feature article

Geodetic laser scanning

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Producing surface maps at submeter resolution, even over heavily forested terrain, GLS can reveal the fine structure of such features as faults, landslides, and drainage patterns.

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If you even occasionally enjoy surfing the Web, there is a good chance that you have visited the Google Earth site (http://earth.google.com). There seems to be a certain universal appeal to viewing Earth from the edge of space, selecting a point of interest, and zooming in until objects as familiar as the flowerbeds in your own yard become visible. Imagine then how appealing it would be for Earth scientists, who devote their careers to studying the evolution of the planet's surface—by examining processes as diverse as erosion, uplift, tectonic-plate motion, seismicity, and volcanism—to have access to a similar resource, but one that offers accurate three-dimensional coordinates of closely spaced points covering any area of Earth's surface.

The measurements necessary to develop a scientifically rigorous version of Google Earth are the province of geodetic science, or geodesy, a branch of applied science that deals with measuring Earth's size, shape, topography, orientation, gravitational field, and the variations of those quantities with time. Geodesy is one of the oldest of the physical sciences, with a recorded history dating back at least two millennia. Some of the world's greatest physicists, astronomers, and mathematicians, including Isaac Newton, Leonhard Euler, Carl Friedrich Gauss, George Airy, Simon Newcomb, Albert Michelson, and most notably Albert Einstein (see the box on page 42), contributed to advances in its theory and technology. But the golden age of geodesy began just a half century ago with the birth of the space age.

Building a reference frame

The development of rockets that can deliver warheads anywhere on Earth, of artificial satellites that could be launched into orbit, and of spacecraft able to reach the Moon and planets beyond it provided both the need and the means for geodesists to determine highly accurate coordinates of points around the globe, along with the relative distances and directions to objects in space. Earth's surface is composed of ever-moving lithospheric plates, and its rate of rotation and orientation in space continually change as mass is redistributed and angular momentum exchanged between the crust and the atmosphere, ocean, and fluid core. Because of those dynamics, establishing and maintaining a global reference frame in which to locate points proved challenging.

By the 1980s, space-age technology had led to the development of several powerful new geodetic observing techniques, including satellite and lunar laser ranging, very long baseline interferometry (VLBI), and the carrier-phase differential global positioning system. Rather than use the time-tagged range observations transmitted by GPS satellites designed to provide real-time point positioning accurate to a few meters, the scientific community essentially reinvented GPS by recording the phases of the carrier waves from those satellites. Observations made at two or more ground stations are then brought together, and the differences in the phases are used to obtain relative positions accurate to millimeters. Geodesists and astronomers from many nations worked together with the entire suite of new observing methods to establish and operate the International Earth Rotation Service.

Today, through that service, a sparse global VLBI network regularly observes quasars and other natural radio sources to provide a stable celestial reference frame and to monitor the motions of the lithospheric plates and variations in the diurnal rotation and wobble—that is, nutation and polar motion—of Earth relative to that reference frame.[1] In addition, hundreds of continuously operating GPS stations, some colocated with VLBI stations, contribute information on short-period changes in Earth orientation and, even more important, provide a relatively dense international terrestrial reference frame (ITRF), with station coordinates accurate to about one centimeter and station velocities accurate to a millimeter or two per year.[2]

Carrier-phase differential GPS makes it possible to determine the coordinates of virtually any point on Earth relative to the ITRF, from a day or two of observations. With kinematic GPS (which still uses carrier-phase difference observations but takes into account the changing geometry caused by the motion of one of the receivers), the trajectories of aircraft flying up to 30 kilometers or so away from ground stations can be determined to 4–8 cm vertically and a fraction of that horizontally.

Researchers studying the rise of sea level from global warming were among the first to recognize the significance of being able to detect surface deformations at the subcentimeter level. They placed permanent GPS receivers at tide-gauge stations to directly measure any vertical motions of the gauges. They also set up networks of GPS stations across Canada and Scandinavia to measure the rate and pattern of the vertical crustal motion in areas of maximum glacial rebound. Those measurements can be combined with ice models to derive estimates of contemporary rates of vertical motion in Earth's crust—its rise and fall caused by the melting of the continental ice caps. (See the article by Bruce Douglas and Richard Peltier in PHYSICS TODAY, March 2002, page 35.)

