WORKSHOP ON STUDYING EARTH SURFACE PROCESSES WITH HIGH-RESOLUTION TOPOGRAPHIC DATA

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Report to the National Science Foundation

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Synopsis

From June 15 to 18, 2008, fifty scientists met in Boulder, Colorado, at the University Corporation for Atmospheric Research (UCAR) to explore how high-resolution geodetic topographic data are advancing, and can better advance, understanding of geomorphic processes. A list of the participants is provided in Appendix 1, and the daily agenda in Appendix 2. The National Science Foundation (NSF) National Center for Airborne Laser Mapping (NCALM, www.ncalm.org) organized the Workshop on Studying Earth Surface Processes with High-Resolution Topographic Data (WSESP), and the NSF Division of Earth Sciences (Geomorphology and Land Use Dynamics Program, and Instrumentation and Facilities Program) funded it. The workshop was a significant success in terms of the diverse types of pioneering research progress presented by participants, the intensity of discussion during each session, and the demographic distribution of the participants. With regard to the last of these, 13 of the participants were graduate students and another 13 had received their Ph. D. degree within the past 5 years. All of these current students and recent graduates are using LiDAR and other high-resolution topographic databases in their research.

This report, prepared by members of the NCALM steering committee with contributions from participants at the WSESP, highlights key scientific opportunities presented at the workshop, and identifies some of the challenges for maximizing the scientific potential of research with high-resolution topographic data. During the final day of the workshop, participants identified key areas emerging in this field, new ways to detect and characterize processes, and approaches to detect changes in dynamic systems. Three areas that attracted particular attention were 1) the connections between ecosystems and topography, 2) the flux of water, sediment, and other substances down hill slopes and through drainage networks, and 3) the use of repeat LiDAR surveys to study landscape change in response to geological and biological disturbances (e.g., earthquakes, fires, dam breaching, and timber harvest).

The rapid emergence of new technology, datasets, and ideas poses challenges as well as opportunities for the Earth science community. Foremost among the challenges are the needs to 1) better facilitate sharing of public-domain LiDAR databases and tools for analysis and visualization, and 2) maximize dissemination of new ideas and discoveries. Prominent among the analytical needs are new ways to extract landscape features from topographic data, quantify topographic trends, and develop new physical and mathematical descriptions of the landscape that are appropriate for the high resolution of LiDAR topography. Many of these presentations highlighted discoveries and analyses that were intractable in the absence of LiDAR data. Challenges such as these are likely to drive a wide variety of new discoveries across many scientific disciplines that will further our understanding of interactions among geologic, biologic, and anthropogenic processes along the Earth's surface.

Posters (27) remained on boards throughout the entire 3-day duration of the workshop, and 15 talks--each about one hour--were presented (presentation titles, both oral and poster, are listed in Appendix 3). About 4 hours of the meeting were devoted to group discussion involving the entire audience of 50 participants; several microphones were passed around during the final discussion session in order to encourage everyone's participation. A separate room with computers and software installed for the workshop

(ArcGIS, Matlab, etc) was used for tutorial sessions to demonstrate tools and databases. These interactive activities promoted substantial sharing of ideas and the formation of new research collaborations.

I. Introduction

During the past decade, new methods of acquiring high-resolution, high-quality topographic data have provided extraordinary opportunities to study Earth's surface and the processes that shape it. One of the most significant advances is airborne laser swath mapping (ALSM) or LiDAR, which provides the highest resolution topographic data available at present and is facilitating rapid proliferation of new ideas and discoveries. With pixel sizes of 0.5 to 5 m and vertical accuracy of 5 to 20 cm, digital elevation models (DEMs) from ALSM are superior to DEMs that have been widely available for the past 20 years (typically 10- to 30-m pixel sizes and contour intervals of 3 to 20 m). Ground-based LiDAR technology now provides even higher resolution than ALSM, but constraints on data acquisition and computational capacity limit its use to small areas (Figure 1).

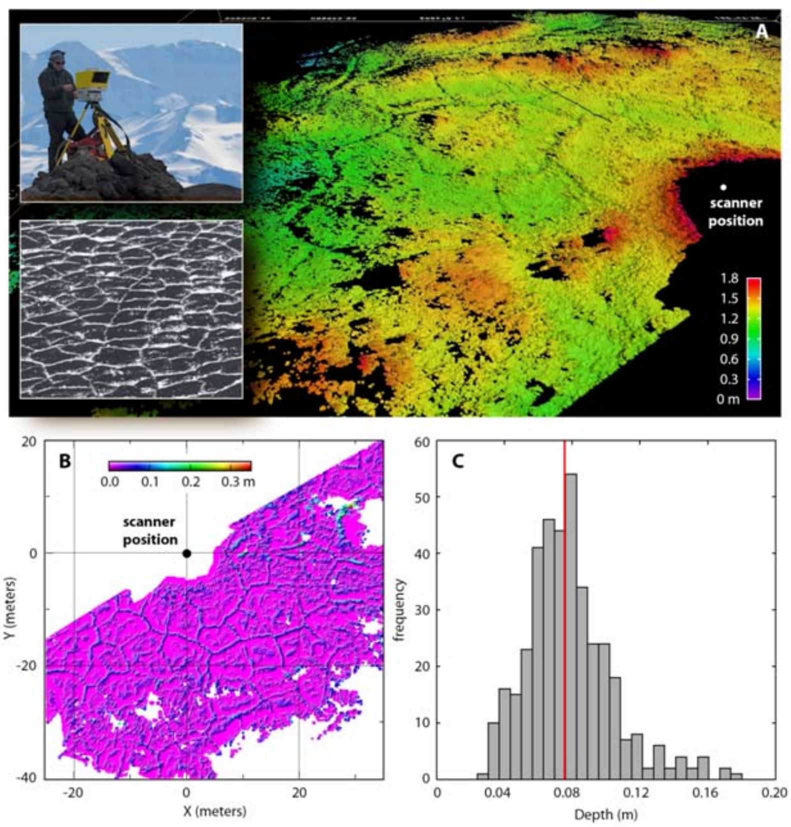


Figure 1. To test models of patterned ground formation, ground-based LiDAR was used to image patterned ground in ice-free areas of the Antarctic Dry Valleys in Austral Summer 2008. A) A perspective view of gridded point-cloud data from the lower slopes of Mt. Morning volcano is ~50 m across and resolves numerous patterned ground polygons. The LiDAR data were collected from a high-standing mound within a lava flow (see upper inset).

The lava flow and patterned ground features have relatively low relief and wavelengths (<10 cm) and thus require the high-resolution provided by a ground-based system. Patterned ground polygons cover the surface of the lava flows and vary in radius from a few meters to >10 meters (see lower inset). B) Gridded data were de-trended in order to enhance the short-wavelength features of interest. C) The de-trended data allow for determination of morphologic characteristics such as the depth of polygon bounding cracks, which in this area have a median depth of 7.5 cm. [Image provided by A. Soule.]

The ability to resolve features with dimensions of 10^{-1} to 10^{1} m scale is critical for research on the Earth's surface, as many landforms and individual processes operate within that range, including stream channels, floodplains, patterned ground, fault strands, debris flows, landslide scars, and sea cliffs. The inability to resolve such features has substantially hampered scientific efforts to characterize and understand erosion, mass movement, flooding, and other common surface processes. With the new ability to resolve landforms at critical geomorphic scales, a new era is opening in our ability to understand the influence of tectonic, climatic, biologic, and anthropogenic factors on topography.

II. SCIENTIFIC OPPORTUNITIES

LiDAR-derived DEMs are revolutionizing our ability to visualize and quantify landscape forms, processes, and changes. The scientific potential of geodetic laser scanning [Carter et. al., 2007] is similar to that opened in the space sciences by the Hubble telescope, or in mineralogy by the scanning electron microscope. Features that are fuzzy or not even visible in older coarser DEMs now can be identified, mapped, measured, and analyzed. In addition, ALSM point-cloud data of vegetation cover and the Earth's solid surface can be processed to produce either bare-earth DEMs or to examine attributes of the vegetation itself, such as its canopy structure. ALSM data thus are particularly valuable for cross-disciplinary research on ecology and landscapes. A very recent tool, water-penetrating LiDAR, is being employed to investigate riverbed forms, identify prime fish spawning habitats, and map the littoral zone along coasts.

Here, we use examples presented at the WSESP to illustrate these new capabilities and scientific opportunities that result from high-resolution topographic data, in particular airborne and ground-based LiDAR. The opportunities are grouped into seven categories:

- Identifying and Extracting Topographic Features
- Coupling Tectonic and Climatic Processes with Landform Evolution
- Testing Landscape Evolution Models
- Detecting Landscape Change
- Feedbacks between Life and Topography
- Routing Water and Sediment through Watersheds
- Linking Structural Geology to Geomorphology

IIa. Identifying and Extracting Topographic Features

The power of high-resolution topography to identify landforms and extract topographic features is clearly evident for the San Andreas fault in the Carrizo Plain of south-central California (Figure 2, research presented by Ramon Arrowsmith). Whereas the trace of the fault cannot be identified with 90-m Shuttle Radar Topography Mission or 10-m National Elevation Dataset grid spacing data, the fault trace is more easily discerned from a 0.25-1-m grid spacing ALSM dataset than it is even in the field. Similarly, the Northern Death Valley Fault stands out in a 1-m grid spacing ALSM dataset, which also can be used to map and quantify different ages of alluvial fan surfaces that are offset along the fault (Figure 3, research presented by Kurt Frankel). Here again, the scale of the measurements of the LiDAR is similar to, or finer than, the signal of interest: meter-scale earthquake offsets.

