano hazards mapping and monitoring, forest canopy and habitat characterization, coastal and fluvial erosion mapping, and a host of other research and operational activities. Lidar instruments can be mounted on multiple platforms such as airplanes, helicopters, and satellites. They also can be mounted on fixed tripods and mobile ground-based platforms such as trucks and four-wheel-drive vehicles to perform terrestrial laser scanning (TLS) that captures three-dimensional (3D) data about the precise position of landscape features. Lasers produce coherent light in different parts of the visible and near-infrared portions of the electromagnetic spectrum. These laser pulses produce return (reflective) signals, which provide precise locations of surface features, vegetation, concrete, and other features. Features below water can also be resolved, depending on the particular lidar technology being used. Our USGS science is only beginning to take advantage of this maturing remote sensing technology.

The 3D Elevation Program (3DEP) is designed to create a national database of high-quality airborne lidar data and a set of new elevation products over the next several years (Sugarbaker and others, 2014). The USGS has identified specific opportunities where nationwide data could provide tremendous benefit for our science investigations. It is important that the USGS take advantage of this new information asset and that we provide leadership in its application within the science community. The USGS also is a leader in developing new lidar instrumentation and related research, particularly in the area of topo-bathymetric lidar systems. Across the Bureau a number of ground-based and mobile lidar systems have been acquired, and terrestrial lidar applications research is also expanding.

A USGS Science Plan for Lidar has been developed by USGS scientists to provide a more cohesive approach for our research. This plan includes the following objectives:

- Utilizing airborne and terrestrial lidar to support our mission-area science investigations to include developing new and innovative uses of lidar data and developing techniques for applying the data to real-world problems.
- Defining our role and conducting lidar research to inform the development of new instruments.
- Using lidar to improve our geospatial assets such as 3DEP, the National Hydrography Dataset (NHD), the Watershed Boundaries Dataset (WBD), geologic maps, and other products.
- Providing cutting-edge guidance, specifications, and standards for acquiring and managing lidar data.

The plan was completed by a team of USGS scientists having expertise in the application of lidar and by USGS lidar scientists who also have expertise in associated technologies—henceforth called the USGS Lidar Science Planning Team (ULSPT). Research applications are wide ranging and can support the science plans of every Bureau mission area.

The team consisted of the following members (mission area):

Jason Stoker (Core Science Systems)
Larry Sugarbaker (Core Science Systems)
Greg Desmond (Core Science Systems)
John Brock (Natural Hazards)
Kernell Ries (Water)
Greg Snyder (Climate & Land Use)
Ben Brooks (Natural Hazards)
Gerald Bawden (Water)
Ryan Gold (Natural Hazards)
John Young (Ecosystems)
Kathy Lee (Environmental Health)
Patti Haggerty (Ecosystems)
Roger Barlow (Core Science Systems)
Steve Schilling (Natural Hazards)
Ben Jones (Climate & Land Use)
Wesley Newton (Ecosystems)
Brenda Densmore (Water)
Ralph Haugerud (Natural Hazards)
Gary Merrill (Core Science Systems)
Nathaniel Plant (Natural Hazards)
Christopher Soulard (Climate & Land Use)
Vito Nuccio (Energy & Minerals)

The USGS has been using lidar remote sensing data and derived information for over 15 years for a wide range of applications (fig. 1). The first USGS lidar workshop was held November 20–22, 2002, in St. Petersburg, Fla., to bring together scientists and managers from across the Bureau. The workshop agenda focused on six themes: (1) current and future lidar technologies, (2) lidar applications within USGS science and disciplines, (3) calibration and accuracy assessment, (4) tools for processing and evaluating lidar datasets, (5) lidar data management, and (6) commercial and contracting issues. These six themes served as the topics for workshop plenary sessions as well as the general focus for associated breakout sessions. A number of possible actions/suggestions were presented regarding the role the USGS could play in the future application and development of lidar technology (Crane and others, 2004). In 2005, several USGS scientists published an article in the journal *Photogrammetric Engineering and Remote Sensing* entitled “Recent U.S. Geological Survey Applications of Lidar” (Queija and others, 2005).

Figure 1. A 3D perspective image of Cheesman Lake and the South Platte River, Colo., looking west, from lidar collected in 2000. Trees are colored according to their height above the ground. Red represents trees taller than 25 m. White represents rock. Scientists use images such as this to better understand the 3D relationship between trees and their environment. (U.S. Geological Survey.)

In 2007 and 2008 the USGS hosted two "national lidar dataset" meetings in which the need and feasibility of a national-scale lidar program were discussed (Stoker and others, 2007, 2008). These discussions demonstrated that there was a strong need for lidar data nationally; however, the meetings also documented the necessity for doing a strong cost/benefit analysis of all the value that lidar could provide.

The National Enhanced Elevation Assessment (NEEA) report (Snyder and others, 2013), accessible at http://dx.doi.org/10.3133/ofr20131237, performed a comprehensive evaluation of the use of lidar across the United States. The report includes three appendixes, which collate the information needs that were provided by many other States, Federal agencies, and local groups. USGS managers identified nine major functional activities having mission-critical requirements for elevation data:

- **Geologic Mapping**, under Business Use No. 9, Geologic Resource Assessment and Hazards Mitigation
- **Seismic Hazards**, under Business Use No. 9, Geologic Resource Assessment and Hazards Mitigation
- **Landslide Hazards**, under Business Use No. 9, Geologic Resource Assessment and Hazards Mitigation
- **Volcano Hazards**, under Business Use No. 9, Geologic Resource Assessment and Hazards Mitigation
- **Water Resource Planning and Management**, under Business Use No. 2, Water Supply and Quality, and Business Use No. 3, River and Stream Resource Management
- **Coastal Zone Management and Sea Level Rise and Subsidence**, under Business Use No. 4, Coastal Zone Management, and Business Use No. 15, Sea Level Rise and Subsidence
- **Flood Risk Management**, under Business Use No. 14, Flood Risk Management
- **Mapping, Monitoring, and Assessment of Biological Carbon Stocks**, under Business Use No. 1, Natural Resources Conservation
- **Mapping, Monitoring, and Assessment of Habitat**, under Business Use No. 7, Wildlife and Habitat Management

In addition to these functional activities, the USGS maintains an Office of Management and Budget (OMB) Circular A–16 responsibility for the terrestrial elevation theme and a set of elevation and remote sensing datasets designated as National Geospatial Data Assets (NGDAs), while the National Oceanic and Atmospheric Administration (NOAA) retains the bathymetric elevation responsibility. The USGS also has a history of producing topographic base maps for the United States, of which mapping using lidar is a key component of new topographic map updates.

Types of Lidar Currently in Use by the USGS

The USGS utilizes many different types of lidar instruments and associated data to achieve its science objectives. There are many differences in terms of platforms, data densities, ease of use, and utility. The USGS contracts with commercial companies to collect data for base mapping (fig. 2) and research purposes, and internally collects both research airborne and ground-based terrestrial laser-scanning data for individual hypothesis-based local projects. The lidar that the USGS uses ranges from highly standardized, wide-area collections to lidar that is now replacing traditional plot-based measurements. All lidar data collected and used by the USGS are considered to be in the public domain; however, some lidar data collected currently are more user friendly and accessible than others.

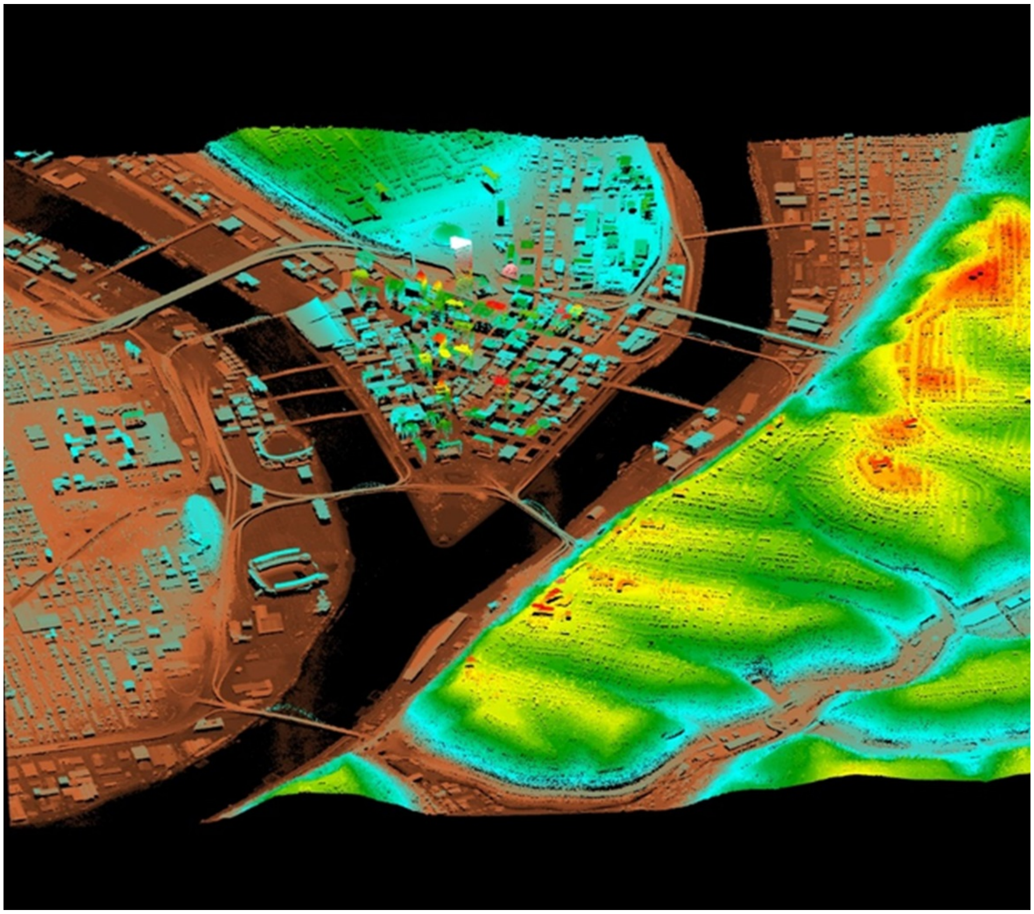

Figure 2. A 3D perspective image of a lidar point cloud (a collection of 3D points from lidar) of Pittsburgh. The view is toward the east. Colors represent elevation (rust-brown is lower elevation, red is higher elevation). (U.S. Geological Survey.)