Researchers studying earthquake mechanisms were also quick to see the potential of the new geodetic capabilities. They installed hundreds of continuously operating GPS stations in areas such as California and Japan to monitor crustal motion and deformation in the highly seismic regions along the edges of colliding tectonic plates. But each station determines the motion of only one surface point, and it is simply not practical to install enough stations to directly monitor crustal motion at scales much less than kilometers. To capture the finer details of surface motion in seismic zones, and to study many other phenomena that continually reshape Earth's surface, scientists need data points spaced less than a meter apart over areas as large as hundreds or even thousands of square kilometers.

For the geodetic community the challenge was clear: Develop a method to accurately determine the coordinates of hundreds of millions, or even billions, of surface points over hundreds of kilometers in a relatively short time, from hours to days. The answer: geodetic laser scanning (GLS).

Albert Einstein and geodesy

Albert Einstein died in 1955, two and a half years before the launch of *Sputnik 1*, but he left behind an invaluable legacy of scientific discoveries. If the theoretical framework of relativity had not first been developed, even the most advanced instruments and observing techniques would not have enabled the geodetic community to create a global geodetic reference frame. One of the most dramatic examples of the effects of relativity is the variation in the rates of the atomic clocks aboard the global positioning system (GPS) satellites. Clocks located in satellites run faster than identical clocks on Earth's surface because they orbit in a weaker gravitational field. But they don't run as fast as they might because their measure of time is slowed slightly by the satellite's orbital velocity. The relativistic effects are large enough that if they were not taken into account, navigational errors of kilometers would accumulate within hours from the difference in time kept by Earth and satellite clocks (see the article by Neil Ashby in PHYSICS TODAY, May 2002, page 41).

The observations collected by satellite and lunar laser ranging and by very long baseline interferometry must also be reduced to the coordinate values of surface points using correct and consistent relativistic formulations, or they yield disparate and confusing results. It took a number of years for experts to agree on common standards and confirm that all of the relativistic corrections were properly applied to the observations so that vectors between points separated by thousands of kilometers measured by laser ranging, baseline interferometry, and GPS should agree to the millimeter level, even if the observations were assumed to be error free.

Einstein also discovered the photoelectric effect, which enabled the later development of the avalanche photodiodes and photomultiplier tubes that are used as sensors in laser-ranging instruments. And the concepts of spontaneous and stimulated emission, set forth in Einstein's 1917 theory of radiation, presaged the development of the maser and laser some four decades later (see the article by Daniel Kleppner in PHYSICS TODAY, February 2005, page 30).

Geodetic laser scanning

The year 1957 will always be remembered for the Soviet Union's opening of the space age by launching the world's first artificial satellite. But it was also in 1957 that Gordon Gould, a graduate student working with I. I. Rabi at Columbia University, first described the principles of the laser. His description included the use of two parallel partially reflecting mirrors to form an optical cavity with a high quality factor Q for photons traveling perpendicular to the mirrors' faces. Gould immediately foresaw the use of the laser in ranging instruments because the highly monochromatic light could be tightly collimated. Among his other visionary contributions were Q-switching—the technique used to produce the short, intense laser pulses that are ideal for measuring the distance, or range, to a target—and single-pass (noncavity) amplifiers to increase the energy in each pulse.[3]

In 1958 Arthur Schawlow and Charles Townes, building on earlier work, published their now famous paper[4] that quantified the expected performance of multimode IR and optical masers. They also suggested, apparently based on independent thinking by Schawlow, that an optical cavity formed by two parallel flat mirrors might be used to suppress most oscillatory modes and select a single output mode.[5] Attempts to build a laser succeeded in 1960 (see the article by Richard Brewer, Aram Mooradian, and Boris Stoicheff in PHYSICS TODAY, January 2007, page 49). And after nearly five decades of refinement, hundreds of different types of lasers have been designed for applications as varied as welding, eye surgery, and GLS.