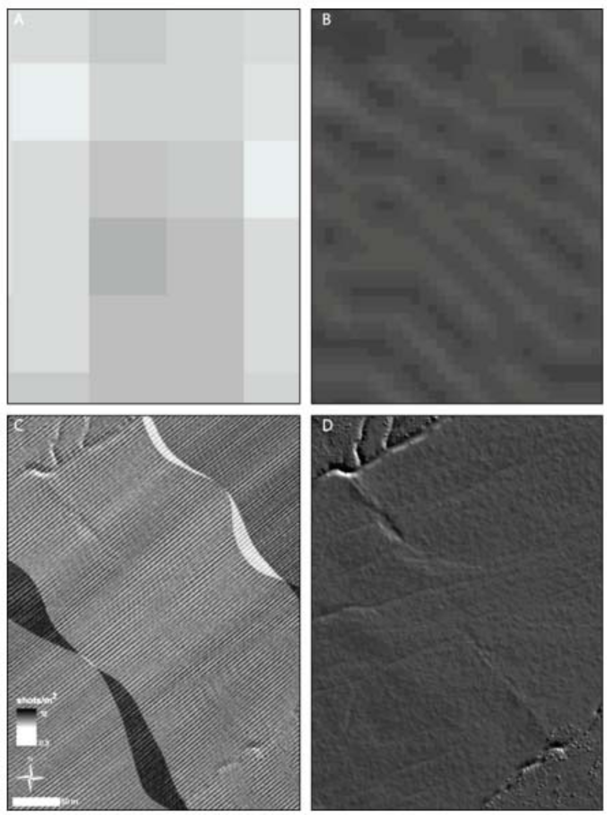


Figure 2: Order-of-magnitude differences for shaded relief computed from digital elevation models for the same location along the San Andreas Fault in south-central California: A) Shuttle Radar Topography Mission (3"- or ~90-m grid spacing with broad global availability, Farr, et al., 2007), B) National Elevation Dataset (1/3"- or ~10-m grid spacing, http://seamless.usgs.gov/) and D) Airborne Laser Swath Mapping (1-m grid spacing from the Southern San Andreas B4 dataset; Bevis, et al., 2005). C) Shot count per m2 from D showing high density and high heterogeneity of laser returns in area covered by multiple swaths. LiDAR DEM and shot count computed using the GEON LiDAR Workflow (e.g., Crosby, et al., 2006; http://www.opentopography.org). [Image provided by R. Arrowsmith.]

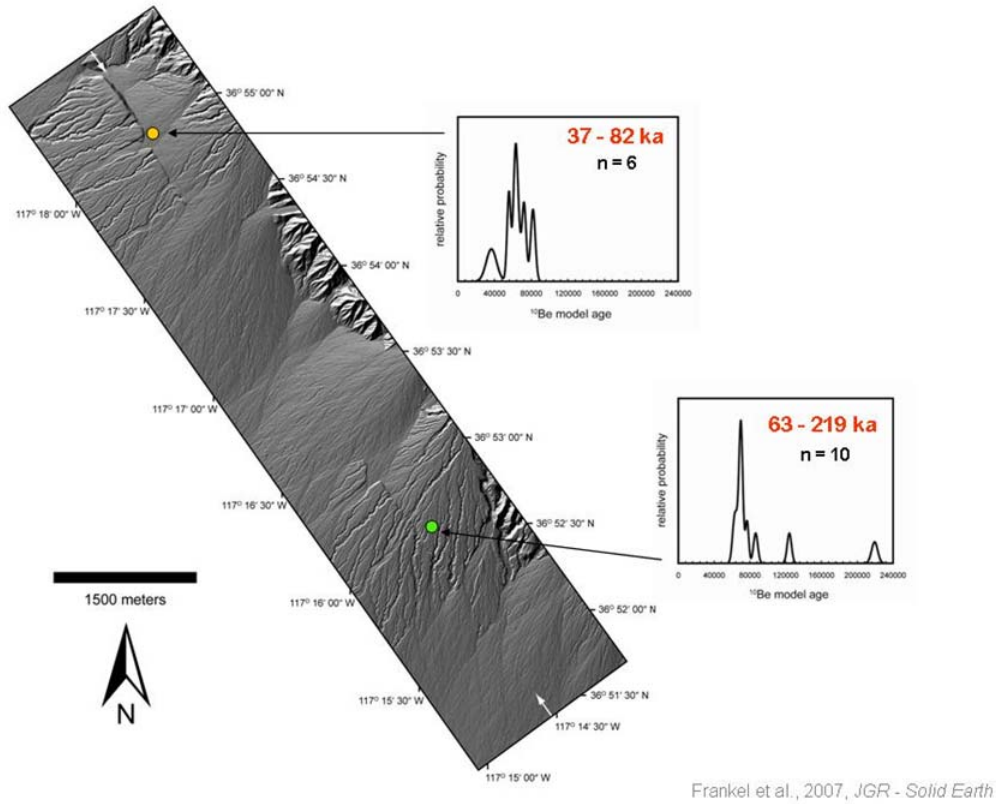


Figure 3. Different ages of alluvial fan deposits form surfaces with varying degrees of surface roughness, desert varnish, and other indicators of relative age. Characteristics such as surface roughness can be quantified with the LiDAR data. Cosmogenic dating, in this case ^{10}Be, provides chronologic control for the ages (i.e., exposure times) of alluvial fan surfaces offset along the Northern Death Valley Fault (fault strikes northwest to southeast along western part of Lidar-derived bare-earth topographic image). These age estimates are used to reconstruct the offset fan surfaces along the fault and to calculate a slip rate of 4.5 mm/yr (Modified from Frankel et al, 2007, JGR). [Image provided by K. Frankel.]

Landscapes responding to human impacts, climate changes, or changes in tectonic displacement rates have the potential to provide information about material transport that is not possible without high-resolution topographic data LiDAR can provide. At short time-scales, high-resolution topographic studies are instrumental in determining the role that humans have, and continue to play, in landscape changes. LiDAR DEMs are invaluable, for example, in locating old low-head dams overgrown with vegetation in heavily vegetated parts of the mid-Atlantic eastern U. S. (Figure 4; research presented by Dorothy Merritts). In this work, high resolution topography was critical to determining that the majority of valley bottoms in the mid-Atlantic piedmont of eastern Pennsylvania and northern Maryland have a distinct topographic signature produced by widespread, ubiquitous damming of valleys for water power throughout the 17th-19th centuries (Walter and Merritts, 2008; Merritts et al, in preparation). This damming led to storage of fine-grained sediment along valley bottoms, and as the obsolete mill dams breach this sediment is released by stream channel erosion. High resolution topographic data are equally valuable in locating breached dams and identifying areas of high rates of stream bank erosion of this stored historic sediment.

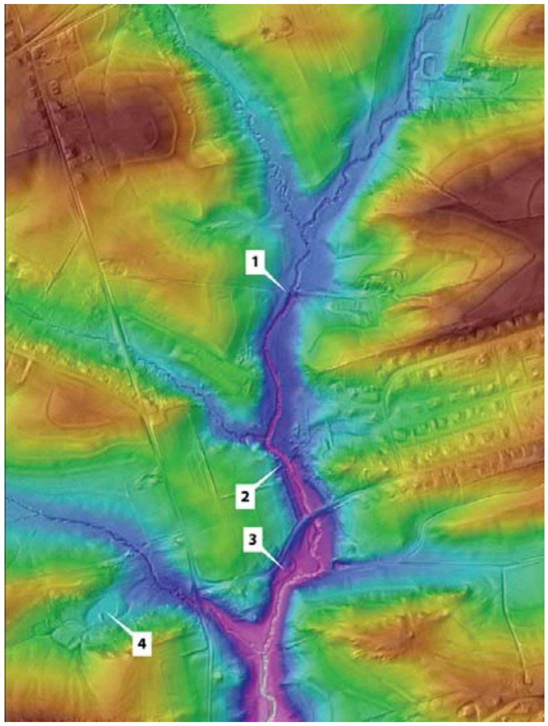


Figure 4. Hillshaded topography from airborne laser swath-mapping (USGS data, 2005), with color tint depicting elevation (white is lowest, brown highest), enables identification of early American millpond siltation and dam breach impacts, and can be used to estimate estimate the volume of sediment eroded from millpond reservoirs by incised streams after dam breaching. This image spans 1.9 km from north to south (top to bottom) and 1.4 km from east to west (right to left). Three reservoir fill surfaces (terraces) produced by damming descend from upstream to downstream (top to bottom) along the valley of the West Branch Little Conestoga River, southeastern Pennsylvania. The oldest dam in this view, labeled "2", was built in the 1700s to supply water to a mill downstream, labeled "3". The road between the dam and mill is Bender Mill Road, and the water race that brought water from the reservoir to the water wheel at the mill can be seen along the western side of the valley; today the race is a dry ditch. The dam was intact as of 1919, when a Pennsylvania dam safety inspector photographed and reported on the dam's condition, and it was still in place in air photos taken in 1940 and 1971. This early American dam was fully breached by 1992, perhaps during the largest 20th c. storm in the region in 1972 (Hurricane Agnes). As a result of dam breaching, the channel upstream became deeply incised into the millpond sediment (note terrace surface with dark blue color between dams at "1" and "2"). A small dam (labeled "1") was built within the incised channel to support a farm road. This 20th c. dam prevented deep incision upstream (note: this small dam was removed in 2008, after the lidar acquisition). The raised farm road and inset dam caused further sedimentation upstream, producing an aggradational terrace about 0.5 m higher than that downstream of the inset dam (light blue surface upstream of dam at "1"). Other small dams and upstream sediment-filled reservoirs on tributaries can be seen in this image, as at lower left (dam "4"). Backwater effects and resultant sedimentation in tributaries are evident, as on the tributary at middle left just upstream of the breached 18th c. dam ("2") on the main stem. Note distinct differences in channel geometry upstream and downstream of each of the various dams. [Image provided by M. Rahnis and D. Merritts.]

Other examples of landforms and processes that can be identified and measured with high resolution topography were presented at the WSESP, including hillslope curvature, area-slope relations along stream networks, longitudinal stream profiles, and surface roughness. Noah Snyder demonstrated the significance of--and new challenges associated with--extracting stream paths and longitudinal profiles from high resolution topographic data with examples of long profiles derived from traditional 10-m and ALSM 1-m DEMs (Figure 5). For a low-gradient part of the Narraguagus River in Maine, the stream line extracted from a traditional 10-m DEM using a standard flow-routing algorithm shortens the path significantly due to pit filling and inability to resolve the channel where it is nearly flat, causing meander loops to be cut off. Conversely, the stream extracted from the ALSM DEM lengthens the path because the pixel size is smaller than the channel width, so the path includes added sinuosity within the channels.