Lidar Relevance to USGS Mission Area Science—Existing Lidar Application to USGS Mission Area Science

In 2010, the USGS aligned itself with the broad science themes outlined in its 10-year Bureau-level science strategy. Teams of USGS scientists also led the creation of 10-year science strategies for each of the USGS mission areas:

- Climate and Land Use Change
- Ecosystems
- Energy and Minerals
- Environmental Health
- Natural Hazards
- Water
- Core Science Systems

Results of this effort can be found at http://www.usgs.gov/start_with_science/. The ULSPT used these mission area science strategy documents in concert with the above baseline information to help identify future strategic directions as they relate to using lidar for each mission area. The following discussions provide guidance of how each mission area can specifically take advantage of lidar to further its mission and goals. While there is overlap between lidar uses in mission areas, these assessments evaluate the use of lidar based on the previously defined mission area goals.

The ULSPT ranked the relevance of all types of lidar to mission area goals. While each mission area science strategy was formatted slightly differently, the ULSPT did its best to maintain consistency throughout the evaluation process. The probability of immediate utility of lidar remote sensing in advancing each goal is rated by the code associated with each goal, as follows:

- VH – Very High
- H – High
- M – Moderate
- L – Low

Climate and Land Use Change

Since the passage of the U.S. Global Change Research Act of 1990, the USGS has made substantial scientific contributions to understanding the interactive living and nonliving components of the Earth system. USGS natural science activities have led to fundamental advances in observing and understanding climate and land-cover change and the effects these changes have on ecosystems, natural-resource availability, and societal sustainability. Over the next 10 years, the USGS is predicted to make substantial contributions to understanding how Earth systems interact with, respond to, and cause global change, and lidar remote sensing can be a key enabling technology. The Climate and Land Use Change (CLU) Science Strategy states that CLU work with science partners, decisionmakers, and resource managers at local to international levels (including Native American tribes) to improve understanding of past and present change; develop relevant forecasts; and identify those lands, resources, and communities most vulnerable to global change processes. Lidar data and derived products can be essential to the success of these activities by providing current-state variables and metrics, useful for hindcasting and forecasting trends. Science made possible by lidar methods can play an expanding role in helping communities and land resource managers understand local to global implications, anticipate effects, prepare for changes, and reduce the risks associated with decisionmaking in a changing environment (fig. 3). USGS partners and stakeholders can benefit from the landscape-scale geospatial datasets, including foundational lidar elevation products, predictive models, and decision support systems and services resulting from the implementation of the CLU Science Strategy (Burkett and others, 2013).

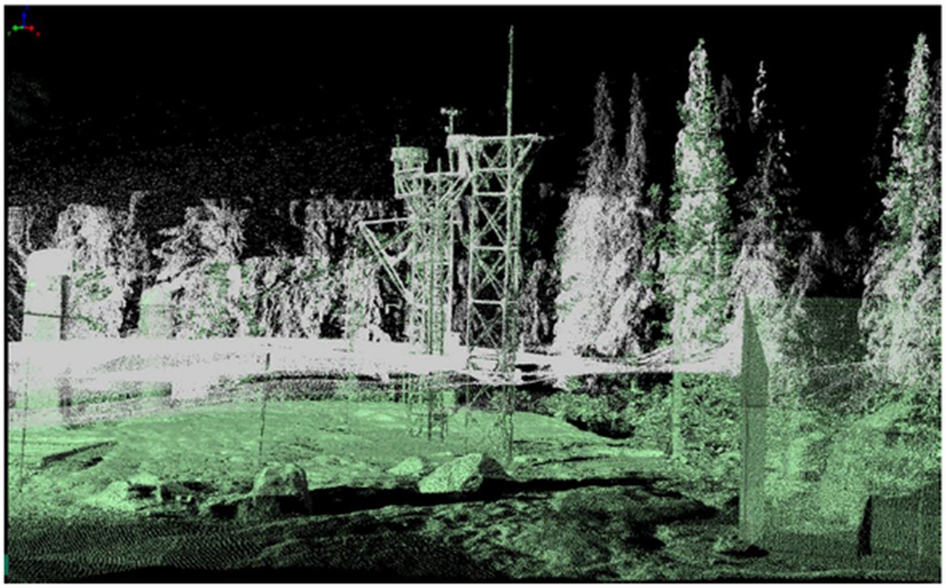

Figure 3. Snowpack-level changes at the Central Sierra Snow Lab, Soda Springs, Calif., measured using terrestrial lidar. Image provided by Sandra Bond (USGS). White color represents snowpack data collected in March 2005; green represents snowpack data collected in June 2005.

Lidar Relevance to Climate and Land Use Change Science Goals

The CLU Science Strategy recognizes core USGS strengths and applies them to key problems in the context of seven programmatic goals focused on past global change, carbon, biogeochemical cycles, land use/land cover, droughts and floods, sea level, and biological changes. Each CLU science goal was selected based on the following criteria, and similarly, these criteria were considered in developing guidance for the priority application of lidar observations to CLU-sponsored science:

- Employs integrated scientific research and assessment to fill knowledge gaps about national priorities regarding climate, land use, ecosystems, and energy.
- Addresses topics critical for managing natural resources and the environment, with tangible effects on environmental goods, services, and risks.
- Uses USGS core capacity, disciplinary strengths, integrative capacities, and long-term databases.
- Invests in comprehensive, integrated observation and monitoring to understand local to global climate-change processes and conditions.
- Leverages or expands partnerships that advance the science goal.
- Addresses topics critical to the Department of the Interior (DOI) for managing natural resources, wildlife habitat, and the environment, while giving special attention to those resources critical to Native American subsistence tribal cultures.

Lidar observations are in general of high relevance to the CLU science goals listed below, but it is possible and necessary to rank the significance of lidar to each goal. The probability of immediate utility of lidar remote sensing in advancing each goal is rated by the code associated with each goal, as follows: VH – Very High; H – High; M – Moderate; L – Low:

Goal 1—Improve understanding of past global changes in support of policy and management decisions (M).

Goal 2—Improve understanding and prediction of the global carbon cycle (H).

Goal 3—Improve understanding of biogeochemical cycles and their coupled interactions (L).

Goal 4—Improve understanding of land-use and land-cover change: rates, causes, and consequences (VH).
Goal 5—Improve understanding and predictions of changes in hydrologic processes, droughts, floods, and water availability under changing land use and climate (VH).
Goal 6—Improve understanding and prediction of coastal response to sea-level rise, climatic changes, and human development (VH).
Goal 7—Improve understanding and prediction of biological responses to global change (H).

Suggested Priorities for Lidar Contributions to Climate and Land Use Change Science

Lidar relevance is ranked as very high for three of the seven CLU Science Goals listed above. Among those goals, the ULSPT judged Goal 4 (Improve understanding of land-use and land-cover change: rates, causes, and consequences) to be most essential to the core mission of CLU and most amenable to enhancement by lidar. The ULSPT suggests that Goals 5, 6, and 7 present excellent opportunities for partnering with other mission areas (Water, Natural Hazards, and Ecosystems, respectively) on lidar-enabled research and applications development. Tapping the promise of lidar techniques with respect to Goals 5, 6, and 7 is covered in the sections of this plan that describe the suggested role of lidar in support of the science goals of those mission areas.

Goal 4 aims to improve understanding of changes in land cover because land cover, use, and condition affect climate; and climate and other global change factors, in turn, affect land cover, use, and condition. These changes at the land surface alter biogeophysical, biogeochemical, and energy exchange processes, which affect weather and climate variability at local, regional, and global scales. Lidar elevation point clouds are highly useful in accomplishing all of the critical elements associated with the CLU land-change Science Goal 4.

Guidance to the Climate and Land Use Change Mission Area

- Increase use of multi-temporal lidar data to better monitor patterns of land change over time.
- Foster the advancement of lidar methods that directly enhance studies aimed at improving understanding of land-use and land-cover change, specifically (1) retrieval of regional 3D vegetation canopy structure, (2) construction of coastal topo-bathymetric elevation models adapted for numerous science applications, and (3) investigation of river corridor hydrology and ecosystem change on the landscape scale.
- Improve calibration of multi-temporal lidar datasets to ensure that errors are well understood and that changes over time are caused by changes in lidar signal, not by lidar noise.
- Assimilate lidar vegetation-canopy metrics into fire models to improve prediction of fire behavior and associated land-cover change, both immediate and postfire; specifically, the succession and buildup of fuels following fires.
- Use lidar point clouds and derived information products to improve assessments of future economic costs to coastal communities that are affected by sea-level rise and storm-surge inundation.
- Seek to advance terrestrial-aquatic lidar to enable regional capture of continuous 3D channel and flood-plain topography.

Ecosystems

The need to understand how ecosystems work, how they vary over space and time, and how physical and ecological processes influence ecosystem services, biodiversity, threatened and endangered species, and other ecosystem attributes that society values is fundamental to the Nation's environmental sustainability and economic success. Ecosystem science is critical to making informed decisions about natural resources that can sustain our Nation's economic and environmental well-being. Resource managers and policymakers at local, regional, and national levels are faced with countless decisions each year on issues as diverse as renewable and nonrenewable energy development, agriculture, forestry, water supply, and resource allocations at the urban-rural interface (Williams and others, 2013).

The urgency for sound decisionmaking is increasing dramatically as the world is being rapidly transformed, creating a pressing need for the rich, multiple-scale geospatial observations afforded by lidar remote sensing. Environmental changes that are observable using lidar mapping are associated with natural hazards, greenhouse gas emissions, and increasing demands for water, land, food, energy, mineral, and living resources. At risk is the Nation's environmental capital, the goods and services provided by resilient ecosystems that are vital to the health and well-being of human societies. Science backed by accurate and precise characterization of various attributes provided by lidar remote sensing can aid in mitigating threats to ecosystems (Williams and others, 2013).