Conceptually, GLS is simple: An optical scanner sends out pulses of light from a laser over the surface to be mapped. The vector (range and direction) obtained from each reflected pulse is added to the instantaneous position and orientation of the GLS instrument to obtain the Cartesian coordinates of a point on the reflecting surface.

Observations from GLS can be collected from a fixed mount on Earth or from a moving vehicle. The instrumental details, including the energy per pulse, number of pulses per second, scanner design, and type of sensor, vary considerably for ground-, airborne-, and spacecraft-based systems. But the underlying principles are common to all of them. Generally, the size of the laser's footprint and the spacing between points shrink from tens of meters to decimeters to centimeters for space-based, airborne, and ground-based GLS units, respectively.[6] Data points spaced by less than 1 millimeter are achievable with some short-range instruments. And by combining observations from more than one type of GLS, researchers can create nested data sets to improve the data density over hot spots of particular interest within a larger area.[7]

We will limit our discussion here primarily to airborne GLS—also referred to as airborne laser swath mapping (ALSM) in some circles and as lidar in others—which is currently the method of choice to study most processes that affect Earth's surface. To be useful for such studies, the surface coordinates derived from ALSM observations must be accurate to 5–10 cm vertically (height) and 20–30 cm horizontally (latitude and longitude), with data points spaced only a few decimeters apart. Some applications, though, require accuracies and point spacings some 3–10 times better than that.[8]

Inside the instrument

The newest commercial ALSM instruments have more similarities than differences. Typically, the optical, electro-optical,

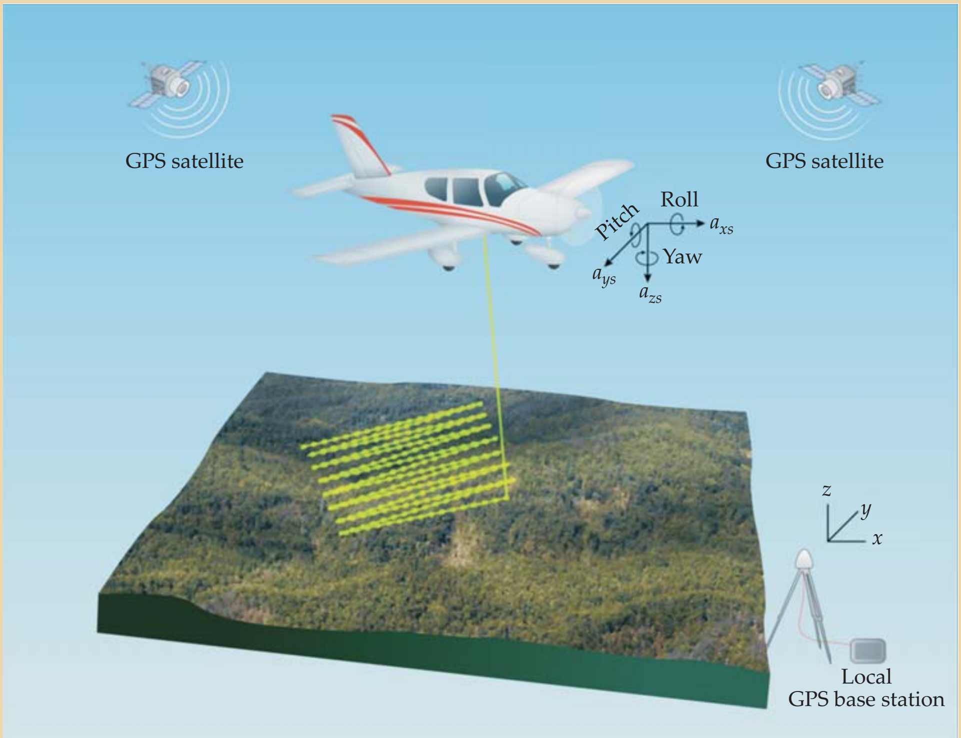

Figure 1. Illustration of a light aircraft collecting airborne laser swath mapping data over forested terrain. An onboard optical scanner distributes IR laser pulses (yellow) in a zigzag pattern. The round-trip time required for each pulse to travel to and from a reflecting point on the surface below is recorded. Global-positioning-system receivers on the aircraft and at a local ground station determine the instantaneous location of the aircraft. The orientation (roll, pitch, and yaw) and accelerations of the sensor head (a_{xs}, a_{ys}, a_{zs}), determined from an inertial measurement unit, are then used, along with the scanner mirror angle and measured range values, to calculate the coordinates of surface points.