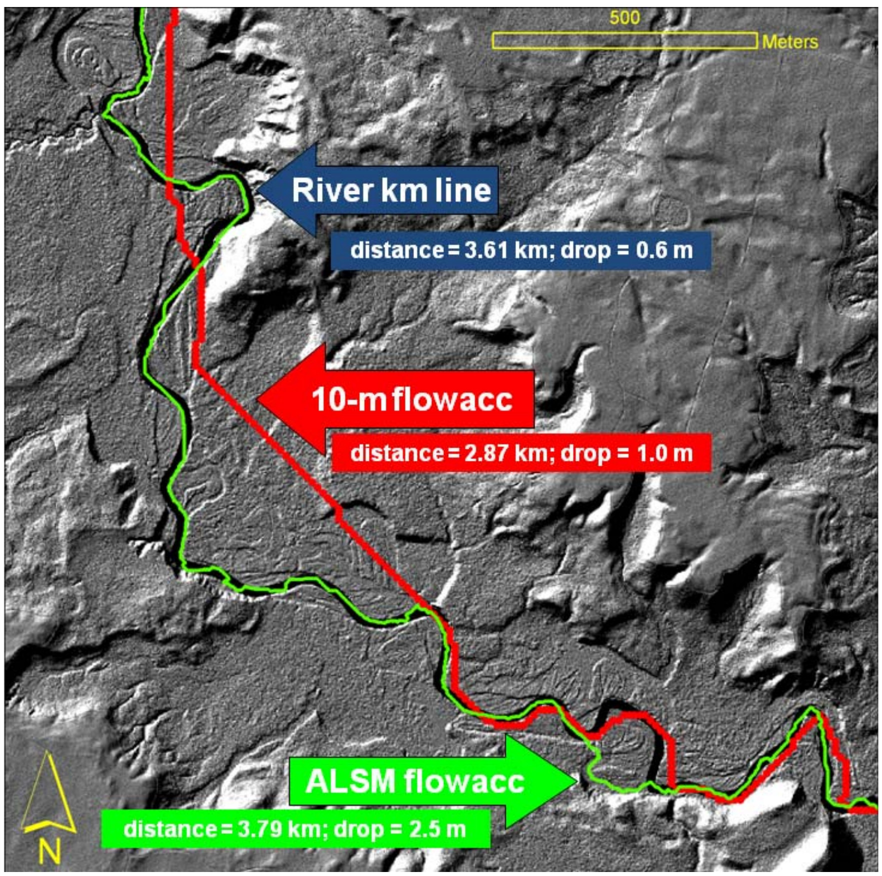


Figure 5. ALSM-derived shaded-relief image of a low-gradient part of the Narraguagus River, Maine. Lines show channel flow paths extracted from various DEMs using both ArcGIS flow-routing algorithms (flowacc) and a mapped channel centerline based on aerial-photograph interpretation (River km). [Image provided by N. Snyder.]

IIb. Coupling Tectonic and Climatic Processes with Landform Evolution

Areas experiencing geologically recent changes in tectonic displacement rates provide essential information about how geomorphic and tectonic processes interact and are linked at Earth's surface over tens to hundreds of thousands of years (Figure 6;

research presented by George Hilley; Hilley and Arrowsmith, 2008). At the Dragons Back pressure ridge along the San Andreas fault in south-central California, for example, erosional processes vary over time as topographic form changes in response to variable rock uplift rates. Topographic relief changes as crust moves through the area where the pressure ridge develops. As relief increases within the uplift zone, channels steepen and incise, initiating mass movement along hill slopes. About 7 to 14 kyr after the pulse of uplift diminishes channel steepness decreases and the channel becomes more concave overall (Figure 7). This up-valley propagating incision, in turn, over-steepens local hill slopes and enables substantial mass movement to persist long after uplift has ceased. Mass movement becomes subdued about 73 kyr after rock uplift ceases. In this example, high resolution topography was essential for measuring relevant topographic forms (e.g., channel gradient and concavity) and for identifying and mapping landforms such as landslide scars.

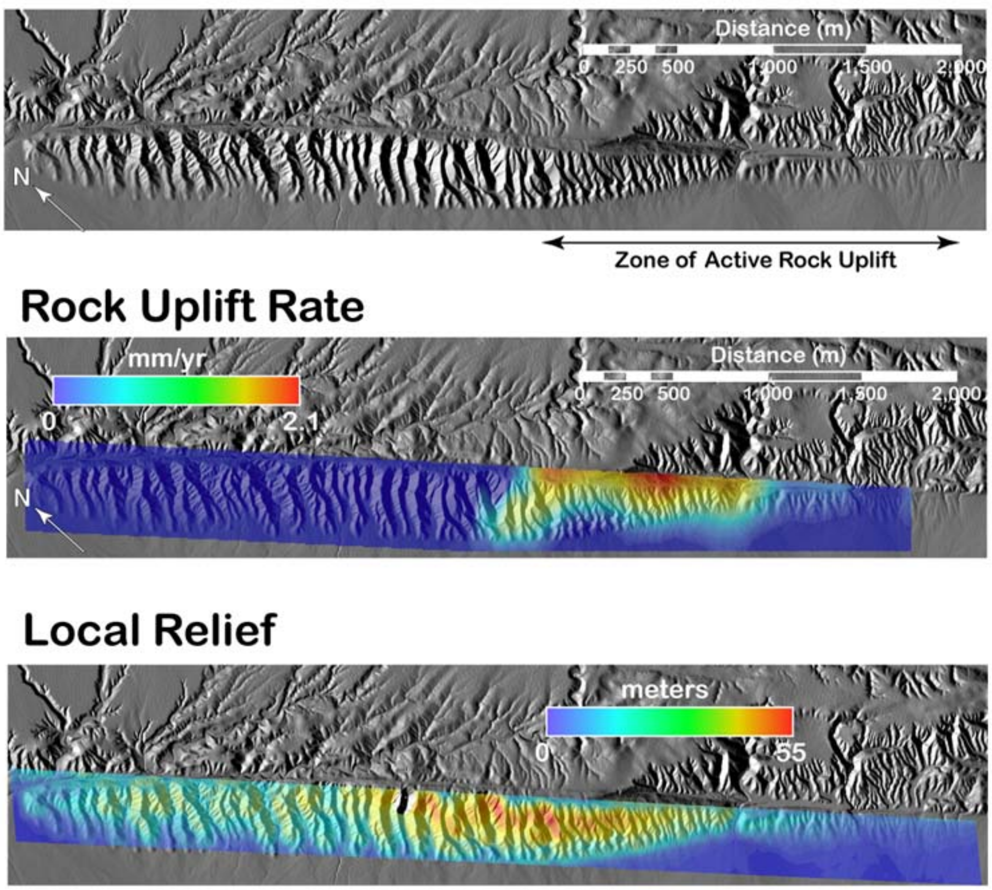


Figure 6. The Dragons Back pressure ridge along the San Andreas fault in south-central California illustrates the erosional response to tectonic forcing and generation of relief. [Image provided by G. Hilley.]

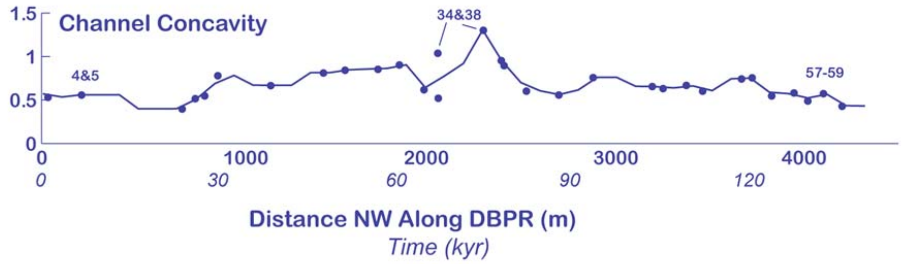


Figure 7. Hilley and Arrowsmith (2008) extracted stream gradient and area-slope metrics from a high resolution ALSM DEM and from that data calculated concavity. Concavity increases in response to greater rock uplift response as the pressure ridge moves through the high uplift zone, but the topographic and erosional responses lag behind the time of peak uplift rate. [Image provided by G. Hilley.]

IIc. Testing Landscape Evolution Models

One of the most exciting aspects of geomorphology is that the forms of the equations describing erosion and sediment transport are actively debated. It is desirable to test these equations by combining them with a conservation of mass statement, solving them forward in time to model the evolution of landforms, and comparing the model landscapes with natural topography. But efforts to perform such tests have been hampered by a lack of well-studied quantitative criteria for comparing models with real landscapes, and by a scarcity of high-resolution topographic data. LiDAR has improved this situation dramatically by promoting the discovery of new landscape metrics that models should be able to reproduce, and by providing a means of quantifying them over large areas. For example, the emergence of characteristic landscape scales such as evenly spaced ridges and valleys (Figure 8) is widely recognized, but was until recently poorly documented because the landforms were too small to be resolved by previous topographic data, and because vegetation precluded accurate topographic measurements. Spectral analysis of LiDAR topography-based maps has now demonstrated the statistical significance of the emergent ridge-valley wavelength and the variability of the wavelength among landscapes (research presented by Taylor Perron; Perron et al., 2008a). These measurements have inspired new models for the formation of such self-organized features (Perron et al., 2008b), and provided a dataset against which the models can be tested.

As another example, we are better able to understand how long-term process rates control hillslope form (Roering et al., 2007), to the extent that we can use comparisons between model results and LiDAR topography to understand the limitations of some widely used expressions for soil transport (Figure 9; research presented by Josh Roering; Roering, 2008). These hill slope evolution results are useful for mapping variations in erosion rate, interpreting patterns of tectonic uplift, and mapping geologic hazards. While LiDAR datasets have enabled quantification of landscape properties for testing long-term (>5,000yr) geomorphic process models, they have also illuminated the topographic signature of short-term processes (such as pit-mound topography associated with tree turnover) for which we lack mechanistic theories. In this sense, LiDAR has incited new paths of theoretical geomorphic research with basic and applied implications. It is clear that the availability of research-grade LiDAR is opening up new possibilities to test landscape evolution models through comparison with landscapes in the field.