Lidar Relevance to Ecosystems Science Goals

During the next decade, ecosystem science will be challenged to integrate ecosystem responses to climate variability and other drivers of ecosystem change such as landscape alterations, introduction of nonnative species, pollutant discharges, and effects of water and energy development. Effective ecosystem management requires the integration of both synoptic and targeted remote sensing observations with scientific discovery and application to solve problems that will increasingly affect the welfare of American citizens and global populations. Enhanced and carefully directed use of lidar observations is closely compatible with the guidance in the Ecosystems Science Strategy. That guidance promotes new directions for interdisciplinary and integrated science aimed at understanding how multiple forces interact to bring about ecological changes. A range of scientific approaches including experimentation, process measurements, remote sensing, analyses of the geologic record, long-term observations, natural history studies, and modeling are required to understand ecosystem functions for adaptive management, and lidar methods are sure to play an increasing role. Lidar-based approaches to investigating ecosystem structure and function can efficiently provide unprecedented spatial detail at landscape scales (fig. 4). Lidar remote sensing is therefore well matched to a common theme that emerges from the priority societal issues identified in the recently developed Ecosystems Strategic Science Plan (Williams and others, 2013), namely, a general sense of urgency in expanding our understanding of ecosystem processes. With increasing human demands on natural resources, the Nation is encouraged to take bold steps to move ecosystem science and management forward using advanced technology to the fullest extent practical.

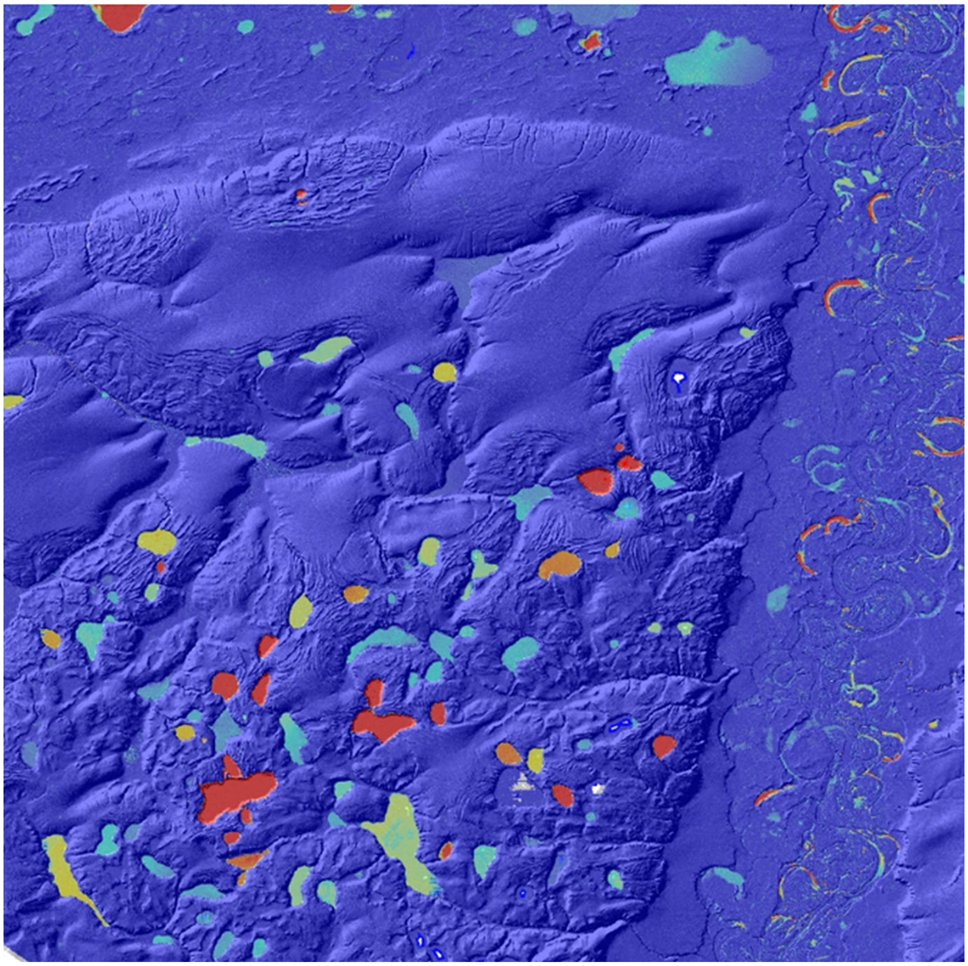

Figure 4. Using lidar to find topographic depressions that reflect ponding potential, Yukon River basin, Alaska. Colored by potential water ponding depth (cyan represents shallower ponding, red represents deeper ponding). (U.S. Geological Survey.)

Lidar observations are of high, but variable, relevance to the Ecosystems Science Goals that are defined in the USGS Ecosystems Science Strategy and listed below. The immediate and obvious value of lidar in advancing each goal is rated by the code associated with each goal, as follows: VH – Very High; H – High; M – Moderate; L – Low:

Goal 1—Improve understanding of ecosystem structure, function, and process (VH).

Goal 2—Advance understanding of how drivers influence ecosystem change (H).

Goal 3—Improve understanding of the services ecosystems provide to society (H).

Goal 4—Develop tools, technologies, and capacities to inform decisionmaking about ecosystems (VH).

Goal 5—Apply science to enhance strategies for ecosystem management and conservation and for justifying ecosystem restoration (M).

Suggested Priorities for Lidar Contributions to Ecosystems Science

Lidar relevance is ranked as very high for two of the five Ecosystems Science Goals, and among those two goals, the ULSPT judged Goal 1 (Improve understanding of ecosystem structure, function, and processes) to be closest to the core mission of Ecosystems. Lidar activities directed toward achieving Goal 1 will inherently also address Goal 4 (Develop tools, technologies, and capacities to inform decisionmaking about ecosystems), because such lidar-based studies can naturally serve to aid in development of specialized lidar instruments and analysis algorithms. These lidar technologies can then be available to feed highly specific geospatial data products to the next generation of information management and decision-support systems for ecosystem based, adaptive resource management for restoration, mitigation, and adaptation (fig. 5). The ULSPT notes that much unrealized potential exists for highly productive collaboration between Ecosystems, Climate and Land Use Change, and Core Science Systems to create lidar-based technical capacities for acquiring and integrating knowledge of changing ecosystem conditions and the consequences of these changes into resource management decisions for effective conservation of terrestrial, freshwater, and marine ecosystems.

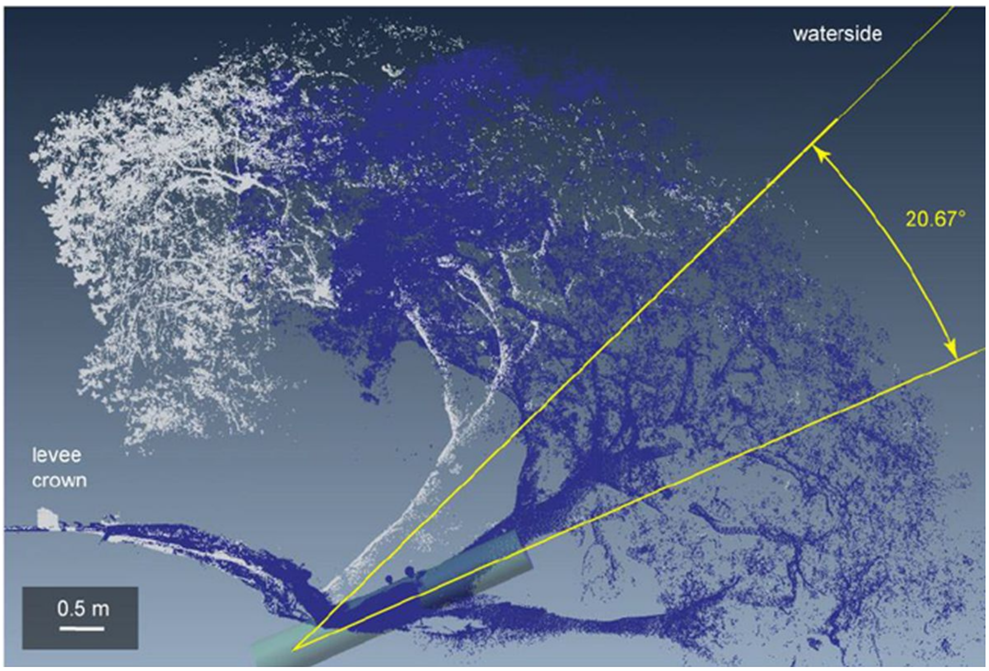

Figure 5. Two lidar scans, taken on April 4, 2012 (white points), and June 6, 2012 (blue points), show how a tree is slowly falling into the water from the side of a levee, Twitchell Island, Calif. Multiple scans such as these can accurately measure changes in 3D and help identify how quickly potential mitigation effects may be needed. Image provided by Sandra Bond (USGS).

Applying lidar observations widely in support of Ecosystems Science Goal 1 is quite timely, because the rapid changes now taking place in all the Nation's ecosystems make it imperative to understand ecosystem structure, function, and processes and how ecosystems directly or indirectly support human populations and security of the country. Highly detailed yet regional objective information from lidar point clouds can increasingly inform and accelerate the scientific understanding needed to adequately inform natural resource management policy in the United States in the coming decades. The ULSPT poses, without reservation, that recent and quite feasible new developments in lidar could fill gaps in current knowledge that presently leave managers' questions unresolved about the causes and consequences of change, the ability of species to adapt to ecosystem change, how ecosystem resiliency can be maintained, or how degraded ecosystems can be restored.

Guidance to the Ecosystems Mission Area

- Develop and apply lidar methods to determine the quality of wildlife habitat for an endangered species, especially on DOI land.
- Increase use of terrestrial-aquatic lidar capture of continuous 3D channel and flood-plain topography to advance the status of fish habitat models.
- Provide a mechanism to coordinate with Core Science Systems on 3DEP collections so that fieldwork can be performed concurrently with airborne campaigns.
- Increase use of TLS and Unmanned Aerial Systems (UAS) lidar collections in research in order to better understand how local ecosystem processes operate and how they scale up to larger areas.
- Increase use of and expand research in large-area lidar from 3DEP for regional-scale habitat mapping.
- Explore restoration and mitigation progress in vegetated landscapes using lidar change analyses.

Energy and Minerals

The economic vitality, national security, and standard of living of the United States depend heavily on having adequate and reliable supplies of energy and mineral resources. On the basis of population and consumption trends, the Nation’s use of energy and minerals can be expected to grow, driving the demand for ever broader scientific understanding of resource formation, location, and availability. In addition, the increasing importance of environmental stewardship, human health, and sustainable growth places further emphasis on energy and mineral resources research and understanding. Collectively, these trends in resource demand and the interdependencies among demands for various resources will lead to new challenges and, in turn, require cutting-edge science for the next generation of societal decisions. The long and continuing history of USGS contributions to energy and mineral resources science and national geologic and topographic mapping provides a solid foundation of core capabilities upon which new research directions can grow (Ferrero and others, 2013).