and mechanical components that measure the vectors from the instrument to points on a reflecting surface below are all mounted in a rigid, compact, sealed unit referred to as the sensor head. The electronics, including power supplies, laser pump diodes, data storage unit, and GPS receiver, are mounted in a separate enclosure and are connected to the sensor head by fiber optics and electronics cables.

More specifically, the sensor head contains the laser, optical scanner, inertial measurement unit (IMU), photodetector, and such ancillary components as beam expanders, collecting optics, and optical and spatial filters—all of which must be kept finely aligned and clean. Today the laser is likely to be diode-pumped, passively Q-switched, neodymium-doped yttrium aluminum garnet and produce 50 000 to 150 000 pulses per second, with each pulse 5–10 ns in length and containing 50–100 μJ at a wavelength of 1.064 μm. The near-IR wavelength is strongly reflected by chlorophyll in vegetation but does not penetrate water. Some units therefore send light through frequency-doubling crystals to obtain a wavelength of 0.532 μm, which does penetrate water.

The laser pulses are passed through a beam expander to better collimate the light and improve the energy distribution across the beam. They are then routed to the optical scanner. The most popular scanner uses a single flat oscillating mirror that distributes the pulses back and forth along a straight line perpendicular to the flight of the aircraft. With the scanner pattern added to the forward motion of the aircraft, the pulses are distributed over the terrain in a zigzag pattern, as depicted in figure 1. The maximum scan angle and scan frequency can generally be set to discrete values over ranges from zero to perhaps ±30°, and from zero to 60 Hz, respectively.

A small fraction of the light from each pulse is directed to a photodetector to start the clock that measures the roundtrip travel time of the light to and from the reflecting surface. After passing through collection optics and spatial and spectral filters, the returning pulses are focused onto another photodetector, usually an avalanche photodiode or photomultiplier tube. Various methods are used to minimize systematic errors in the measured distance. Range walk, for instance, is caused by large variations in the strength of the return signals as the surface reflectivity varies or as only a fraction of a laser footprint is reflected. In forested areas, each laser pulse can spawn multiple returns, as portions of the footprint are reflected from different levels of the canopy. To capture that information, most systems record the peak signal intensities and ranges for as many as four returns for each pulse.

The direction of each transmitted pulse is determined by adding the scanner angle to the roll, pitch, and yaw, readings obtained from an IMU mounted in the sensor head to avoid the effects of the aircraft's flexure. The IMU contains three orthogonally mounted sets of solid-state accelerometers and fiber-optic or ring-laser gyroscopes that are read hundreds of times per second. A dual-frequency GPS receiver records carrier-signal phases typically between 1 and 10 times per second. The GPS and IMU observations are combined during the post-flight processing to obtain the final estimate of the sensor head's position and orientation at the time of each range measurement.

Early scientific results

NASA began experimenting with airborne laser altimetry systems to map terrain in the late 1970s.[9] By the late 1990s, commercial ALSM instruments became available that were largely used to produce general-purpose topographic maps. As ALSM data sets became known to the Earth sciences