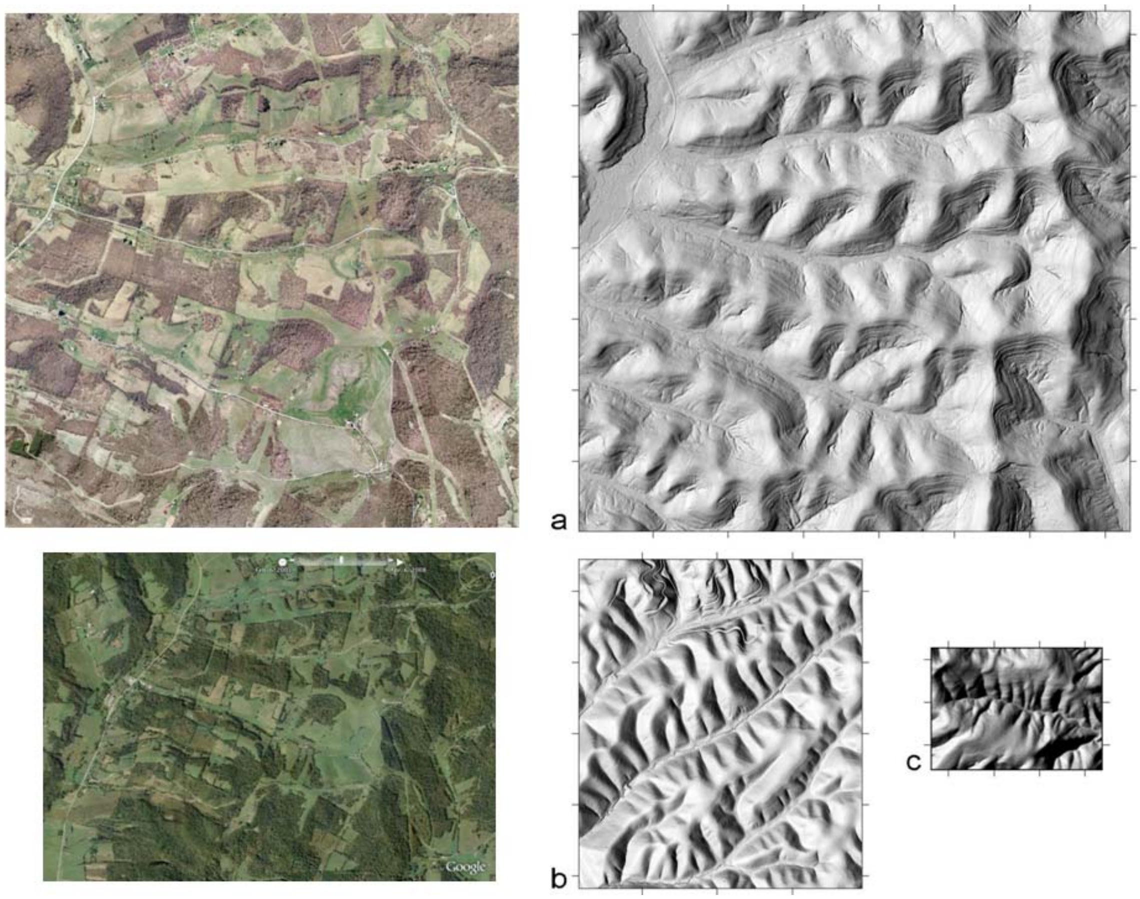


Figure 8. Shaded relief maps showing evenly-spaced valleys at multiple scales. (a) Eaton Hollow, Pennsylvania; data from PAMAP; (b) Gabilan Mesa, California; data from NCALM; (c) Death Valley, California; data from NCALM. (a) and (b) are shown at the same scale, with 500-m ticks. (c) has been enlarged by a factor of 6 relative to (a) and (b), and is shown with 50-m ticks. [Image provided by T. Perron.]

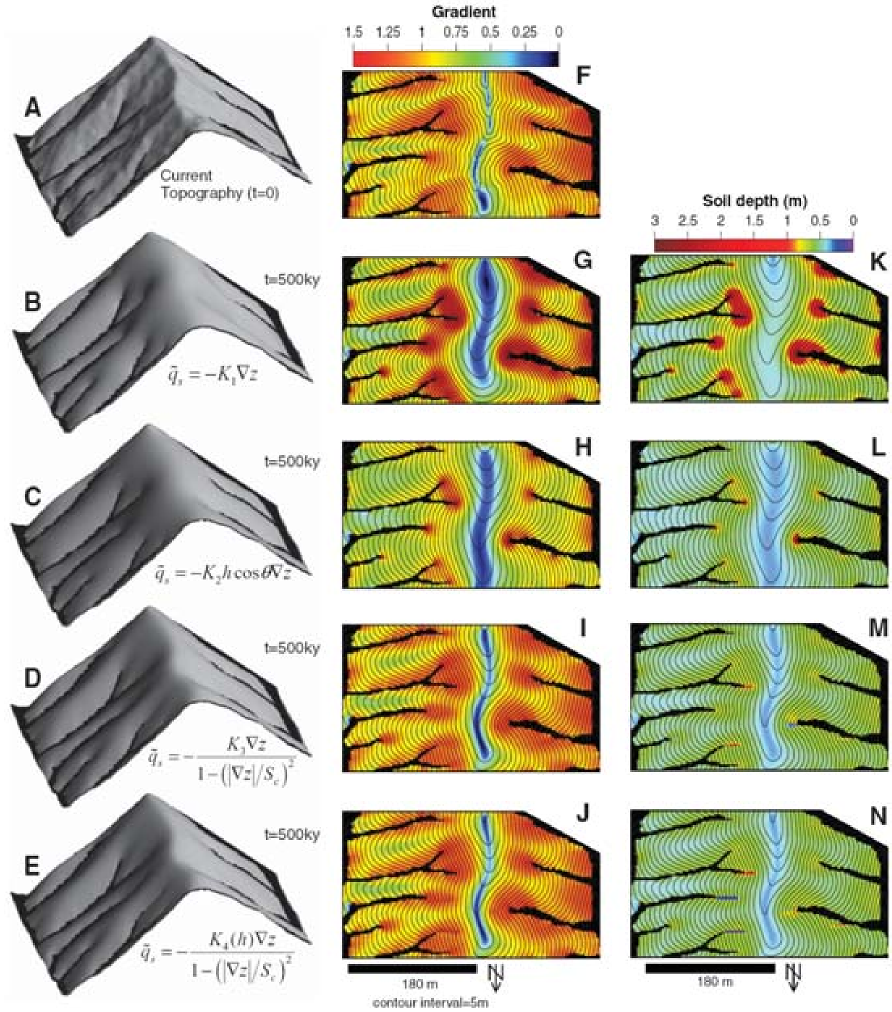


Figure 9. Comparison of simulation surfaces with current topography. (A–E) Perspective-view, shaded relief images of current and modeled topography. Modeled surface reflects 500,000 yr of evolution via a calibrated non-linear, depth- and slope-dependent transport model in concert with a slope-dependent, exponential soil production model. Incision is imposed along the valley axes at a constant rate to represent incision via fluvial and debris flow processes. The general correspondence of the two surfaces suggests that the essence of slope-forming processes may be captured through the model. The current surface is pockmarked due to bioturbation and vegetation classification errors, whereas the modeled surfaces are uniformly smooth because of the continuum assumption used here. (F-J) Spatial variation of hillslope gradient for current and modeled surfaces. The nonlinear slope-dependent models (I and J) best represent the sharp, steep-sided slope morphology of the field site. (K-N) Spatial variation of simulated soil depth for the four transport models. Each model predicts thin soils near the ridge top and thicker soils along sideslopes. (From Roering, 2008) [Image provided by J. Roering.]

IId. Detecting Landscape Change

Perhaps one of the most obvious and powerful uses of high-resolution topographic data is the detection of changes in the landscape that would otherwise be nearly impossible to document and quantify. Storms clearly cause soil erosion on steep, exposed, unvegetated hillslopes, but determining the amount of overland flow erosion is challenging because it might only be a few mm to cm per storm event. Airborne LiDAR can detect cumulative overland flow erosion over a period of months after multiple storms, and ground-based LiDAR can detect erosion for individual storms, as in the work presented by Jonathan Stock (Figure 10). Another example of change detection is the work presented by Nick Rosser (Figure 11), in which ground-based LiDAR is being used to determine the amount of rock face removed during individual and cumulative rockfall events. These types of analyses were nearly impossible prior to development of high-resolution topographic data acquisition.

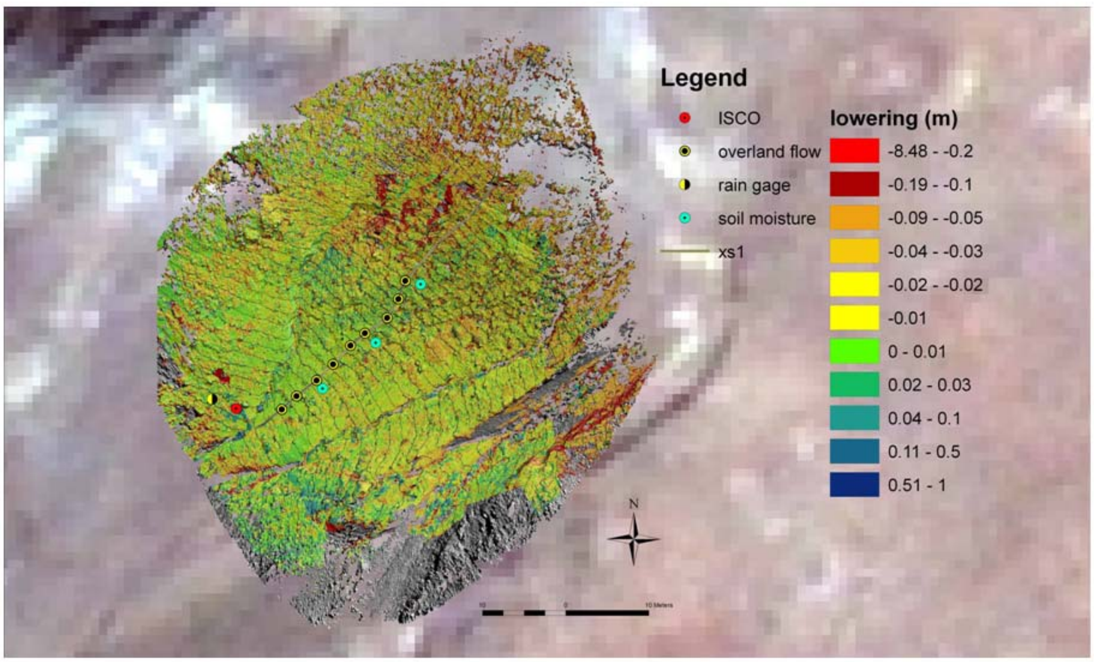


Figure 10. Use of repeat ground-based LiDAR to capture event-scale overland flow erosion, south side of Moloka'i, Hawai'i, USA. Colors indicate meters of elevation change over 5 months, draped over a hill shade terrain model of the 3-cm grid-cell topography. Symbols indicate sensors for detecting sediment concentration (ISCO), overland flow depth, rainfall and soil moisture. These variables are used to calibrate an overland flow erosion law. Yellow and green areas indicate cm-scale lowering by overland flow detachment of soil. Red tones indicate decimeter-scale lowering associated with movement of cobbles by overland flow over the indurated soil surface. Blue areas indicate aggradation of coarse material. Isolated sub-meter scale patches shown as red in lower part of catchment represent movable field gear in initial scan. LiDAR scan and point-cloud processing by Dr. Benjamin Brooks, UH Manoa, using an Optech ILRIS-3D. Post-processed by Dr. Jonathan Stock, USGS, using Terrascan and ArcGIS. [Image provide by J. Stock.]