Lidar Relevance to Energy and Minerals Science Goals

Energy and mineral resources are essential to society. The USGS, as the Nation’s principal natural-science bureau, advances the science of energy and mineral resources and provides statistical information and analysis on the global flow of minerals and mineral materials. Understanding the science, quality, quantity, and spatial distribution of energy and mineral resources has been a core function of the USGS since its inception, and lidar remote sensing can now aid the USGS in fulfilling this essential agency role.

Lidar observations can assist in achieving the Energy and Minerals Science Goals that are listed below, along with a ranking of the significance of lidar to each individual goal. The probability of immediate utility of lidar remote sensing in advancing each goal is rated by the code associated with each goal, as follows: VH – Very High; H – High; M – Moderate; L – Low:

Goal 1—Understand fundamental Earth processes that form energy and mineral resources (L).

Goal 2—Understand the environmental behavior of energy and mineral resources and their waste products (H).

Goal 3—Provide inventories and assessments of energy and mineral resources (L).

Goal 4—Understand the effects of energy and mineral development on natural resources and society (M).

Goal 5—Understand the reliability and availability of energy and mineral supplies (L).

Suggested Priorities for Lidar Contributions to Energy and Minerals Science

Lidar relevance is ranked as low for Energy and Minerals Science Goals 1, 3, and 5, is judged as only moderate for Goal 4, but is set at high for Goal 2 (Understand the environmental behavior of energy and mineral resources and their waste products). Goal 2 is directed toward gaining a more comprehensive understanding of the interactions among energy and mineral resources. Environmental and biological receptors can help resource industries identify efficient and cost-effective means of mitigating adverse environmental effects, and can aid land-use managers and regulators in ensuring proper stewardship and protection of the environment (National Research Council, 2007). Research that combines foundational geomorphic information from lidar (fig. 6) with physical, chemical, biological, and toxicological observations of contaminant transport models to characterize the interactions among energy and mineral resources can facilitate scientifically informed decisionmaking regarding the sustainable development of these resources (Ferrero and others, 2013).

Previous extraction and development activities have sometimes had adverse environmental effects. Research at legacy resource extraction sites can provide insights into potential alternative sources of resources through reprocessing of waste streams or beneficial reuse. Furthermore, studies at legacy sites can provide understanding of long-term biogeochemical processes influencing environmental signatures; insight into complex natural exposure routes to surrounding ecosystems and humans; and information needed for mitigation and remediation as well as to inform responsible resource development in the future (Ferrero and others, 2013).

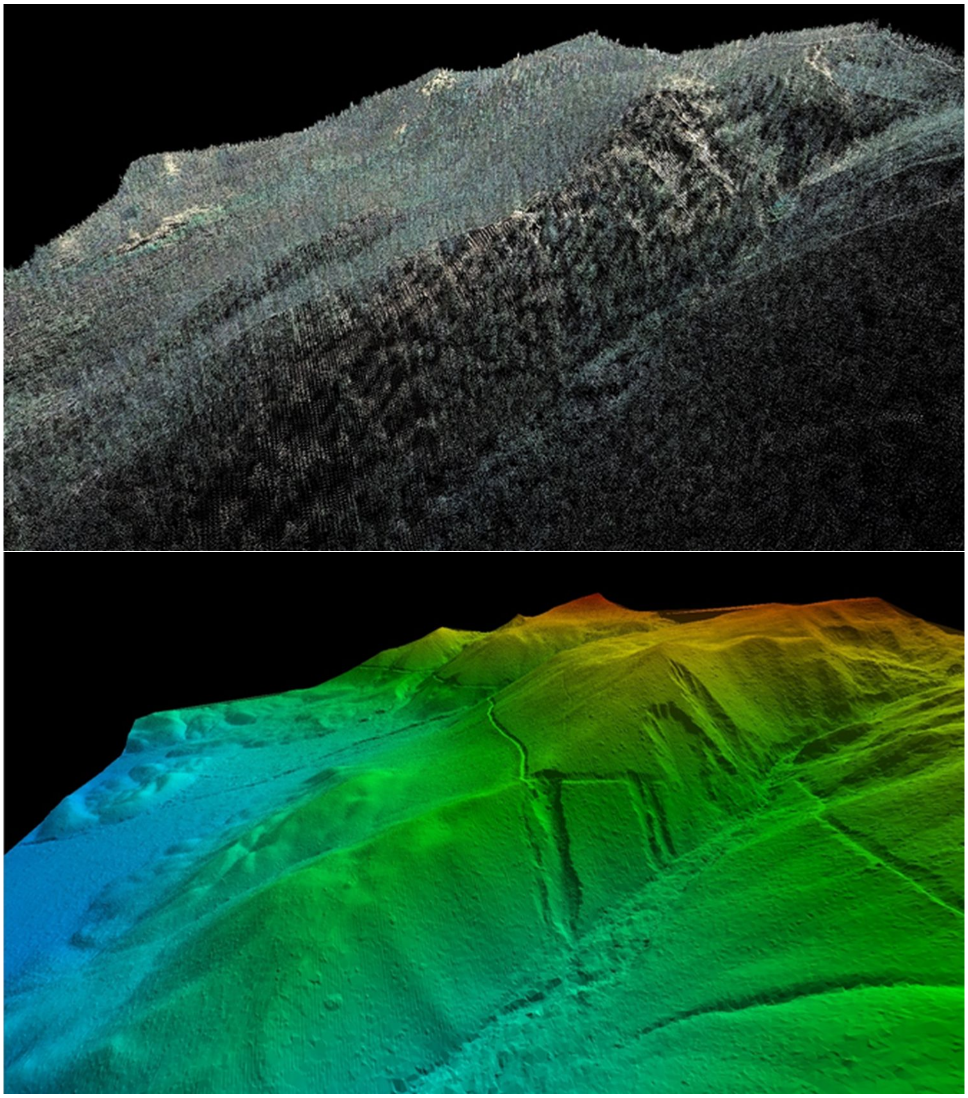

Figure 6. Lidar point cloud, colored by color imagery fusion (top), and bare earth digital elevation model (DEM) (bottom), Arkansas Valley, Colo. View is toward the north. By removing vegetation points and creating a bare earth surface, features that were invisible such as roads and even landslides become apparent. (U.S. Geological Survey.)

Guidance to the Energy and Minerals Mission Area

- Incorporate lidar-derived 3DEP very high resolution seamless bare earth topography into fluvial channel bathymetric elevation models to investigate perturbations to the natural landscape during the resource lifecycle at a legacy extraction site.
- Employ lidar-derived 3DEP very high resolution seamless bare earth topography with fluvial channel bathymetry elevation models within transport models to characterize waste streams associated with energy and mineral production and processing.
- Continue to investigate the relationship between lidar-derived bare earth topography and geophysical observations such as gravity, magnetic, electromagnetic, and seismic.
- Increase use of multi-temporal lidar datasets to better understand the effects of landslide displacement, erosion, and other surface-change events and processes.

Environmental Health

America has an abundance of natural resources. In addition to plentiful minerals and energy, we have bountiful clean water, fertile soil, and a scenic beauty that has led to the establishment of unrivaled national parks and forests, wildlife refuges, and other public lands. These “scenic resources” enrich our lives and contribute to our health and well-being. They have been maintained because of our history of respect for their value and an enduring commitment to their vigilant protection. Awareness of the social, economic, and personal value of the health of our environment is increasing. The emergence of environmentally driven diseases caused by exposure to contaminants and pathogens, even in these scenic areas, is a growing concern worldwide. New health threats and patterns of established threats are affected by both natural and anthropogenic changes to the environment. Human activities are key drivers of emerging (new and re-emerging) health threats. Societal demands for land and natural resources, quality of life, and economic prosperity lead to environmental change. Natural earth processes, climate trends, and related climatic events compound the environmental impact of human activities. These environmental drivers influence exposure to disease agents, including viral, bacterial, prion, and fungal pathogens; parasites; synthetic chemicals and substances; natural earth materials; toxins; and other biogenic compounds (Bright and others, 2013).

The USGS broadly defines environmental health science as the interdisciplinary study of relations among the quality of the physical environment, the health of the living environment, and human health. Interactions among these three spheres are driven by human activities, ecological processes, and natural earth processes. These interactions include exposure to contaminants and pathogens and the severity of environmentally driven diseases in animals and people. This definition provides the USGS with a framework for synthesizing natural science information from across the Bureau and providing it to environmental, natural resource, agricultural, and public health managers (fig.7).

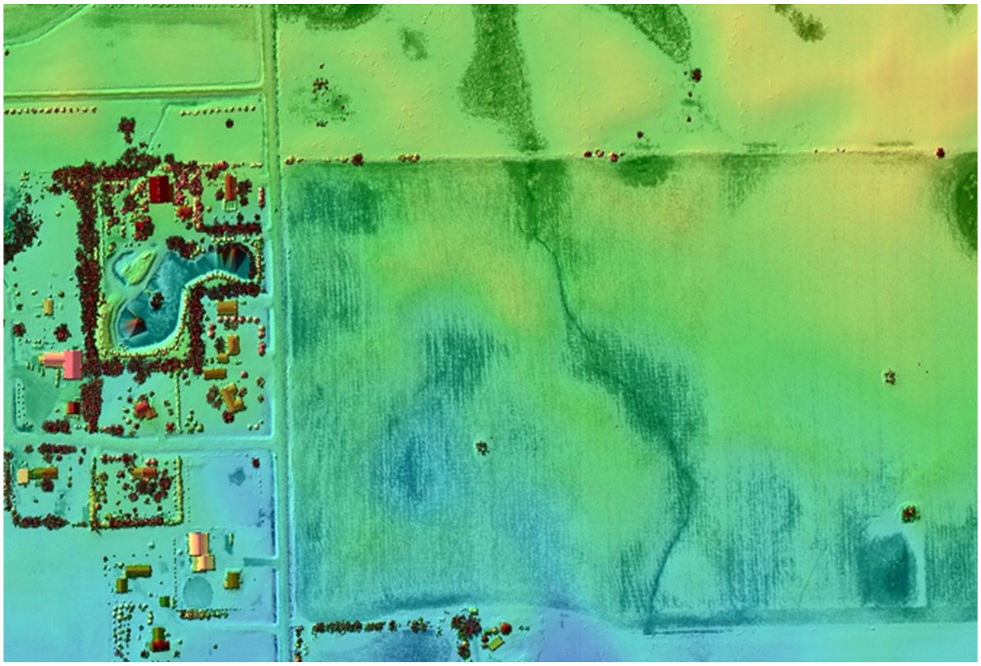

Figure 7. A digital surface model (DSM) of a rural area in South Dakota, colored by elevation. Area of image is approximately 1 square kilometer. The ability to see 3D relationships between agricultural fields, windbreaks, and buildings, for example, is very useful in environmental health studies. (U.S. Geological Survey.)