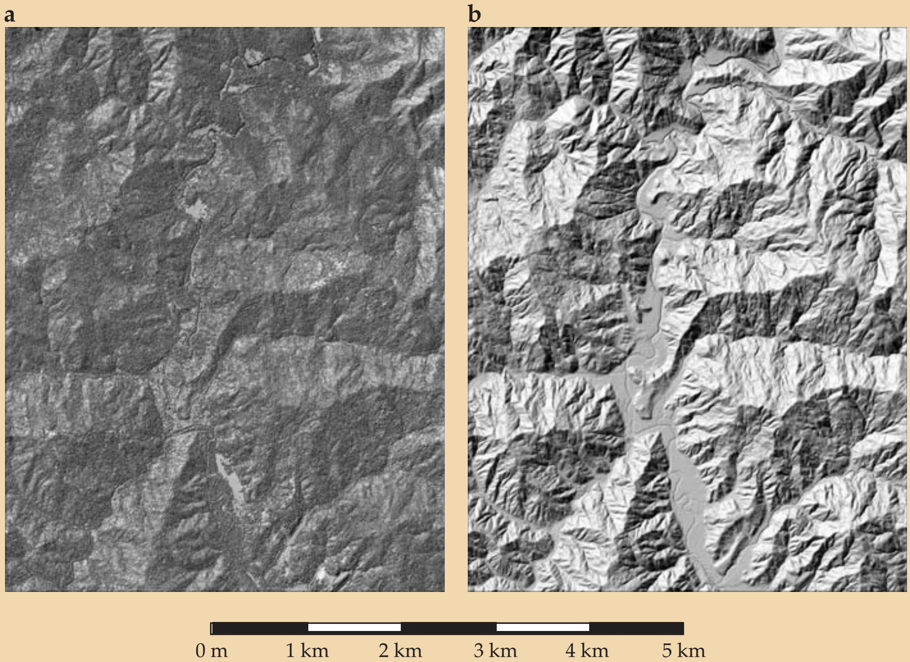

Figure 2. Shaded-relief images of the South Fork Eel River in northern California show the heavy coverage of redwood, fir, and oak forest **(a)**, and the "bare-Earth" surface **(b)** extracted from airborne laser swatch mapping observations. The filtering process used to extract bare-Earth data from the set of complex laser reflections from forested terrain reveals subtle landslide features that would otherwise be hidden.

community, interest in the technology grew. Collecting ALSM observations for scientific applications was expensive, however, and the early results were mixed—observations were often contaminated with range walk and errors in aircraft trajectory and scanning. And sometimes there were gaps in the data because return signals were too weak or the aircraft deviated too far from planned flight paths. Still, members of the Puget Sound Lidar Consortium managed to work around such imperfections and use ALSM to better delineate scarps, terraces, and other features associated with known faults; they even unexpectedly discovered previously unknown faults.[10] Another early application of ALSM documented and measured the surface fault rupture associated with California's Hector-mine earthquake of 1999.[11]

The purchase of ALSM systems, first by our group at the University of Florida and shortly thereafter by Roberto Gutierrez and colleagues at the University of Texas at Austin,[12] led to marked changes in the philosophy and practice of collecting ALSM observations for scientific applications. As both providers and users of the data, the academic groups focused on producing the highest resolution and most accurate observations possible. Procedures were developed to determine the sources and magnitudes of errors and to remove or minimize them. For example, adjacent swaths are overlapped and data from the same areas compared with each other and with ground measurements to detect such problems as offsets, slopes, and quasi-periodic deviations in the aircraft trajectories. Similar checks guide the processing, filtering, and analysis of observations.[8]

In April 2003 a workshop was held in Gainesville, Florida, to discuss the potential impact and applications of ALSM observations in the study of surface geophysics. The participants recommended that NSF establish a new center to provide academic investigators with research-quality ALSM observations through the traditional proposal and peer-review process. In August 2003 the National Center for Airborne Laser Mapping opened, operated jointly by the University of Florida and the University of California, Berkeley, and funded by NSF.

During the first four years of operation, NCALM collected ALSM observations for more than 50 research projects across the nation. The applications included measuring winter snowpack; delineating drainage patterns; analyzing landslides; mapping faults, scarps, and terraces; studying a local food web above a stream through a wooded area; and many others. Nearly half of the data collections were done explicitly (in response to proposals submitted directly to NCALM) to provide graduate students with observations for thesis research. To appreciate how ALSM is being used to learn about the evolution of Earth's surface, consider the following ongoing projects.