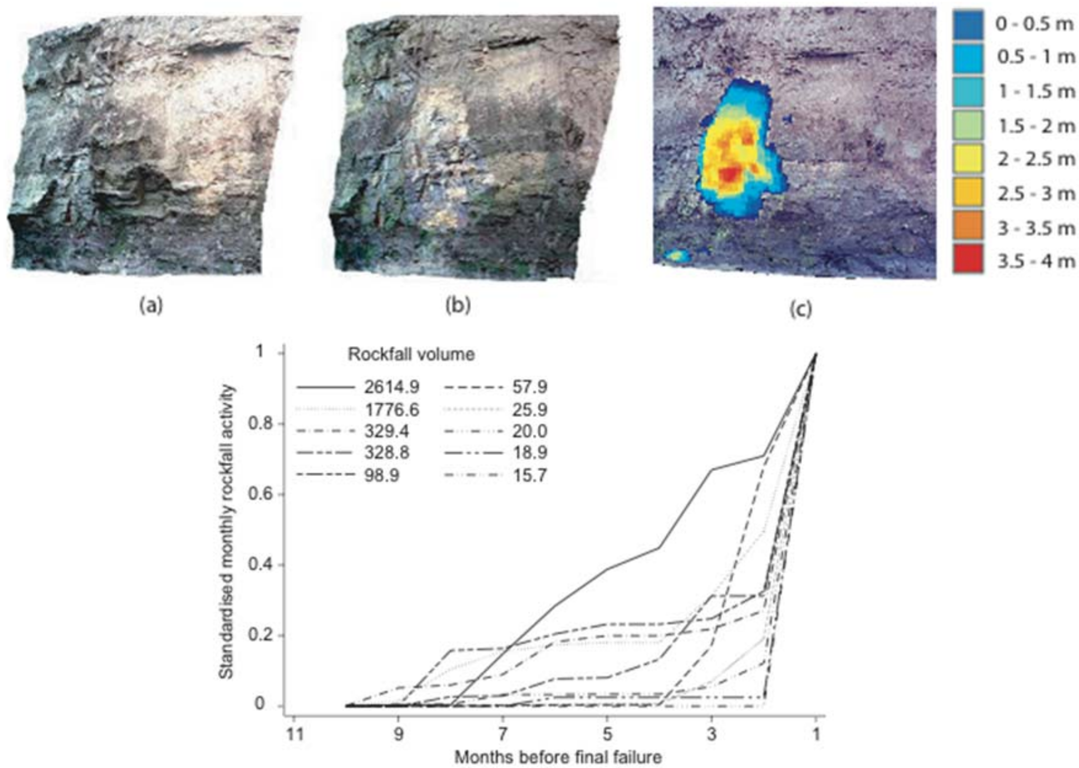


Figure 11. (a) An orthoimage derived from combined laser scanning and digital photogrammetry, January, 2004. The area of rock face in view is approximately 10 m across and 12 m high. (b) the same area as shown in (a) after a significant (15 m^3) rock fall indicated by the newly exposed clean rock face; and (c) the change during this period, illustrated by a calculation of the Hausdorff distance between the two surface models, showing the volume lost. (d) Graph illustrating the increase in rock fall activity prior to the 10 largest failures recorded, using monthly laser scanning to monitoring coastal rock faces. Volumes of the final failures are given in the legend in m^3. Rock fall activity is displayed as the mean volume of material lost per month per metre square of the rock face within the area of the final failure on the rock face. This measure is standardised to the rate measured in the month prior to failure to allow scale free comparison of the behaviour between rock fall of different sizes. [Image provide by N. Rosser.]

IIe. Feedbacks between Life and Topography

Workshop participants were very enthusiastic about new research that explores the co-evolution of biologic and geomorphic systems. Numerous examples of these linkages were discussed during the workshop. For instance, LiDAR-based mapping techniques permit quantitative investigations of the interplay between river morphologic and ecologic processes, such as gravel bar formation and the placement of salmon-spawning sites, and between fluvial transport competence and aquatic habitat characteristics (Figure 12, research presented by Noah Snyder). High-resolution datasets from forested landscapes offer other research opportunities, for example to explore relationships among biologic factors (canopy height, vegetation density), land-use management issues (fire history, fire suppression), and geomorphic processes (soil production, hillslope sediment transport). Repeat LiDAR surveys offer exciting opportunities to study landscape change

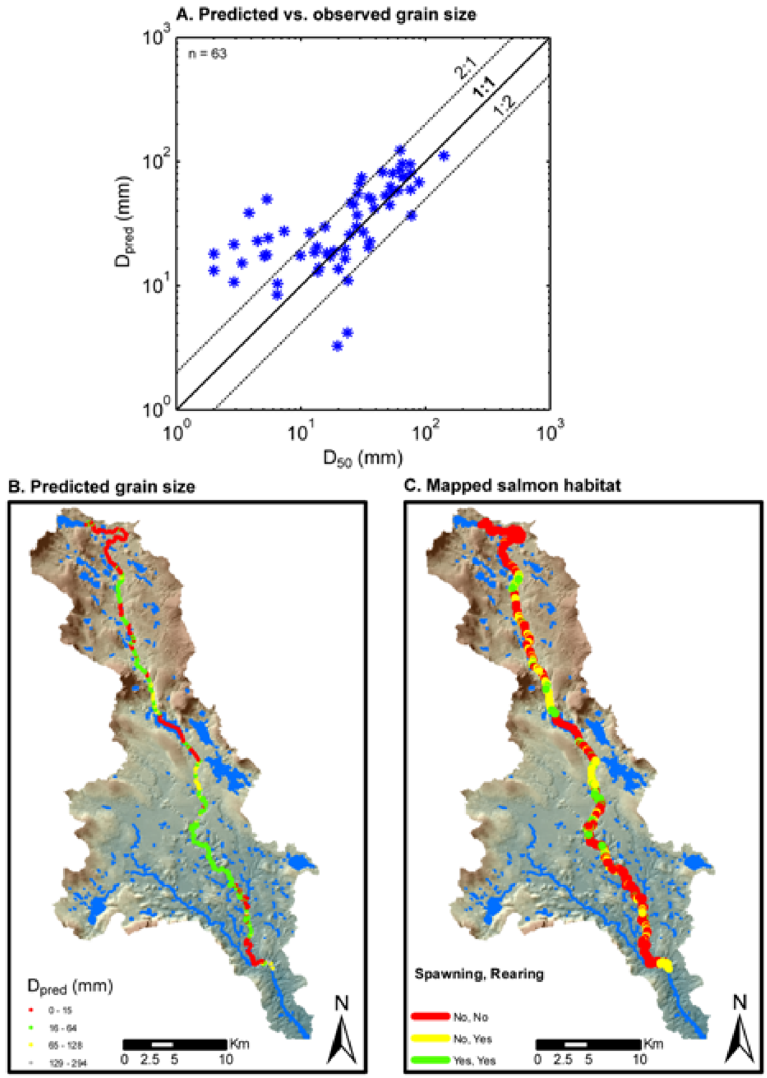


Figure 12. Data from the Narraguagus River, Maine. A. Comparison of predicted grain size (D_{pred}) using a model based on channel gradient and width measured from lidar DEMs with observed grain size (D_{50}). Seventy percent of the D_{pred} values are within a factor of 2 of D_{50}. B. Map of D_{pred} along the length of the mainstem river. C. Field mapping of Atlantic salmon habitat. Note the correspondence of $D_{pred} > 16$ mm (B) with mapped habitat (C). [Image provided by N. Snyder.]

in response to biologic disturbances (fires, timber harvest). These types of research opportunities are core elements of the new NSF-funded Critical Zone Observatories. More generally, rates and processes of eco-geomorphic change are particularly important in the context of global climate and land-use changes expected over the next centuries.

IIf. Routing Water and Sediment through Watersheds

Presentations and group discussion during the meeting identified both ALSM and ground-based LiDAR data as key inputs to models that predict how water, sediment, and biological fluxes are controlled by landscape form. Several presentations highlighted the utility of such data in creating detailed hydrologic models of short-lived, high intensity urban runoff events with fluxes that could not be adequately captured with point measurements of discharge because of the flashiness of these events (Figure 13, research presented by Andy Miller]. Likewise, group discussions noted that such applications need not be restricted to the routing of water over the detailed LiDAR-derived landscape, but could be applied to any geophysical flow (including sediment transported by both fluvial and debris flow processes, lava and pyroclastic flows, and density-driven air flow across Earth's surface) to make detailed predictions and provide rigorous tests of physical flow

