Sharpening our view of earth processes with high resolution topography

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Borah Peak earthquake rupture (ILC)

Granite Dells AZ point cloud (NCALM student seed grant)
Main Application types

• Feature mapping at fine scale
• Landscape reconstruction (offsets)
• Surface process interactions with tectonic processes
• Differencing of repeat surveys
Major US community studies recognize the scientific value of high resolution topography.
Example scientific motivations

- How do geopatterns on the Earth’s surface arise and what do they tell us about processes?
- How do landscapes influence and record climate and tectonics?
- What are the transport laws that govern the evolution of the Earth’s surface?
- How does the landscape record evidence of prior earthquakes?
- Coupled hydrogeomorphic-ecosystem response to natural and anthropogenic change
- Landscape and ecosystem dynamics
- Volcano form and process
- Changes in volume of domes, edifice, flows over time
Global and regional topography/bathy (10s-100s m/pix)

Stereo-Photogrammetric Elevation Model (Polar Geospatial Center)

Getting the right coverage in time, space, and resolution for the question

Local to site scale topography (dm to m / pix)

A Airborne LiDAR

B Terrestrial LiDAR

C Structure from Motion

Presentation outline

• Introduction and measuring topography
• “Seeing” and working at the appropriate scale
• Applications
Science requirements

• Need topography data with sufficient spatial extent and resolution to capture phenomena of interest

• Need topography data with sufficient temporal repeat to capture changes of interest
430km of ground rupture, above 4000m

Yann Klinger, IPGP;
Length scales $>10^5 \text{m}$ and $<1 \text{ m}$

Wells and Coppersmith, 1994

\[ M = 5.08 + 1.16 \log(\text{SRL}) \]

\[ M = 6.93 + 0.82 \log(\text{AD}) \]
“Seeing” at the appropriate scale means measuring at the right scale.

Surface processes act to change elevation through erosion and deposition while tectonic processes depress or elevate the surface directly—their record is best characterized with the right fine scale.

Applies in particular to statistical self similarity.

http://en.wikipedia.org/wiki/How_Long_Is_the_Coast_of_Britain%3F_Statistical_Self-Similarity_and_Fractional_Dimension

How long is the coast of Britain?
Statistical self-similarity and fractional dimension
Science: 156, 1967, 636-638

B. B. Mandelbrot
Granite Dells AZ point cloud (Haddad, et al. 2012)

UNAVCO Terrestrial Laser Scanner

absolute measurement capability sufficient to characterize features and changes in challenging geometric arrangements
Landers, 1992 earthquake rupture repeated investigations on the decadal time scale: rupture zone sharp with secondary structures still evident.
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Northern San Andreas Fault, California
Northern San Andreas Fault, California
Combine aerial photographic and topographic analysis of Digital Elevation Models and their derivatives: Characterize landforms and measure drivers of process
Combine aerial photographic and topographic analysis of Digital Elevation Models and their derivatives: Increase detail and confidence in feature delineation (fault traces)
Area of proposed USFS road reroute near Potters Ponds. Landslides on tree-covered slope above proposed road are difficult to discern on 2011 aerial photograph (A), but are clearly evident on 1-meter contour map generated from high-resolution LiDAR (B).

Landslides too

https://geology.utah.gov/map-pub/survey-notes/lidar-tool-for-geologists/
Three views of the historically active City Creek landslides that lie between Capitol Boulevard and the City Creek Canyon floor. (A) In the 1990s aerial photograph, the landslides are obscured by brush on the canyon wall, whereas in the new (B) 0.5-meter 2013–14 LiDAR slopeshade map the landslides and their geomorphology are clearly visible. (C) The newly remapped landslides are shown in red on the 2009 aerial photograph.
Going beyond pretty pictures: the hillshades are very nice, but...
Landslide inventory maps produced with traditional methods — aerial photograph interpretation, topographic map analysis, and field inspection — are often subjective and incomplete. Availability of high-resolution topographic data invites new, automated landslide mapping procedures.