Case studies

Hundreds of millions of dollars are spent each year to study potential and actual landslides, primarily to assess and mitigate the threats posed to major engineering projects, such as the construction of dams, tunnels, and highways. But those local studies use geomechanical theories and models that may not apply beyond the scale of an individual hillslope. Material properties can vary widely from hillslope to hillslope, as can the factors—including the local surface relief, vegetation, climate, and seismic activity—that determine where and when landslides will occur.

For scientists trying to understand and predict changes in Earth's surface, the study of landslides is also important in undeveloped regions; landsliding is the dominant erosion in mountainous areas, for example. A single large landslide or the combined effects of numerous smaller ones can displace large amounts of material, change the shapes and steepness of hillslopes, and cause significant, potentially hazardous changes in local and regional drainage patterns. And because they affect the amount, grain size, and periodicity of material entering drainage-channel networks, landslides control the incision of streams and rivers into surrounding bedrock and ultimately the deposition of sediments along shorelines.

Josh Roering of the University of Oregon, along with colleagues there and at Idaho State University, the US Forest Service in Boise, and the University of California, Berkeley, are studying the 3D landslide pattern along a 52-km section on the South Fork Eel River in northern California (see figure 2) to understand the correlation between the location of deep-seated landslides and river incision.[13] The team is using a 1-meter-resolution digital elevation model—a grid of interpolated data points that locates the surface—based on ALSM observations collected by NCALM in 2005.

The South Fork Eel River project is an excellent example of research that could not have been done before ALSM observations were available. The area is covered by a mixture of redwood, fir, and oak forest that obscures surface details year-round, making photogrammetric and other mapping methods impractical, if not impossible. The surface could be imaged through the forest using airborne or satellite interferometric synthetic aperture radar, but as Matt Pritchard points out in his brief overview of InSAR (see PHYSICS TODAY, July 2006, page 68), the spatial resolution achieved would generally be no better than several meters. The ALSM system illuminates the terrain from nearly directly overhead with tens to hundreds of thousands of laser shots per second. That yields several shots per square meter. Some of those densely spaced shots pass through openings in the forest canopy and determine the coordinates of a significant number of ground points, even in heavily forested areas. The challenge is to identify the ground points, and many filters have been developed for just that purpose.

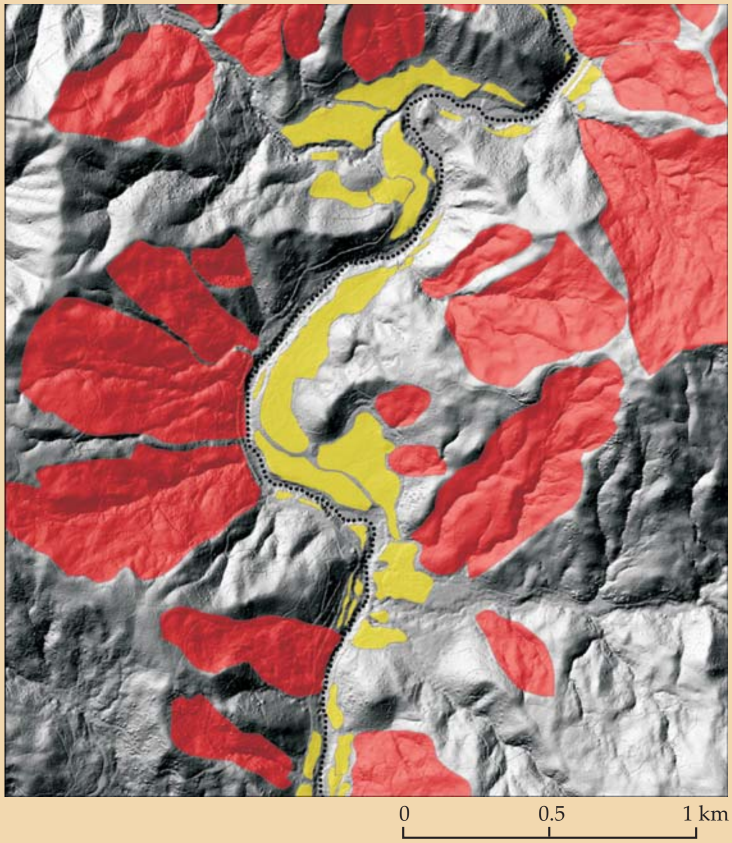

Figure 3. Enlarged bare-Earth shaded-relief image of a section of the South Fork Eel River (dotted line) displays several terraces (yellow) and landslides (red). The large landslides in the left center of the image are typical of many slides on the outer banks at turns in the river, where lateral incision is progressing rapidly. (Courtesy of Josh Roering.)