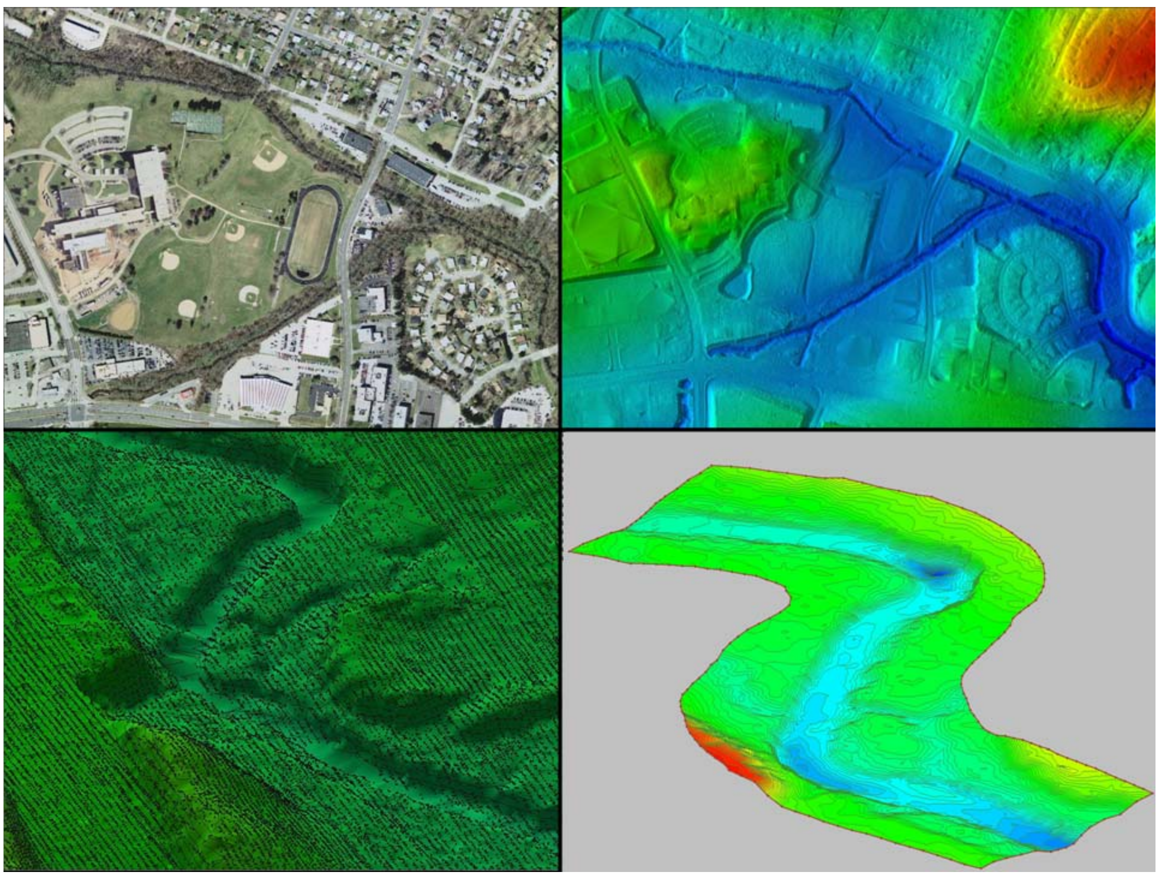
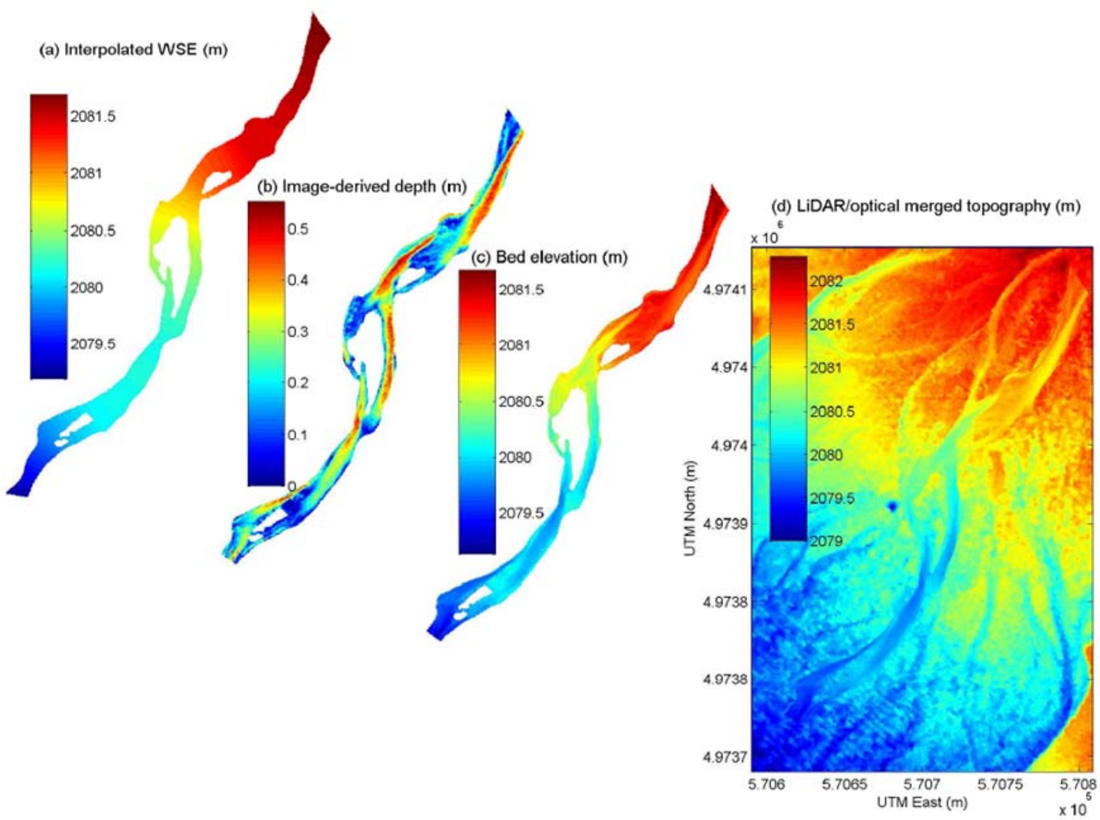


Figure 13. Orthophoto (upper left) and LiDAR-derived hillshade relief map (upper right) for heavily urbanized area near Baltimore, MD. Hydrologic and hydraulic modeling for areas with flashy urban runoff demonstrates the problem of routing flow in areas with large percentages of impervious surfaces, and with numerous underground stream structures. 3-D views of urban stream channels (lower left and right) illustrate how LiDAR (dots are LiDAR points) combined with channel surveying (total geodetic station) can be combined to estimate

channel geometry and water depth for input to hydrologic models. [Images provided by A. Miller.]

models. These types of studies could significantly impact, for example, the evaluation of natural hazards and estimations of sediment budgets, as well as contribute to an understanding of how human impacts may change geophysical flows.

A pioneering approach presented by Carl Legleiter uses passive optical image data to estimate flow depths within the wetted channel (Legleiter et al., 2004, Legleiter, 2008, Legleiter et al., In press), which cannot be mapped effectively by most LiDAR systems due to strong absorption of near-infrared laser pulses by water. The bathymetric information derived from optical data is then combined with LiDAR data from exposed bars and floodplains to characterize subtle topographic features along gravel-bed rivers (Figure 14).



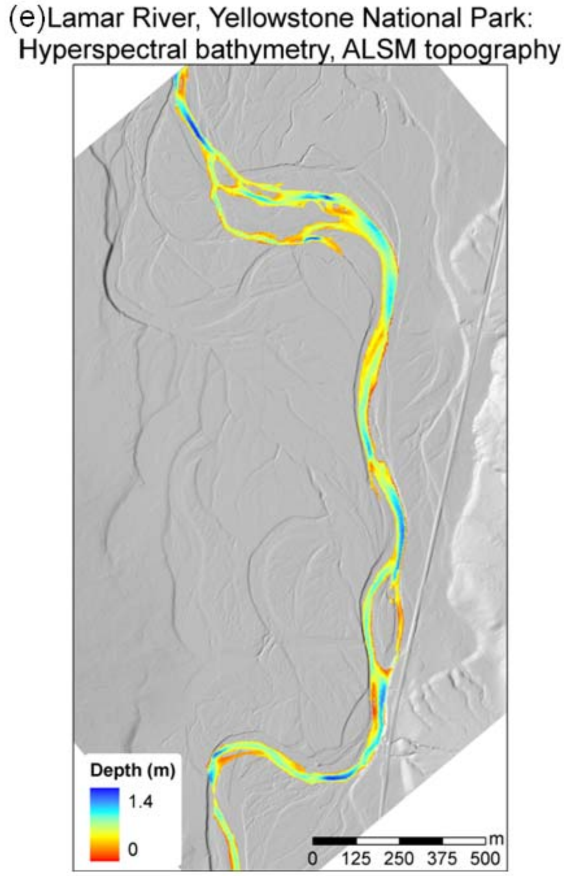


Figure 14. Water surface elevations derived from LiDAR (a) can be combined with flow depths inferred via passive optical remote sensing (b) to estimate bed elevations within the wetted channel (c). Merging this information with bare-earth digital terrain models of exposed bars and floodplains developed from LiDAR thus provides a continuous topographic representation of the fluvial environment (d), as is also shown (e) for a stream in Yellowstone National Park . [Image provided by C. Legleiter.]

As demonstrated in several presentations, flow modeling of detailed, LiDAR-derived topography may be used to assess the stresses to which biota in various landscape positions may be subjected, and how these may be altered by land-use change. Thus, all of the participants saw a great potential for both airborne and ground-based LiDAR-derived topography to revolutionize physical models that predict the path geophysical flows may be routed across and beneath Earth's surface.

IIg. Linking Structural Geology to Geomorphology

High-resolution topographic data from ALSM and ground-based LiDAR permits the study of recent or active rock deformation at the earth's surface and could open a new sub-discipline that links geomorphology and quantitative structural geology. One presentation focused on this (Figure 15, research presented by Stephen Martel). This research blends analyses of the shape of bedrock surfaces using differential geometry, measurements and analyses of near-surface stresses, and geologic mapping of fractures. High resolution topographic data can be used to measure the curvature and slope of a bedrock surface, and to map fractures that emerge at the surface. Near-surface fractures play critical roles in weathering of bedrock, slope stability, and the hydrology of the shallow subsurface. The stresses that lead to near-surface rock fracture are highly sensitive to the shape of the topographic surface. As a result, detailed measurements of the topography permit quantitative predictions of where recent near-surface fractures should occur, and possibly reconstructions of previous shapes of a surface when ancient near-surface fractures formed. Discussions about this research highlighted the importance of accounting for measurement error in evaluating surface curvature and surface slope.

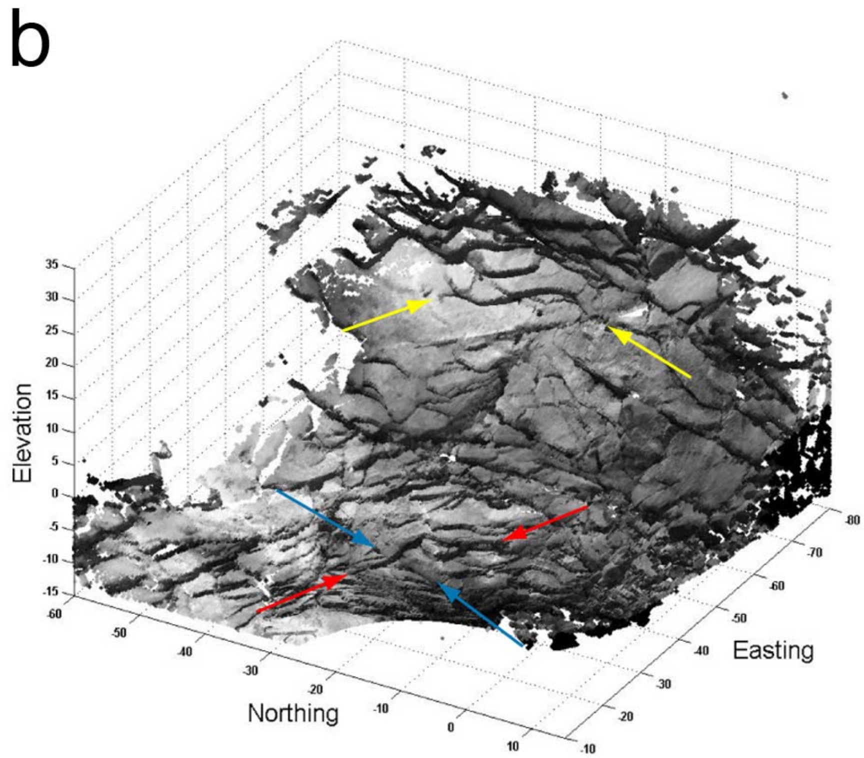


Figure 15. (a) Photograph and (b) tripod LiDAR image of sheeting joints in a slope in Yosemite National Park. Colored arrows mark fractures in both images. Red circles in the lower left portion of the photograph mark people for scale. [Images provided by S.J. Martel.]