The USGS, as a Federal science agency having a broad range of natural science expertise relevant to environmental health, specializes in science at the environment/health interface by characterizing the processes that affect the interaction among the physical environment, the living environment, and people, and by characterizing the resulting factors that affect ecological and human exposure to disease agents. The USGS provides scientific information and tools as a scientific basis for management and policy decisionmaking.

Environmental Health Science currently utilizes lidar to:

- Examine sediment deposition and erosion for models that predict overland sediment (and associated contaminant) transport pathways related to Hurricane Sandy and other storm events.
- Create accurate digital elevation models (DEMs) for use in defining watershed boundaries for inclusion in watershed models.
- Estimate vegetative canopy leaf area, volume, and mass in watersheds.
- Better define hydrologic characteristics such as the location of ephemeral stream channels across land-use gradients, and delineate flood plains.
- Detect erosion-prone areas along stream-channel networks.

Lidar Relevance to Environmental Health Science Goals

Lidar observations can assist in achieving the Environmental Health Science Goals that are listed below, along with a ranking of the significance of lidar to each individual goal. The probability of immediate utility of lidar remote sensing in advancing each goal is rated by the code associated with each goal, as follows: VH – Very High; H – High; M – Moderate; L – Low:

Goal 1—Identify, prioritize, and detect contaminants and pathogens of emerging environmental concern (H).

Goal 2—Reduce the impact of contaminants on the environment and on fish and wildlife, domesticated animals, and people (H).

Goal 3—Reduce the impact of pathogens on the environment and on fish and wildlife, domesticated animals, and people (H).

Goal 4—Discover the complex interactions between, and the combined effects of, exposure to contaminants and pathogens (M).

Goal 5—Prepare for and respond to the environmental impacts and related health threats of natural and anthropogenic disasters (VH).

Guidance to the Environmental Health Mission Area

- Identify disease vectors and contaminant transport to identify vulnerable environmental settings.
- Delineate more refined characteristics of wetland and other surface vegetation cover to estimate biomass in order to quantify the role of plants in uptake, cycling, and release of contaminants.
- Delineate subsurface habitat features, including vegetation and substrate type in aquatic systems, to estimate suitable habitat cover.
- Identify storm-related impacts and investigate transport pathways and landscape-scale source and sink linkages.
- Identify mine-waste transport pathways.
- Identify fracture lineations in order to identify water and contaminant transport pathways.
- Identify subsidence and fissures at contaminated sites that can lead to preferential flow paths.
- Identify surface barriers and transport mechanisms for airborne pollutants and contaminants.
- Increase understanding of subsurface oil degradation through enhanced topographic landform delineation.

In addition to lidar, scientists have identified “Structure from Motion” (SfM) as a relatively new and developing technology that shows promise as a tool that could be used in place of lidar or as a complement to lidar. SfM is a technique whereby a 3D point cloud can be generated from stereo imagery, and it is similar in characteristics to lidar; however, it does not necessarily retain the ability to penetrate through dense vegetation canopy.

Natural Hazards

The mission of the USGS in natural hazards is to develop and apply hazard science to help protect the safety, security, and economic well-being of the Nation. The costs and consequences of natural hazards can be enormous, and each year more people and infrastructure are at risk (Holmes and others, 2013). USGS scientific research, based in part on detailed lidar observations, can increase understanding and help reduce natural hazard risks (fig. 8). Graphical depictions based on 3D lidar-based maps can be used to effectively communicate reliable information about natural-hazard characteristics, such as magnitude, extent, and consequences.

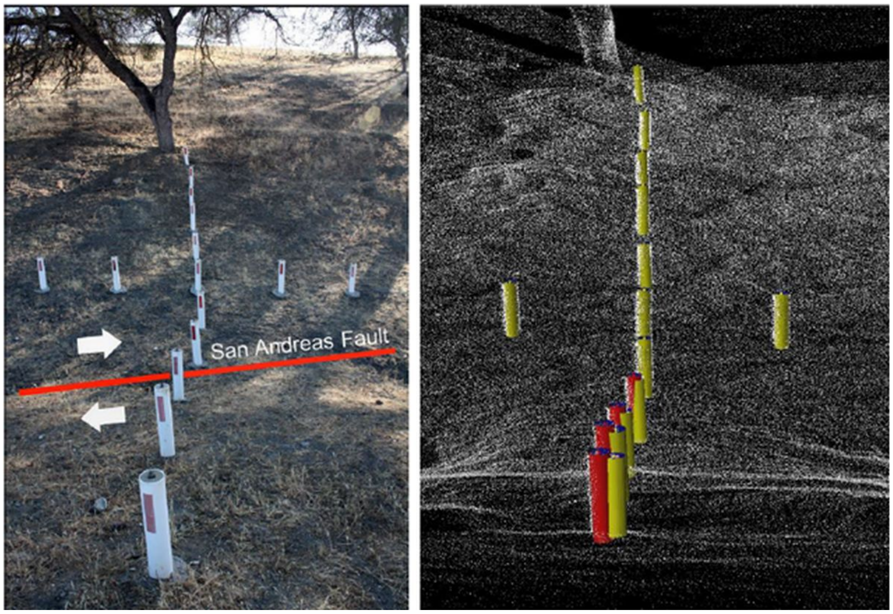

Figure 8. Measurement of post-seismic motion following the September 2004 Parkfield earthquake in central California was observed at the USGS video array at Car Hill, Calif. Post-seismic creep displacements are shown between September 2004 (yellow posts) and December 2004 (red posts). Image provided by Sandra Bond (USGS).

The USGS conducts hazard research to inform a broad range of planning and response activities at individual, local, State, national, and international levels. Seamless lidar topography available through 3DEP enables the robust assessments that (1) are needed by those potentially affected by natural hazards, (2) can help to prepare for hazardous events, and (3) fulfill the need for information about updated hazards for situational awareness during times of crisis. To meet these needs, scientists, in turn, require fundamental understanding of natural processes and observations of natural events, and here again lidar mapping can provide substantial benefits. The Natural Hazards Science Strategy (Holmes and others, 2013) lists four overarching and interrelated goals regarding observations, understanding, assessments, and situational awareness, and identifies the core responsibilities and strategic actions required to accomplish each goal. Core responsibilities are activities that the USGS must continue in order to uphold its mission. In many cases, these are mandated activities that help protect lives and assets, or are strengths developed as a consequence of longstanding national need. Strategic actions are high-value, high-priority efforts that go beyond the core responsibilities and that reduce uncertainties about hazards and improve communication, thus enhancing the ability to provide accurate, effective assessments and situational awareness. The ULSPT found broad relevance of lidar observations across many of the core responsibilities and strategic actions needed to achieve the science goals of the Natural Hazards Mission Area, thus demonstrating the ubiquitous crosscutting needs for 3DEP lidar within Natural Hazards programs.

Lidar Relevance to Natural Hazards Science Goals

The broad utility and integrating power of lidar observations tends to associate lidar and many other remote sensing techniques with interdisciplinary research, but within Natural Hazards the value of lidar methods to numerous single-subdiscipline science applications is quite apparent. Lidar either has already become, or is becoming, an enabling technology for meeting core responsibilities and pursuing the strategic actions relevant to coastal, earthquake, landslide, and volcanic hazards. The need for increased access to lidar technology and national-scale datasets promised by 3DEP is acknowledged throughout the chapters of the Natural Hazards Science Strategy (Holmes and others, 2013). For example, the Natural Hazards Science Strategy states that "In the last two decades, the introduction of high-resolution lidar and multibeam swath mapping has revolutionized the ability to unravel complicated landscapes, and hazard history, on land, offshore and along the Nation's coastlines" (Holmes and others, 2013, p. 13).

Lidar observations can assist in achieving all of the Natural Hazards Science Goals that are listed below, and accordingly, a ULSPT consensus ranking of the significance of lidar is provided for each individual goal. The probability of immediate utility of lidar remote sensing in advancing each goal is rated by the following codes: VH – Very High; H – High; M – Moderate; L – Low. The core responsibilities associated by the Natural Hazards Science Strategy with these goals are listed under each goal and ranked for lidar relevance.

Goal 1—Enhanced observations (VH)

- Operate monitoring networks for earthquakes, streamflow, volcanic activity and geomagnetic storms, and produce datasets of observations and near-real-time products (VH).
- Conduct surveys, such as geologic mapping and acquisition of geophysical data, to enable a better understanding of hazardous processes, including sources and impacts (VH).
- Collect the ephemeral data during hazardous events that will support future research to reduce loss (VH).
- Develop long-term chronologies, with associated magnitudes, of hazardous events from both historical and paleohazard studies (M).
- Distribute this information to the wide range of users through a variety of data portals (L).

Goal 2—Fundamental understanding of hazards and impacts (H)

- Increase understanding of the underlying physical processes that produce the hazard and determine where and under what conditions hazards occur (H).
- Uphold the tradition of innovation in instrumentation, measurement, and experimental techniques (VH).
- Foster USGS scientific expertise to provide expert guidance as needed in crisis and noncrisis situations (L).
- Publish peer reviewed results and distribute to appropriate audiences through relevant mechanisms (L).
- Support innovation and creativity in the conduct of our science (H).

Goal 3—Improved assessment products and services (VH)

- Create hazard assessments used to inform decisionmaking, based on fundamental understanding of natural hazards (VH).
- Evaluate the assessments using observations made at national and regional scales and over long time periods, in order to capture significant and infrequent events (VH).
- Develop new assessment tools to improve the scientific foundation of assessments as new understanding evolves (VH).
- Inform the public about natural hazards to promote risk-wise behavior by publishing assessments and providing assessment tools using USGS scientific information (H).

Goal 4—Effective situational awareness (H)

- Collect the data and conduct analyses to inform warnings by the USGS or others of impending crises (VH).
- Issue warnings and advisories of impending potential hazardous events and their termination (M).
- Provide timely information to other agencies, emergency managers, the media, and the public about hazardous events as they occur (VH).
- Invest appropriate resources in natural-hazards education during crisis as well as noncrisis times (H).