Generally, the filters used to process ALSM observations locate a sparse set of the lowest elevation points, search the surrounding points, and then use the elevation difference or surface slope to determine the likelihood that each point represents ground level. The expected change in the elevation between neighboring ground points is obviously different in flat terrain such as coastal plains than in steep mountainous terrain. The filter parameters must therefore be selected for each project area by a person familiar with the terrain. Filtering the data can easily consume as much time as collecting them, and the development of fast and accurate filters continues to be an important area of research.

For the team working on the South Fork Eel River project, the bare-Earth digital elevation model derived from observations has proven an efficient and effective tool to map subtle landslide features (see figure 3). The study shows that landslides occur more frequently in zones with vertical incision greater than 15 meters and along the outer edges of river bends where there is lateral incision.

The famous San Andreas Fault complex is an example of a very different type of surface feature that can be studied using ALSM observations. The San Andreas is one of the most studied faults in the world, but only bits and pieces of the terrain within a few hundred meters of the fault had ever been mapped precisely enough to capture the locations of surface features with decimeter-scale accuracy at specific dates in time. One of the first proposals submitted to NSF for NCALM came from Michael Bevis at the Ohio State University and Ken Hudnut at the US Geological Survey. They wanted ALSM observations covering 1-km-wide corridors centered along the San Jacinto Fault and the southern half of the San Andreas Fault.[14] The ALSM observations for this project, referred to as B4 because it captures the surface features along the faults "before" the next major earthquake, were collected in 2005.

In 2007 Unavco, a consortium of research institutions headquartered in Boulder, Colorado, contracted with NCALM to collect observations covering the northern San Andreas Fault and associated faults. Unavco is developing the Plate Boundary Observatory project to collect data on the interactions between the Pacific and North American plates, including 3D crustal deformations and motions associated with seismic events.[15]

Together, the B4 and PBO projects cover approximately 2000 km of fault lines, as shown in figure 4. The combined data sets contain about 25 billion surface points. The point spacing is generally small enough to create bare-Earth digital elevation models with 25- to 50-cm resolution, except in heavily forested areas north of San Francisco, where the number of laser shots reaching the ground limits the resolution to about 1 meter.

A special effort, led by the Ohio State team, was made to obtain the most accurate aircraft trajectories possible for the