III. SOFTWARE TOOLS, TUTORIALS, AND EDUCATION

Workshop participants recognized that the volume and heterogeneity of LiDAR data can make their distribution and analysis challenging.. With typical shot densities from airborne data of several per square meter, and study areas as large as 1000 km^2, hundreds of millions to billions of points are commonly processed into high resolution digital elevation models (DEMs). Terrestrial Laser Scanning (TLS) typically samples the surface at 1 or 2 orders of magnitude higher spatial resolution, but of smaller areas, yielding datasets of similar size. A subset of the workshop participants that included Arrowsmith, Glenn, Cowgill, and Crosby worked together to consider software and training associated with LiDAR data analysis. A longer version of this section is available at https://arrowsmith.blog.asu.edu/2008/12/05/current-capabilities-and-community-needs-for-software-tools-and-educational-resources-for-use-with-lidar-high-resolution-topography-data.

Software needs will vary based on the position within the LiDAR workflow and the application. The major LiDAR workflow steps of direct interest to the end user begin with the delivery of the classified point cloud. Reprocessing the point cloud for position is not a high priority for the majority of users. Thus, software is needed to measure and visualize the point cloud, to generate digital elevation models, to assess the quality of the LiDAR data products, and to compute topographic metrics or to perform other higher level scientific analyses.

Two representation approaches often are used with LiDAR data. The first treats the point cloud as an attributed three dimensional data set. Some software tools—more commonly used with Terrestrial Laser Scan data— perform 3D tessellation and texture mapping on the point cloud-defined surface. The other representation is often called "2.5D" in which the data are represented on a 2 dimensional map grid with constant spacing and only one value at each horizontal grid node (i.e., a Digital Elevation Model). Exploration and awareness of the gridding process is valuable and often necessary because of the requirements of analytical tools such as slope and flow direction and area calculations.

When working with LiDAR data, most people use multiple pieces of software, each doing a few actions well. These tools also vary from expensive commercial software (e.g., Polyworks), to relatively inexpensive readily available through site licenses in academic institutions (ArcGIS, ENVI, MATLAB with some LiDAR specific extensions or codes), and free open source software (e.g., GRASS—http://grass.itc.it; GEON Points2Grid--http://lidar.asu.edu/points2grid.html; GEON LVIZ--http://lidar.asu.edu/LViz.html) The principal software for 2.5D-based cartography and data integration is Arc-GIS. Nancy Glenn and colleagues from Idaho State University have developed a free set of LiDAR Tools which is an extension to ENVI (http://geology.isu.edu/BCAL/tools/EnviTools/index.html) (Glenn et al., 2006; Streutker and Glenn, 2006). Kelin Whipple (ASU) and colleagues have developed free extensions to MATLAB and ArcGIS to extract stream profiles from DEMs and analyze their steepness index and concavity (http://www.geomorphtools.org/Tools/StPro/StPro.htm). George Hilley (Stanford) offered up a large number of Matlab functions for computation of topographic metrics, especially those based on local slope and upslope contributing area. . Stephen Martel (University of Hawaii) has posted Matlab codes on his website for curvature analysis (http://www.soest.hawaii.edu/martel/Martel_curvature_dir/). Members of the UC Davis W.M. Keck Center for Active Visualization in the Earth Sciences (KeckCAVES) (http://www.keckcaves.org/) have created tools to allow real-time interactive visual analysis of massive point cloud (LidarViewer) and DEM (RIMS) data (Bernardin et al., 2006; Bernardin et al., 2008; Kellogg et al., 2008) as the first steps in developing a comprehensive point cloud analysis tool (Kreylos et al., 2007; Gold et al., 2007).

Despite these many tools, there remains a considerable need for expansion of software resources that can handle the challenges posed by LiDAR point cloud and DEM data. For example, an open-source toolkit for various platforms (Matlab, C, ENVI/IDL, etc.) for basic operations is a valuable target that was identified at the workshop. Furthermore, software tools that are well linked with on-line data sources or archives can take advantage of significant computational resources beyond the user's desktops. A comprehensive software scheme for high resolution topography data should include a field computing (e.g., mobile, PDA, tablet) to desktop to grid- or "cloud"-based architecture.

Many LiDAR point clouds are initially acquired as community datasets, and all are valuable in many ways beyond the original motivation for their collection. Some are valuable as iconic datasets on which important research has been performed (e.g., Roering and others Oregon Coast Range LiDAR DEMs, etc.). Others are valuable because they serve the needs of another scientific discipline (e.g. data being valued by the ecology community for its representation of vegetative canopy may be useful for earth scientists). Data collected and preprocessed by commercial vendors and NCALM (National Center for Airborne Laser Mapping) are typically provided to the purchaser (individual PI, state or federal agency, UNAVCO) on DVD or portable hard drive. The degree to which these data are then made available to the general community and the format in which they are provided is currently quite variable. Although no single data clearinghouse for community data has been established, there are several sites where such data may be downloaded and processed. The USGS CLICK effort (http://lidar.cr.usgs.gov/) provides data primarily in raw form as provided by the dataset owner.

Alternatively, Web-based LiDAR data access, data management, and data processing has been pioneered by the GEON (GEON LiDAR Workflow; Crosby, et al., 2006; Jaeger-Frank, 2006) and NOAA's LDART tool (http://www.csc.noaa.gov/crs/tcm/about_ldart.html). The GEON LiDAR system begins with user-defined selection of a subset of point data and ends with download (including dynamically generated metadata) and visualization of DEMs and derived products. Users perform point cloud data selection, interactive DEM generation and analysis, and visualization all from an internet-based portal. Users may experiment with DEM resolution and DEM generation algorithms so as to optimize terrain models for their application. By using cyberinfrastructure resources, this approach allows users to carry out computationally intensive LiDAR data processing without having appropriate resources locally. This system gives users access to datasets of interest and basic tools to process and interact with the data. But, at some point, the user will need to process the data independently for their specific science objectives.

Training, education, and curricula on technology, tools, science and management applications is an area in which significant impacts can be made. Two recent topography and LiDAR-oriented workshops[1] were sold out. The demand for these data and knowledge of how to handle and analyze them are high. Such 1-2 day courses with 20-30 people are one of the most effective mechanisms for the engagement of the communities interested in the data and for the propagation of the scientific discoveries and enhanced management that come from their analysis.

Finally, many participants saw the new LiDAR-derived topography as a powerful tool for classroom education and public outreach. The effect of databases such as those assembled by Google already has had a clear, positive effect on education and public understanding of Earth's surface. Participants also agreed that LiDAR-derived

[1] 2007 Geological Society of America Meeting: *New Tools for Quantitative Geomorphology: Extraction and Interpretation of Stream Profiles from Digital Topographic Data* & *Processing and Analysis of GeoEarthscope and Other Community LiDAR Topography Datasets*. See http://www.geosociety.org/meetings/2007/cw_gsa.htm and UNAVCO http://www.unavco.org/edu_outreach/uscs/2008/LiDAR_Course_2008.html

topography already has led to many discoveries in earth and biological sciences that could not have been anticipated just a decade ago.

Additional needs for the community identified at the workshop include the following:

- A single-point internet-based clearing house for LiDAR point cloud and DEM data that makes it simple for dataset holders to make their data available to the user community and for users to discover data of scientific interest. All publically-funded LiDAR missions should be required to post data on this site within a specified timeframe (1-2 years). Ideally, this system should also provide tools for users to perform basic data processing, analysis and visualization tasks (e.g. the GEON LiDAR system). The site should provide comprehensive metadata characterizing each data set and all processing steps used to produce derived products such as an attributed, classified, merged and georeferenced point cloud or a bare-earth DEM. Standards for data delivery are included in this requirement.

- Format conversion capability: no one software solution will be achieved for the entire community interested in these data. Therefore, delivery in and conversion between common file formats for both point data (LAS, ASCII) and DEM data (ASCII grid, binary grid, etc.) is necessary. Data from publicly supported data acquisitions should be released in such common non-proprietary formats.

- The community would most benefit from a Wiki or similar system where users could post tools, tutorials, scripts etc. that they have found useful in building LiDAR processing workflows to address their science goals. A community forum for idea and method exchange. Existing venues that could be adopted by the community include: the HydroVent (http://pasternack.ucdavis.edu/hydrovent.html), GEON Forums (http://www.geongrid.org), the USGS CLICK Bulletin Board (http://lidar.cr.usgs.gov/), or email listserves (TLS listserv from U. New Mexico, lidar@asu.edu, GEOMORPH-L@listserv.boisestate.edu). The GEON LiDAR team (led by Chris Crosby) is building the OpenTopography Portal (http://www.opentopography.org/) would be a logical place to host such a Wiki and some of the other community-based functionality we have identified.

- Development of community-oriented data systems and software libraries can be enhanced with external support for collaboration with computer scientists and employment of professional programmers to build a framework on top of which the community could develop specific tools and workflows. Support for such an effort could come from NASA or NSF collaborative geoscience initiatives. Such support will be particularly important for developing new algorithms to handle quantitative analysis of point data, because a number of these algorithmic challenges are on the frontier of scientific computing.

IV. Improvements in Gathering and Disseminating High-Resolution Topographic Data

As long as high quality data are available from GPS ground stations within a few tens of kilometers from an ALSM aircraft, the errors introduced by the aircraft trajectory are usually less than a decimeter and do not dominate the LiDAR error budget. Errors in the direction of the ranging vectors are caused by imperfections in the recorded roll, pitch, and yaw values of the sensor, measured by the inertial measurement unit (IMU), and errors in the scanner. Errors associated with the orientation of the range vectors scale with the flying height (above local ground level) of the aircraft, generally making it advisable to fly as low as safe operating conditions, and eye safety considerations, permit. Sensor orientation, scanner scale and offset, and aircraft trajectory errors each produce distinctive artifacts in the final surface coordinates, and users of ALSM data should familiarize themselves with the artifacts and always be looking for them. Usually artifacts are most easily detected in the overlap of adjacent swaths, and to achieve the highest possible accuracy, ALSM data should always be collected with generous overlap of swaths (50% or more overlap is recommended).

The raw ALSM observations currently must be processed with proprietary software to obtain surface point coordinates that can then be analyzed by any of several commercial programs to classify and filter the observations, and to create products such as shaded relief images. Since a typical project may comprise terabytes of data, the data are often sent to archives on hard disk drives. The data are also divided into tiles, which can be obtained by users over the internet.