Guidance to the Natural Hazards Mission Area

- Incorporate waveform-resolving autonomous fixed ground-based lidar scanning and telemetry in the implementation of a multisensor volcano monitoring system as outlined in the National Volcano Early Warning System (NVEWS) Implementation Plan, in order to provide next-generation monitoring capabilities.
- Under the auspices of 3DEP, establish a cross-hazard/cross-mission-area working group to define the operational requirements for collection, processing, archiving, analysis, and timely distribution of all-platform lidar remote sensing information related to hazards and disasters, in order to improve coordination.
- Expand the acquisition, use, and analysis of current and future generations of lidar remote-sensing surveys for hazard monitoring and event response, in order to improve monitoring capabilities.
- Foster new terrestrial and terrestrial/mobile technologies specific to particular hazards, namely, portable, smart, and cost-effective systems, to improve the quality of local information.
- Adapt 3DEP lidar collection to include acquisition in response to hurricane landfalls with major storm surge, to allow investigation of linkages between storm-surge magnitude and duration and resulting coastal erosion.
- Pursue the translation of hazard assessments that are heavily based on 3DEP lidar into decision-support methods and tools.
- Use terrestrial lidar to provide foundational data to operational alarm systems in order to detect volcanic unrest and eruptions.
- Use 3DEP lidar topography to construct state-of-the-art, near-real-time dynamic flood inundation maps and applications to meet a host of needs ranging from flood response and mitigation to dam- and levee-break simulations.

Water

USGS Circular 1383–G, published in 2013, defines the USGS strategy for the next 5 to 10 years for observing, understanding, predicting, and delivering water science to the Nation. This report looks at the relevant issues facing society and lays out a strategy built around developing new capabilities, tools, and delivery systems to meet the Nation's water-resource needs. The report begins by presenting the vision of water science for the USGS and the societal issues that are influenced by, and that in turn influence, the water resources of the Nation. The essence of the Water Science Strategy is built on the concept of "water availability," defined as the spatial and temporal distribution of water quantity and quality, as related to human and ecosystem needs and as affected by human and natural influences. The report also describes the core capabilities of the USGS in water science—the strengths, partnerships, and science integrity that the USGS has built over its 136-year history.

The Water Science Strategy is slightly different from the other science strategies in that it incorporates nine priority actions. Although only Priority Action 6, for flood inundation, specifically mentions the need for lidar-based data, all of the priority actions could be better achieved with the availability of such data. The priority actions, and examples of how the availability of lidar-based data could benefit them, are as follows:

1. *Improve integrated science planning for water.*

   This action emphasizes that the USGS should look for opportunities where its Water programs can intersect and build synergy with other science programs. A great example of where lidar-based data could benefit this goal is the potential for integrating elevation and hydrography to develop a high-resolution "NHD-Plus" product that could be used for a wide variety of water-resource applications.

2. *Expand and enhance water-resource monitoring networks.*

   Lidar-based high-resolution NHD-Plus data could facilitate improvements in methods for analyzing monitoring networks to identify locations that would benefit most from additional monitoring.

3. *Characterize the water cycle through development of states-of-the-art 3D hydrogeologic framework models at multiple scales.*

   3DEP data would be core data used for the construction of the models.

4. *Clarify the linkage between human water use (engineered hydrology) and the water cycle (natural hydrology).*

   3DEP data could be used to analyze how landforms and land uses are related to water use and the overall water budget. For example, these data could help with modeling evapotranspiration from different landforms, land covers, and land uses.

5. *Advance ecological flow science.*

   3DEP data could be useful for delineating drainage areas and computing basin characteristics used in statistical analyses to classify streams and to develop equations for estimating biologically based flow statistics for use in estimating flows at ungaged locations. The data, combined with bathymetry, also could be used to develop in-stream flow models, such as the Physical Habitat Simulation System (PHABSIM).

6. *Provide flood-inundation science and information.*

Lidar data and bathymetry currently are used to develop 1D and 2D inundation models, the outputs from which are used to create static flood-inundation map libraries that show projected areas of inundation for various water levels. These libraries are linked to USGS streamgages and to National Weather Service (NWS) flood-forecast points and served through the Web so that the public can see current and forecast inundation areas. More widespread availability of lidar through 3DEP could reduce or eliminate the need for procurement of such data for specific projects and could reduce the time needed to complete the projects (fig. 9).

7. *Develop rapid deployment teams for water-related emergencies.*

   Readily available lidar data could aid in determining when to trigger team activation based on when areas are expected to be inundated, and also could aid in coordination and management of teams by knowing in advance which travel routes are likely to still be passable during flood events.

8. *Conduct integrated watershed assessment, research, and modeling.*

   3DEP data could facilitate the development of models that would aid in (1) understanding key interactions between physical, chemical, geological, and biological processes in the context of natural and human influences, (2) identifying important gaps in data or understanding, and (3) predicting water availability and optimizing water management at the scale of large watersheds or river basins.

9. *Deliver water data and analyses to the Nation.*

   3DEP data can be used to develop integrated elevation and hydrography datasets, such as high-resolution NHD-Plus, which can be used in applications such as StreamStats to provide functionality that delivers water-resource information to the public that is used for a wide variety of planning, management, and engineering applications.

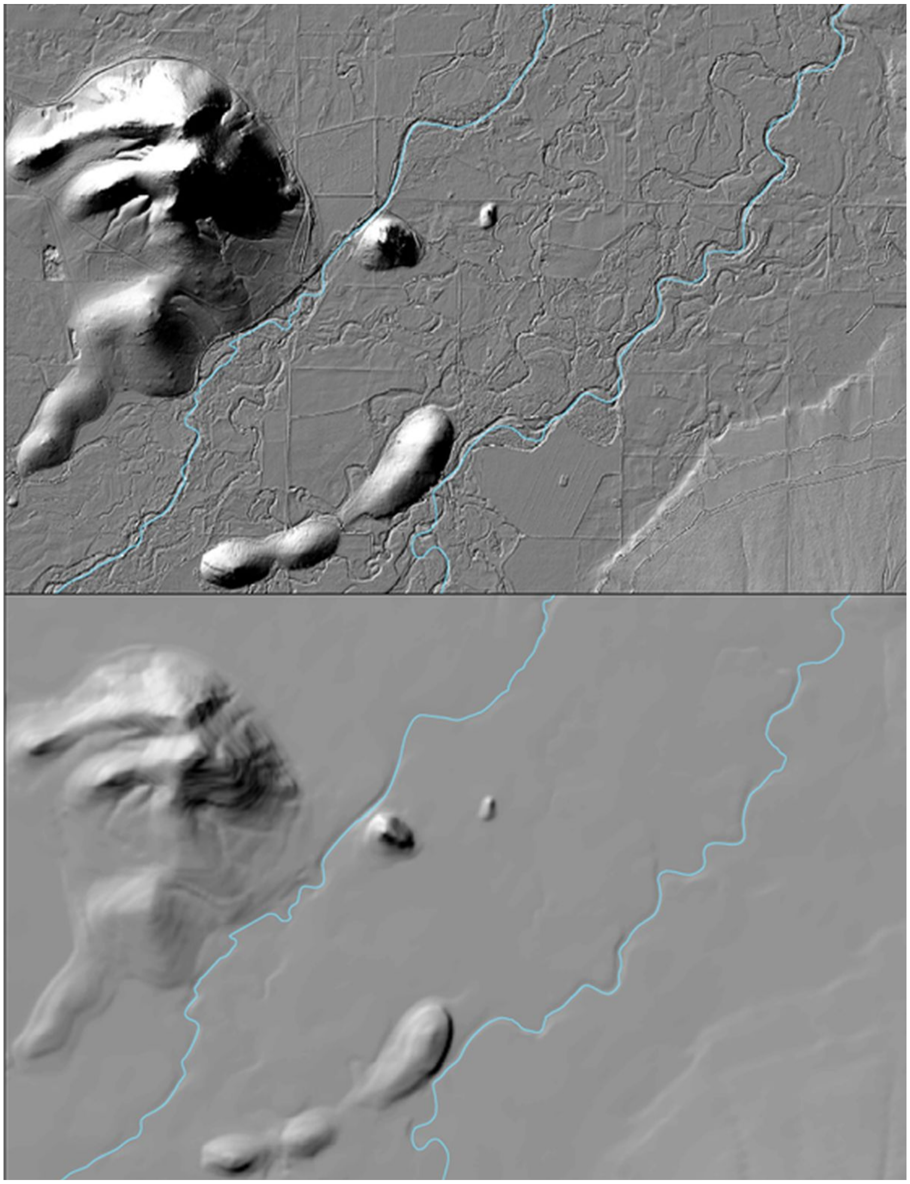

Figure 9. Bottom: USGS standard 10-meter bare earth elevation data for the Conejos River and Rio San Antonio flood plains, Colorado. Top: Lidar bare earth DEM (1-meter resolution) of the same area. The USGS National Hydrography Dataset (NHD) stream lines collected from 1:24,000-scale maps (blue) can potentially be updated using lidar. Images provided by John Kosovich (USGS).

Lidar Relevance to Water Science Goals

Lidar observations can assist in achieving all of the Water Science Goals that are listed below, and accordingly a ULSPT consensus ranking of the significance of lidar is provided for each individual goal. The probability of immediate utility of lidar remote sensing in advancing each goal is rated by the following codes: VH – Very High; H – High; M – Moderate; L – Low.

Goal 1—Provide society the information it needs regarding the amount and quality of water in all components of the water cycle at high temporal and spatial resolution, nationwide (H).

Goal 2—Advance understanding of processes that determine water availability (VH).

Goal 3—Predict changes in the quantity and quality of water resources in response to changing climate, population, land use, and management scenarios (VH).
Goal 4—Anticipate and respond to water-related emergencies and conflicts (VH).
Goal 5—Deliver timely hydrologic data, analyses, and decision-support tools seamlessly across the Nation to support water-resource decisions (H).