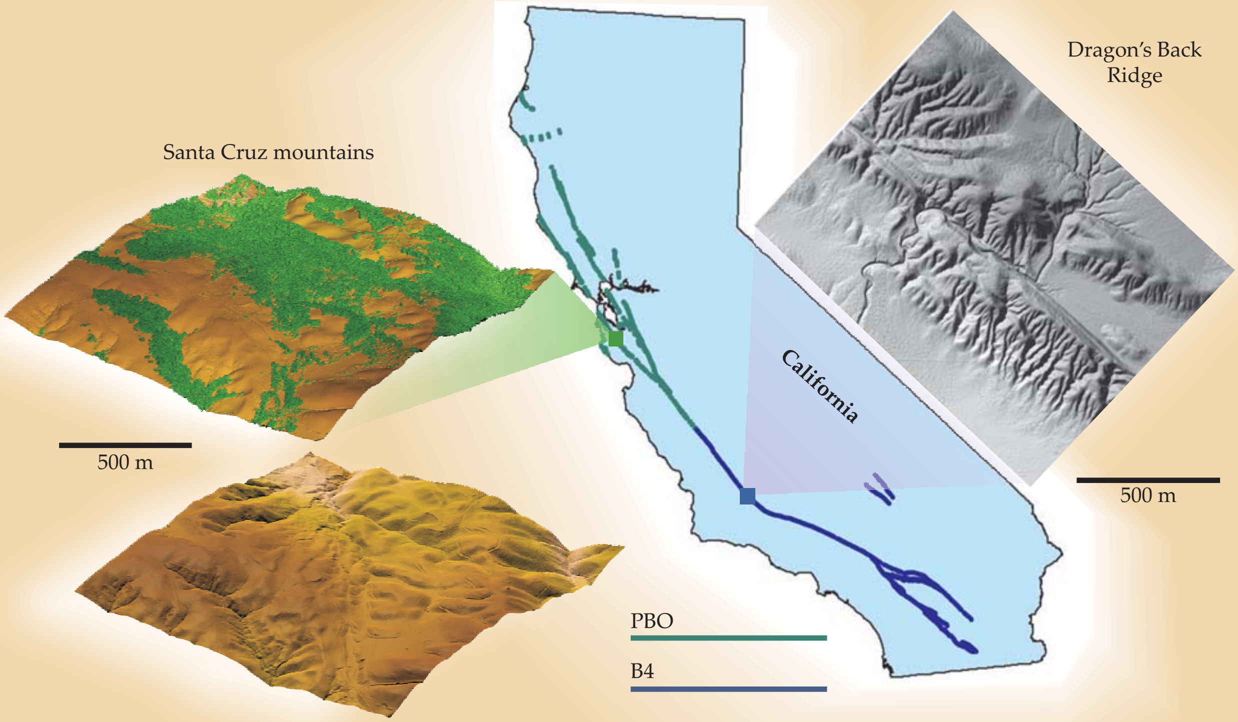

Figure 4. Nearly 2000 km of fault corridors in California were mapped during the B4 (blue) and Plate Boundary Observatory (PBO, green) projects. The false-color perspective images of an area where the San Andreas Fault passes through the Santa Cruz mountains, just south of San Francisco, show the terrain with and without vegetation. Dragon's Back ridge, shown in shaded relief, has only sparse desert vegetation. Similar images can be made anywhere along the fault lines using subsets of the 25 billion range measurements recorded for the combined projects.

B4 and PBO projects using improved kinematic GPS procedures.[14] The observations from both data collections are still being reduced, edited, filtered, and analyzed. Already, dozens of scientists and students are using observations of selected sections of the faults for talks and posters at meetings of the Southern California Earthquake Center, the American Geophysical Union, the Seismological Society of America, and Unavco. When the next large earthquake occurs, new ALSM observations will be collected to quantify surface changes with unprecedented resolution and accuracy.

Toward greater detail

Airborne laser swath mapping is no longer an exotic technique restricted to the domain of the most technologically advanced government agencies such as NASA or the Department of Defense. But ALSM instruments are still evolving rapidly, with a primary goal of increasing the information obtained from each laser pulse. One approach is to use a high-speed (typically 1 GHz) digitizer to capture the waveform of the returning signals rather than a single return time. Recording rapid fluctuations of the signal strength in a return pulse may make it possible to extract information such as surface roughness or the differences in coordinates of closely spaced points whose reflected signals overlap.[16] Another method being explored is to increase the fraction of the surface illuminated in a single pass—currently less than 20%—to contiguous coverage without sacrificing spatial resolution. That can be accomplished by increasing the laser's spot size and using a multichannel sensor in the receiver.[8,17] For Earth scientists to take full advantage of the better data, ever more efficient and reliable filters are needed to handle millions of points per second and remove clutter from the data while retaining critical features such as sharp ridge lines and the edges of stream banks.[18]

Optimistically, it is likely to take decades to create a scientific version of Google Earth, fully populated with research-quality GLS data. Meanwhile, the results of current projects such as B4 are finding their way into Google Earth, thus hastening their distribution and use. The competitive proposal and peer-review process is likely to ensure that the most scientifically important areas and objects are mapped first. And the scientific results should grow rapidly as academic researchers develop new and more powerful ways to extract information from GLS observations.

The collaboration between Unavco and NCALM was supported in part by NSF contracts EAR-0350028 and EAR-0518962.

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