The intensity values recorded by the Optech Gemini unit used by NCALM are proportional to the peak voltage produced by the avalanche photo-diode (APD) detector, digitized by two overlapping 8-bit low and high signal channel analog to digital converters (approximately equivalent to 12 bits of dynamic range). NCALM has software to “automatically” normalize the recorded intensity values, to take into account changes in the strength of signals which arise simply from the variation in distance from the sensor to surface points as the scanner angle, flying height, and topographic relief along the fight line. Methods of correcting the recorded intensities for other factors, such as changes in angle of incidence of the laser with the surface and variations in laser pulse energy , can be significant and are the subject of research at NCALM.

Even the normalized intensity value for any single shot may be much higher or lower than the mean return from a specific surface material. But one of the strengths of ALSM is the large number of samples recorded, and the average intensity of large numbers of shots can still be used to identify areas with relatively subtle differences in reflectivity, such as lava flows from different events [Kaadakainen,et al, 2005]. Even the “raw” recorded intensity values can be used to detect returns from high contrast surfaces, such as paint lines on highways, white sand versus lava rocks, and specular reflections from water surfaces versus ground or vegetation [Carter et. al., 2001]. Some terrestrial laser systems exploit return intensities for interpretation of the point cloud, or “paint” the points with the projected RGB values from simultaneously acquired photography. Comprehensive point cloud delivery such as available from the GEON LiDAR workflow includes the relative intensity value for each point if available.

V. EMERGING SCIENTIFIC AND EDUCATIONAL OPPORTUNITIES

Participants identified a large number of opportunities for LiDAR-derived topography that could revolutionize a wide variety of fields in the geosciences. Collection and analysis of high-resolution LiDAR topography has, and will continue to result in new understanding and assessment of both natural hazards and the way in which the biosphere interacts with Earth's surface. Of particular interest were studies striving to understand how human-induced changes in landscape characteristics have disrupted the food web, fish spawning sites, and hydraulic characteristics of river systems. Higher resolution data and the identification of field settings where these tools might be applied would greatly enhance progress in all of these scientific endeavors, and would likely lead to new multi-disciplinary collaborations between earth, life, and atmospheric scientists. In addition, many participants saw the new LiDAR-derived topography as a powerful tool that could be used to enhance educational experiences and awareness of the earth sciences. Using high-resolution topography in the classroom and finding ways to make it accessible to the general public provides great potential for earth scientists to reach out to students and the general public, as well as to inform these groups about changes that currently impact Earth's surface.

Participants agreed that the LiDAR-derived topography has already led to many discoveries in earth and biological sciences that could not have been anticipated just a decade ago.   We are at a historical turning point similar to that during which the initial topography of the United States was surveyed. As during that time, the collection of high-resolution topographic data would lead to numerous scientific discoveries and practical and commercial applications that emerge from the widespread availability of these data. Such topographic data bring new challenges to the engineering and scientific community, including discovering new ways of extracting landscape features from the topographic data, identifying new methods to quantify topographic trends, and developing new physical and mathematical descriptions of the landscape that are appropriate for the high resolution of LiDAR topography. Challenges such as these will likely drive a wide variety of new discoveries across many scientific disciplines that will further our understanding of how Earth's near surface, its biosphere, and changes induced by humans influence one another.

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APPENDIX 1

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APPENDIX 2

MEETING SCHEDULE: WORKSHOP ON EARTH SURFACE PROCESSES WITH HIGH –RESOLUTION TOPOGRAPHIC DATA

Sunday, June 15

6:00pm – 8:00pm	Reception, Mesa Lab Cafeteria with Hosted Bar and Hors d'Oeuvres

Monday, June 16

8:00am - 8:05am	Welcome, Plenary Room Dorothy Merritts
8:05am – 9:00am	Morning Oral Session I, Plenary Room Jonathon Stock
9:00am – 10:00am	Noah Snyder
10:00am – 11:00am	Morning Break/Poster Session II, Plenary Room Breakout, Room 2126
11:00am - 11:30am	Morning Oral Session III, Plenary Room Jim Svitsky
11:30am - 11:45am	Andrew Miller
11:45am - 12:00pm	Group Discussion, Plenary Room
12:00pm - 1:30pm	Lunch/Poster Session IV, Plenary Room Breakout, Room 2126
1:30pm - 2:30pm	Afternoon Oral Session V, Plenary Room Arjun Heimsmath
2:30pm - 3:30pm	Josh Roering
3:30pm – 5:00pm	Afternoon Break/Poster Session VI, Plenary Room Breakout, Room 2126
5:00pm – 6:00pm	Afternoon Oral Session VII, Plenary Room Dorothy Merritts
6:00pm – 8:00pm	Optional Additional Poster Viewing, Plenary Room
7:00pm	Dinner On Own

Tuesday, June 17

8:00am - 8:05am	Welcome, Plenary Room Dorothy Merritts
8:05am – 9:00am	Morning Oral Session VIII, Plenary Room Adam Soule
9:00am – 10:00am	Steve Martel
10:00am - 11:00am	Morning Break/Poster Session IX, Plenary Room
11:00am - 12:00pm	Morning Oral Session X, Plenary Room Bill Dietrich (for Jim McKean)
12:00pm - 12:15pm	Group Discussion, Plenary Room
12:15pm - 1:30pm	Lunch/Poster Session XI, Plenary Room Breakout, Room 2126
1:30pm - 2:30pm	Afternoon Oral Session XII, Plenary Room Nancy Glenn
2:30pm - 3:30pm	Nick Rosser
3:30pm – 5:00pm	Afternoon Break/Poster Session XIII, Plenary Room Breakout, Room 2126
5:00pm - 6:00pm	Afternoon Oral Session XIV, Plenary Room George Hilley
6:00pm – 7:00pm	Posters, Plenary Room Breakout, Room 2126
7:00pm – 8:30pm	Catered Dinner, Upper Cafeteria

Wednesday, June 18

8:00am - 8:05am	Welcome, Plenary Room Dorothy Merritts
8:05am – 9:00am	Morning Oral Session XV, Plenary Room Ramon Arrowsmith
9:00am – 10:00am	Kurt Frankel
10:00am - 10:45am	Morning Break/Poster Session XVI, Plenary Room Breakout, Room 2126

10:45am - 11:45am	Morning Oral Session XVII, Plenary Room Ramesh Shrestha/Bill Carter/Clint Statton Bill Dietrich
11:45am - 12:30pm	Group Discussion, Plenary Room
1:00pm	Meeting Adjourned

APPENDIX 3

Earth Surface Processes and High-Resolution Topographic Data

List of Presentations and Posters

Berlin, Maureen	Transient landscapes explored through ALSM data: Channel evolution and hillslope response
Booth, Adam	Characterizing landslide-prone terrain using Fourier and wavelet analysis with high-resolution topographic data
Carter, Bill	NCALM and advances in LiDAR technology and data acquisition
Cowgill, Eric	Visual analysis of LiDAR and terrain data at the W.M. Keck Center for Active Visualization in Earth Sciences (KeckCAVES)
Delong, Stephen B.	Surface process monitoring using terrestrial LiDAR and environmental sensor arrays: Methods and progress
Dietrich, Bill and Jim McKean	Presenting for Jim McKean: Geologic controls on channel morphology and the distribution of aquatic habitat: seeing through the water with a narrow-beam, aquatic-terrestrial lidar
Eldridge, Daniel	Developing a method to analyze alpine debris-flow channels using LiDAR data in the Arapahoe basin ski area
Finnegan, Noah	Modeling open-channel flow with airborne-laser swath mapping (ALSM)
Frankel, Kurt	Using Airborne Laser Swath Mapping to Determine Fault Slip Rates and Patterns of Landscape Evolution along the Death Valley-Fish Lake Valley Fault Zone

Glenn, Nancy	LiDAR derived surface morphology and change detection
Griffin, Eleanor	Use of high-resolution topographic data to study geomorphic processes within the Rio Puerco Arroyo, New Mexico
Guitierrez, Hugo	Analysis of catchment hydro-geomorphology, vegetation patterns and incoming solar radiation based on sequentially-improved terrain datasets: IFSAR, dGPS AND ALSM
James, Allan	Legacy sediments and channel morphology: Feather and Yuba Rivers, CA
Jungers, Matt	High-resolution hillslope morphometry and hillslope sediment transport
Kelsey, Harvey	Using LiDAR in regions of blind reverse fault and blind master ramps
Legleiter, Carl	Remote measurement of river channel morphology from LiDAR passive optical image data
Mackey, Ben	Earthflow terrain revealed, Eel River Ca
Madej, Mary Ann	Emerging opportunities using LiDAR in north coast California
Martel, Steve	Curvature of Topography, Formation of Sheeting Joints and the Long-term Strength of Rock-High-resolution LiDAr topographic data and near-surface formation of bedrock fractures in Yosemite National Park

Merritts, Dorothy	Dammed Valleys and Fluvial Processes
Miller, Andrew	Application of LiDAR for 2-D hydraulic modeling of floods in urban watersheds
Moody, John	Extreme floods, erosion, and sediment transport after wildfire
Passalacqua Paola	Exploiting topographic signatures: Estimating resource attributes, up-scaling, and feature extraction
Perron, Taylor	Special signatures of characteristic scales in landscapes
Prentice, Carol	Using LiDAR data for studying active tectonics in northern California
Reed, Sarah	A new approach to testing a biologic hypothesis of mina mount formation using airborne-based LiDAR and spatial pattern analysis
Roering, Josh	Using LiDAR to simulate hill slope evolution and to detect and map landslides in mountainous terrain
Rosser, Nick	Investigating the controls on coastal cliff failure using high-resolution 3D topography
Sheets, Ben	High-resolution topographic measurement in physical experiments
Shrestha, Ramesh	NCALM and advances in LiDAR technology and data acquisition

Snyder, Noah	Channel responses to climate and land-use change: applications of high-resolution topographic data in California and Maine
Soule, Adam	Application of ground-based laser mapping to patterned ground in periglacial environments
Syvitski, James	InSAR sensing (SRTM) of low lying topography in river floodplains and deltas: An assessment
Tarboton, David	Generalized methods for terrain-based flow analysis of digital elevation models
Truslow, Danna	Using catchment geomorphology and heat-tracers to understand stream-hyporheic zone dynamics in a coastal NH watershed
Tucker, Greg	Imaging Rapid Landscape Change along the West Bijou Creek Escarpment
Vande Castle, John	Remote sensing activities for the NSF Long-Term Ecological Research (LTER) Network
Vincent, Kirk	Geomorphic processes within the Rio Puerco arroyo in north-central New Mexico
Wilcox, Andrew	Topographic input for two-dimensional hydraulic modeling along a desert river to investigate flow-vegetation feedbacks
Yanites, Brian	Channel incision and morphology in response to active faulting