Guidance to the Water Mission Area

- Work closely with Core Science Systems (defined in next section) to successfully implement the full integration of elevation data with hydrography (NHD) and watershed boundaries (Watershed Boundaries Dataset, or WBD).
- Increase internal training on use of lidar-derived data as it relates to water resources.
- Use 3DEP data to assign elevation values on the NHD stream lines, opening the door for a range of new channel-analysis functionality in StreamStats and other applications.
- Extract new types of basin characteristics or improved measurements of old ones from the 3DEP data for use in various modeling and characterization activities.
- Ensure that the raster (3DEP) and vector (NHD) teams at the National Geospatial Program (NGP) communicate and coordinate with one another to integrate their products in a sophisticated manner. Hydro enforcement (making sure water flows downstream) of elevation models needs to be an integral part of moving forward.
- The Water Mission Area should consider embracing to the extent possible the use of bathymetric lidar to map the Nation's rivers and streams. Like streamgaging data, this could be a cornerstone product of the Water Mission Area, data that cut across mission areas and agencies.
- Investigate the extent to which lidar data are readily available, which could help determine when to trigger team activation based on when areas are expected to be inundated, and could also aid in coordination and management of teams by informing them in advance which travel routes are likely to still be useable during flood events.
- Investigate the use of 3DEP data for delineating drainage areas and computing basin characteristics used in statistical analyses to classify streams and to develop equations for estimating biologically based flow statistics for use in estimating flows at ungaged locations. The data, combined with bathymetry, also could be used to develop in-stream flow models, such as PHABSIM.

Core Science Systems

Core Science Systems (CSS) is a new mission of the USGS that resulted from the 2007 Science Strategy, "Facing Tomorrow's Challenges: U.S. Geological Survey Science in the Decade 2007–2017" (U.S. Geological Survey, 2007). This report describes the CSS vision and outlines a strategy to facilitate integrated characterization and understanding of the complex Earth system. The vision and suggested actions are bold and far-reaching, describing a conceptual model and framework to enhance the ability of the USGS to bring its core strengths to bear on pressing societal problems through data integration and scientific synthesis across the breadth of science.

The vision for CSS builds on core strengths of the USGS in characterizing and understanding complex Earth and biological systems through research, modeling, mapping, and the production of high-quality data on the Nation's natural resource infrastructure. Together, these research activities provide a foundation for ecosystem-based approaches through geologic mapping, topographic mapping, and biodiversity mapping. The vision describes a framework founded on these core mapping strengths that makes it easier for USGS scientists to discover critical information, share and publish results, and identify potential collaborations across all USGS missions. The framework is designed to improve the efficiency of scientific work within the USGS by (1) establishing a means to preserve and recall data for future applications, (2) organizing existing scientific knowledge and data to facilitate new use of older information, and (3) establishing a future workflow that naturally integrates new data, applications, and other science products to make interdisciplinary research easier and more efficient. Given the increasing need for integrated data and interdisciplinary approaches to solve modern problems, leadership by the CSS Mission Area can facilitate problem solving by all USGS mission areas in ways not previously possible (Bristol and others, 2013).

Lidar Relevance to Core Science Systems Science Goals

Lidar observations are of very high relevance to all the CSS Science Goals listed below. The probability of immediate utility of lidar remote sensing in advancing each goal is rated by the code associated with each goal, as follows: VH – Very High; H – High; M – Moderate; L – Low.

Goal 1—Conduct research to produce timely, nationwide, seamless, authoritative, open-access digital knowledge for ecosystem processes sustaining the critical zone.[1] Provide research and data to characterize and understand the critical zone (VH).

Goal 2—Expand applications of USGS research through scientific services (VH).

Goal 3—Conduct scientific analysis and synthesis to improve coverage, scientific quality, usability, and timeliness of information (VH).

Suggested Priorities for Lidar Contributions to Core Science Systems Science

The 3DEP effort is accelerating the rate of collection of 3D elevation data in response to a call for action to address a wide range of urgent needs nationwide (Sugarbaker and others, 2014). The call for action began in 2012 with the guidance/direction to collect (1) high-quality lidar data for the conterminous United States (CONUS), Hawaii, and the U.S. territories and (2) interferometric synthetic aperture radar (ifsar) data for Alaska. Specifications were created for collecting 3D elevation data, and the data management and delivery systems are being modernized. The bare earth DEM component of 3DEP, previously known as the National Elevation Dataset (NED), will be completely refreshed with new elevation data products and services. The call for action requires broad support from a large partnership community committed to the achievement of national 3D elevation data coverage. The initiative is being led by the USGS and includes many partners—Federal agencies and State, Tribal, and local governments—who plan to work together to build on existing programs to complete the national collection of 3D elevation data in eight years, contingent on funding. Private sector firms, under contract to the Federal Government, will continue to collect the data and provide essential technology solutions for the Government to manage and deliver these data and services. A fully funded program will provide a 5:1 return on investment and more than $690 million annually in new benefits to government entities, the private sector, and citizens (Sugarbaker and others, 2014). 3DEP presents a unique opportunity for collaboration between all levels of government, to leverage the services and expertise of private sector mapping firms that acquire the data, and to create jobs now and in the future. The 3DEP governance structure includes (1) an executive forum established in May 2013 to have oversight functions and (2) a multi-agency coordinating committee based upon the committee structure already in place under the

[1] The critical zone is the interface of geologic, atmospheric, biologic, and hydrologic processes at the Earth's surface that are critical for life. This zone extends from shallow groundwater to the top of the vegetative canopy.

National Digital Elevation Program (NDEP). The 3DEP initiative is based on the results of the National Enhanced Elevation Assessment (NEEA) that was funded by NDEP agencies and completed in 2011. The study, led by the USGS, identified more than 600 requirements for enhanced (3D) elevation data to address mission-critical information requirements of 34 Federal agencies, all 50 States, and several private sector companies and Tribal and local governments.

The National Geospatial Program under CSS has the primary responsibility of acquiring, checking, assessing, managing and delivering all 3DEP data. These data will be used by many of the mission areas, and may be the only lidar data that they use (fig. 10). As a result, it is important for CSS to provide the highest quality lidar possible in formats that are easy to use for all mission area scientists. A key role for CSS in lidar for the USGS involves facilitation and coordination of lidar data, as well as helping provide information that is useful to the mission areas. Providing lidar-derived informational products that are easy to use is a key component of the CSS Mission Area's success. Another key capability of CSS is to provide access to data and information. There are many ground-based lidar datasets that could be useful to the public if CSS were positioned to help the project scientist make them available. The following suggestions are geared toward making CSS the leader in providing lidar data and information to help facilitate other mission area goals.

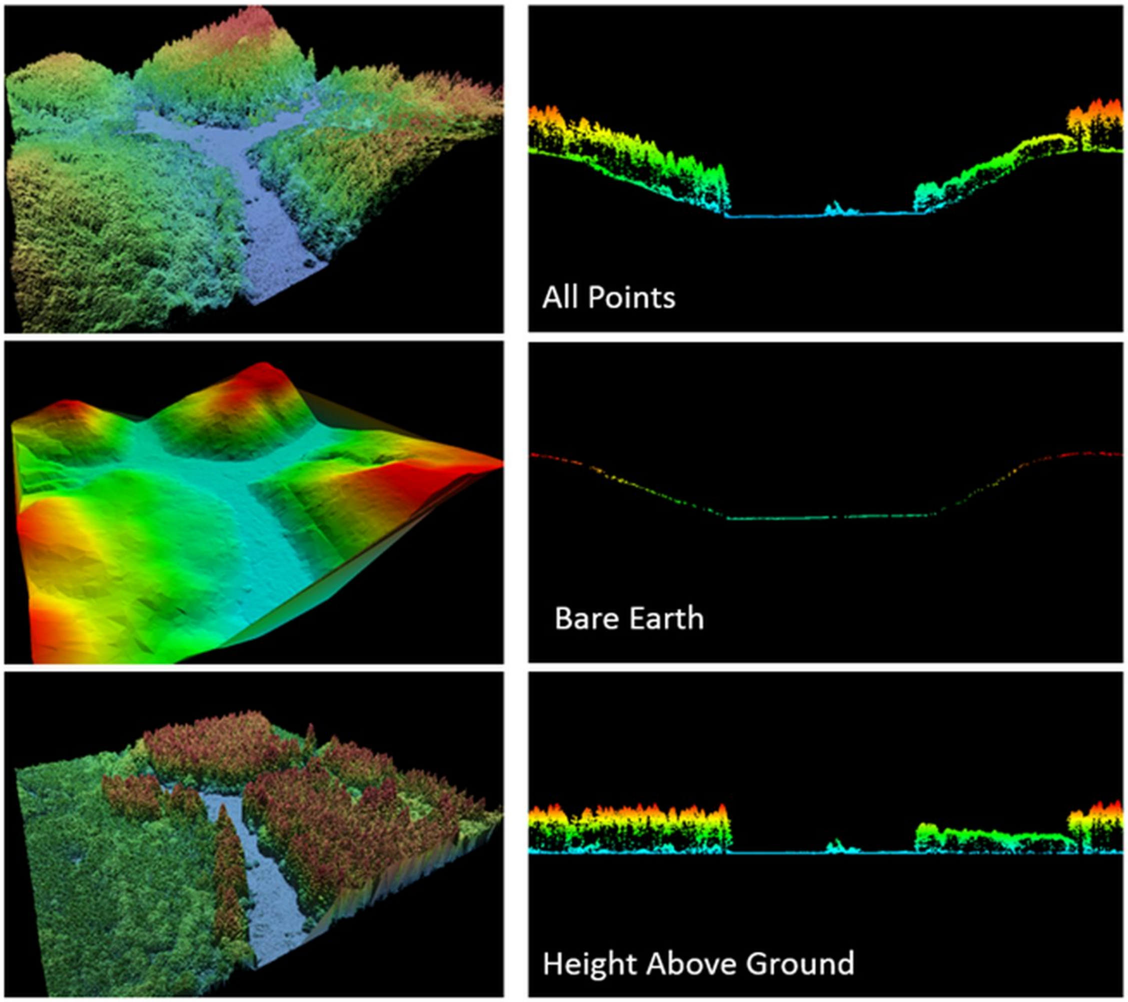

Figure 10. An example of a lidar dataset showing all points (top), bare earth classified points and their associated bare earth surface (middle), and a normalizing of those points to the bare earth for a height-above-ground model and surface (bottom). Perspective view is on the left; profile view is on the right. (U.S. Geological Survey.)

Guidance to the Core Science Systems Mission Area

- Provide consistent, standardized, authoritative lidar source data across the United States via 3DEP with well-documented metadata, and easy-to-use tools to access and work with these data (fig. 11).
- Increase the preference to very-large-area, multiple-instrument collections over smaller, county-size lidar collections.
- Provide mechanisms to help calibrate and validate airborne lidar collections, including using survey-grade ground-based terrestrial laser-scanning data collected by others.
- Develop methods to systematically compare interswath accuracies, and methods to compare adjacent or overlapping lidar data, in order to develop a more seamless 3DEP product and to guarantee the user is getting the best data possible.
- Increase output of map products using a single lidar source as input: contours, integrated elevation and hydrography, structures, vegetation, and registration of orthophotos, all from a single lidar collection.