Morphologic dating of fault scarps using airborne laser swath mapping (ALSM) data

G. E. Hilley,¹ S. DeLong,² C. Prentice,² K. Blisniuk,³ and JR. Arrowsmith⁴

GRL, 2010
Main Application types

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Historical Rupture

3-D Trenching

Geomorphology

Fault-normal Trenching
Figure 2. Oblique view of Hector Mine earthquake surface rupture that experienced 3.5–4.5 m of right-lateral displacement. The rupture trace is pointed out by finger icons; the light and dark bands below and above the surface rupture are subparallel, topographic escarpments. Several offset ridges are now juxtaposed with gullies, forming "shutter" ridges. Raw laser hits are used to illuminate the ground surface in this point-cloud image. From tens to hundreds of hits per square meter were collected along the primary surface ruptures.

High-Resolution Topography along Surface Rupture of the 16 October 1999 Hector Mine, California, Earthquake ($M_w$ 7.1) from Airborne Laser Swath Mapping

by K. W. Hudnut, A. Borsa, C. Glennie, and J.-B. Minster

Figure 6. (a) Cross sections through the raw laser data on either side of the surface rupture, along the east and west profiles shown in Figure 4, are shown projected onto the fault plane (a ground-slope correction has already been removed). (b) Comparison of the topographic profiles on either side of the fault, after shifting the profiles shown in Figure 6a to remove our best estimate of the lateral and vertical offset along this 300-m section.
LiDAR Measurements
Validation of offset measurements from field and LiDAR data: San Jacinto Fault Clark section

Salisbury et al., 2012
Salisbury et al., 2012

Distance Along Fault (km)

Offset (m)

Offset (m)

UCERF 3
Main Application types

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Uplift rate

Material moves along fault though relatively stationary uplift zone:
How does landscape respond?
What will the landscape tell us about the geometry of the uplift?

Total rock uplift

-G. E. Hilley
Dragon’s Back Pressure Ridge, Carrizo Plain California

Arrowsmith, 1995; Hilley, 2001; Hilley and Arrowsmith, 2008
Uplift rate

Total rock uplift

Topographic metric: residual relief (ridge elevations – drainage elevation)

Hilley and Arrowsmith, 2008
Duvall, Kirby, and Burbank, 2004, JGR-ES

\[ \theta = \frac{m}{n} \]

\[ S = k_s A^{-\theta} \]

\( U = \text{Rock Uplift Rate} \)

Concavity (\( \theta \)) invariant with \( U \)

Steepness (\( k_s \)) varies with \( U \)

--K. X Whipple
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4/15計測 DSMデータによる赤色立体地図
益城町 津森小学校周辺

http://www.ajiko.co.jp/saigai/kumamoto_2016_04_2/gif_a.gif
Fault zone deformation and shallow slip from LiDAR differencing

Ed Nissen (Colorado School of Mines)
Tadashi Maruyama (AIST),
Ramon Arrowsmith, Sri Saripalli, Aravindhan Krishnan (Arizona State University)

Vertical displacements in the 2011 Mw 6.6 Iwaki earthquake with thanks to:

SC/EC an NSF + USGS center

E. Nissen
The 2008 Iwate-Miyagi earthquake (Mw 6.9), Japan

Pre-earthquake DEM (2m)
The 2008 Iwate-Miyagi earthquake (Mw 6.9), Japan

Post-earthquake DEM (1m)
14 June 2008 Iwate-Miyagi earthquake

2006-2008 vertical difference (m)

-E. Nissen
The 2008 Iwate-Miyagi earthquake (Mw 6.9), Japan

Dense 3-D displacements in an area InSAR cannot image

The displacement sense and magnitude agrees with (limited) field observations

-E. Nissen
Summary

- LiDAR provides dm to cm global accurate measure of the earth’s surface
- Meter scale (high resolution topography) is critical for measuring and understanding volcanic, structural, & geomorphic processes
- Main applications in volcano- and faulting-related investigations can be separated into fault zone mapping, reconstructing offsets, investigating geomorphic responses to active deformation, and differencing of repeat surveys

Looking ahead

- Lots more data and problems out there!
- 4 dimensions: directly measuring the displacements
- Processing and filtering enhancements: looking for the signal in all the data (e.g., Hilley, et al., 2010; Delong, et al., 2010)
- Bring these data and their depiction of the earth’s volcanic, geomorphic, and tectonic processes to geoscience education/public outreach