- Build the bridge between lidar data and derived information for USGS science by developing services to create customized derivative products from lidar source data, so that researchers can spend less time processing data and more time using 3D information.
- Provide leadership in coordinating lidar knowledge and information exchanges via internal communication mechanisms.
- Investigate providing a clearinghouse for all non-3DEP data that other USGS mission areas collect, and help mission areas enhance the data to meet the White House's Open Data Policy (https://www.whitehouse.gov/open).
- Take a leadership role in investigating and assessing new technologies as they relate to 3D information; specifically high-altitude systems that can collect data from larger areas at lower costs, and point clouds derived from non-lidar-derived methods.
- Design and improve scientific computing systems (cloud-based and High Performance Computing) to remove the lidar data management and processing burden from the individual scientist.

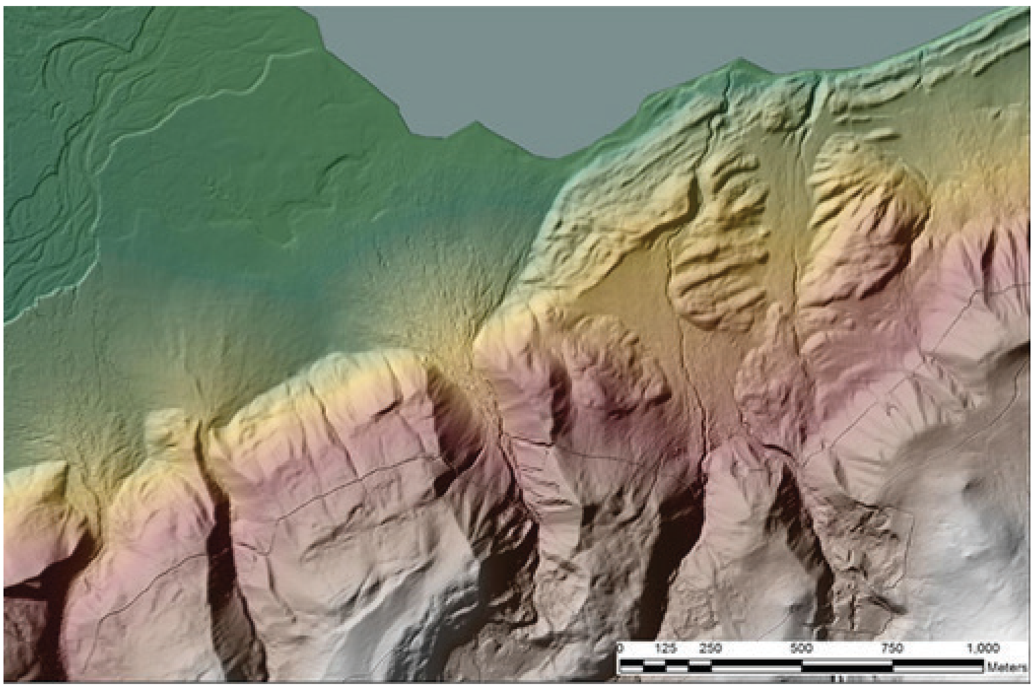

Figure 11. An example of an authoritative-source 1-meter bare-earth DEM, Arkansas Valley, Colo. (U.S. Geological Survey.)

USGS-wide Summary and Guidance

Based on individual interviews from scientists and reports from the ULSPT, there were several common themes that crossed mission areas. For the most part, all mission areas are utilizing all types of lidar, but those with locally based studies are utilizing ground-based lidar information. There is a strong reliance on CSS by the other mission areas to lead in providing data for large-area collections for base data; however, individual scientists may be the direct customers of those data collections. Ground-based lidar data are considered more independent and therefore more variable, based on mission area-specific, principal-investigator-based local research.

There is the potential that ground-based lidar data could be useful for quality assurance and control and for comparisons of large-area airborne data, if such data were available and in an easy-to-access format. One of the drawbacks with this, however, is that the differences in dates of collection would have to be taken into account. Common complaints across mission area responses include data availability and data accessibility. All mission areas documented the need for temporal information, either for assessing trends or for field-planning purposes. Lidar training and enterprise-wide software are desired by all mission areas to further their goals. Finally, mission areas desire to have lidar experts employed within each mission area, rather than having to rely on experts from other mission areas for help. However, coordination between mission area experts is welcomed. Internal communication is crucial. Knowledge of upcoming lidar acquisitions allows for mobilization and reconnaissance with fieldwork for calibration purposes. Post-acquisition studies, particularly those having large time lapses, decrease the ability to add value to lidar acquisitions across all mission areas. USGS liaisons and contracting personnel can and should play a critical role in disseminating dates of upcoming acquisitions to all science centers.

Some of the key differences between mission areas included the high use of ground-based lidar and research instruments by the Natural Hazards Mission Area compared to others. The Energy and Minerals, Natural Hazards, and Water Mission Areas are predominantly interested in bare earth 3D data; however, the CLU and Ecosystems Mission Areas are more interested in vegetation/habitat data. Some mission areas are more event-driven than others; as a result, a standard collection strategy will not always meet their needs. It should be noted, though, that highly accurate baseline information is extremely valuable to all the mission areas, even those that are event driven.

Some of the future technologies that are of interest to a wide range of USGS lidar scientists include obtaining 3D information from non-lidar instruments. Examples include close-range photogrammetry, stereo autocorrelation from aircraft, and interferometric synthetic aperture radar. Developments and research on these fronts could also have positive impacts on lidar science research in the USGS. Topographic/bathymetric lidar instruments are highly desired for their ability to collect 3D data nearshore and even to create inland bathymetry. Data fusions with passive optical and thermal instruments are also deemed important. New instruments and platforms that collect data at very low altitudes (such as UAS) or at very high altitudes (such as Geiger-mode/photon-counting instruments) are appealing to a wide range of scientists. Additionally, the possibility exists to use wind lidar to examine the interaction between the atmosphere and the biosphere.

The 3D Elevation Program provides an opportunity for all mission areas to take advantage of three-dimensional information. Conversely, localized, high-accuracy ground-based acquisitions collected for USGS scientists could be used in the calibration and validation of 3DEP data if these data were standardized and if locations of data were known for all categories of lidar. Coordination and cooperation among all mission areas is critical to take full advantage of all these different types of data.

An important issue to keep in mind is that the USGS should complete its base elevation layer via the first cycle of lidar collection for 3DEP, while integrating multi-temporal collections to understand 3D change. In order to make this possible, the USGS should foster and encourage multiple uses of all types of lidar data, so that others can take advantage of existing data (fig. 12).

Figure 12. Perspective view of an existing lidar point cloud for an area of Denver, shaded according to the intensity of lidar signal return. (U.S. Geological Survey.)

Summary of Lidar Portfolio: Strategic Actions for all Mission Areas

A key direction suggested by the ULSPT is for all mission areas to transition away from using ground-based lidar that is not georeferenced to making all data georeferenced. In general, the ULSPT suggests that all mission areas decrease the use of non-georeferenced lidar, as these types of data have limited utility and are harder to use and meet the President's Open Data Policy because they are not directly georeferenced or well described. Similarly, the team suggests in general decreasing the collection of individual projects that do not consider the areas around the immediate collection area, and increasing the collection of large-area data that will be provided via 3DEP and other sources. This requirement could be lessened if the individual projects were better coordinated with each other as well as with other projects. The team also suggests an increase in coordination among mission areas in respect to lidar collections, for all types of lidar, as well as increasing the ability to share information, knowledge, and software within and across all mission areas. Ideally the USGS could foster concerted efforts to demonstrate the ability of a single lidar collection to achieve multiple objectives. We highly suggest that the use of specific, individual lidar collections be curtailed to allow for more seamless integration of data across project boundaries.

The ULSPT established some concrete USGS-wide lidar science goals that all mission areas should work together on, as follows:

Goal 1—Foster cross-disciplinary and interdisciplinary lidar-enabled research within the USGS by identifying high-return opportunities for lidar data and information uses that are of high relevance to mission area science goals.

- Provide a USGS-wide mechanism (such as funding via proposal) to demonstrate interdisciplinary science being performed using the same lidar data, or integration between lidar categories over the same area.
- Organize and conduct an annual or biannual USGS-wide lidar science workshop to promote cross-pollination of ideas and collaboration between mission areas.

Goal 2—Coordinate USGS scientific lidar acquisition with the 3DEP acquisition plan to reduce redundancy, maximize the benefits of investments in lidar mapping, and build external partnerships that advance the 3DEP eight-year national acquisition strategy.

- Provide a formal coordination mechanism between USGS scientists and the 3DEP Broad Agency Announcement process (http://nationalmap.gov/3DEP/BAAReferenceMaterials.html), so that internal USGS science is considered in acquisition prioritization.
- Provide a coordination mechanism between 3DEP collections and the collection of higher resolution data for calibration and validation purposes, as well as between leaf-on versus leaf-off collection justifications.
- Communicate with other mission areas when new lidar is collected, either as part of the 3DEP or when a plot-based dataset is collected.
- Form a group having regional and mission-area points of contact to discuss lidar acquisitions on a regular basis and to coordinate NGP acquisitions with science priorities.

Goal 3—Advance lidar instrumentation, deployment options, algorithms, analysis methods, data management, and geoportal designs that contribute to achieving the goals of the USGS mission area science strategies.

- Develop and build upon existing and past efforts that provide places for internal USGS lidar science discussions and information sharing.
- Increase the amount of USGS enterprise-wide available software that can be used to process and visualize lidar data (such as Global Mapper/lidar, LAStools, LP360, ENVI lidar, QT Modeler, and others).
- Cultivate research on new 3D hardware (such as UAS and close-range photogrammetry) and software (such as user-friendly freeware to increase and simplify use by researchers, land managers, and the general public).
- Foster research on emerging lidar technologies and 3D information to demonstrate the utility of these new systems, both for 3DEP as well as for individual research applications.

Conclusion

The USGS has a long and fruitful history of using lidar data and associated derived information as a tool to help achieve a wide range of science objectives across the Bureau. This report documents and summarizes the current lidar portfolio in the USGS and presents mission area-specific suggestions to guide future planning of 3D data acquisition to meet each mission area's science strategy objective. We believe that if properly executed, this plan can help the USGS take full advantage of the wealth of 3D information being collected for science and applications.

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