Fault zone deformation and shallow slip from LiDAR differencing

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with thanks to:

Vertical displacements in the 2011 Mw 6.6 Iwaki earthquake

SC/EC

an NSF + USGS center

Kokusai Kogyo Group
• Methodology
  
  LiDAR differencing with the ICP algorithm

• Case studies
  
  2008 Iwate-Miyagi thrust earthquake
  2011 Iwaki normal faulting earthquake

• Conclusions
  
  A comparison with other geodetic techniques used for high-resolution earthquake mapping
Pre-earthquake point cloud
Post-earthquake LiDAR survey
Post-earthquake point cloud
Pre-earthquake point cloud
The Challenges of LiDAR differencing

• Data are irregularly spaced (we can rasterize them, but we lose information doing so).

• There can be large mismatches in point density (typically the newer dataset is denser than the older one).

• There may also be large errors in absolute point positioning (for instance at the edges of scan lines, as we saw at El Mayor).
The Iterative Closest Point algorithm: a method for registering (aligning) two sets of points

Fig. 4. Iterative point-based registration of phantom face range data
The Iterative Closest Point algorithm: a method for registering (aligning) two sets of points

- the two point clouds are first split into square “windows”, 50 m in diameter
- ICP is run separately on each pair of windows. (An additional “fringe” of 5 m is included in the post-event window in order to capture the coseismic displacement)
- ICP finds the displacement and rotation that best aligns the pre-event and post-event point clouds.
- This alignment corresponds to the local coseismic displacement for that window.

*see Nissen et al. (2012), Geophys. Res. Lett., for details*
Pre-earthquake point cloud

Post-earthquake point cloud
Pre-earthquake point cloud

Post-earthquake point cloud

Find closest points
Find closest points

Transform point cloud

Iterate

\[ \phi = \begin{pmatrix} 1 & -\gamma & \beta & t_x \\ \gamma & 1 & -\alpha & t_y \\ -\beta & \alpha & 1 & t_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \]
Find closest points

Transform point cloud
Find closest points
Transform point cloud
Find closest points

Transform point cloud
Find closest points
Transform point cloud
Find closest points

Transform point cloud
Find closest points
Transform point cloud
Find closest points
Transform point cloud
Find closest points
Transform point cloud

earthquake displacement
Case studies

Map showing a region of Japan with the Okhotsk plate, Amuria plate, Japan Sea, and Philippine Sea plate. The map highlights Sendai, Tokyo, Fukue, and the Japan trench. The text notes that on 11 March 2011, an earthquake of magnitude $M_w = 9.0$ occurred. The map also indicates a rate of 78 mm yr$^{-1}$ and a distance of 200 km.
Case studies

*Interseismic GPS velocities, 1996-2000*  
*from Hashimoto et al. (2009)*
Case studies

Coseismic GPS velocities from March 11 2011 from Ozawa et al. (2011)

during earthquake elastic strain is released

between earthquakes elastic strain accumulates
Case studies

between earthquakes elastic strain accumulates
during earthquake elastic strain is released
The 2008 Iwate-Miyagi earthquake (Mw 6.9), Japan
The 2008 Iwate-Miyagi earthquake (Mw 6.9), Japan

Takada et al. (2009), Earth Planets Space

Japan Geographical Survey Institute
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)
The 2008 Iwate-Miyagi earthquake (Mw 6.9), Japan

DEM subtraction (height change, m)
The 2008 Iwate-Miyagi earthquake (Mw 6.9), Japan
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)
The 2008 Iwate-Miyagi earthquake (Mw 6.9), Japan
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
The 2011 Iwaki earthquake (Mw 6.7), Japan

The Iwaki earthquake produced two sub-parallel surface ruptures along the SW-dipping Yunotake and Idosawa faults. The Idosawa rupture is spanned by repeat LiDAR in an area where InSAR data are largely incoherent.

11-14 April 2011 Fukushima earthquakes

- 12.04.2011, Mw 5.9
- 11.04.2011b, Mw 5.1
- 11.04.2011a, Mw 5.5
- 10.04.2011
- 13.04.2011, Mw 5.3
- 14.04.2011, Mw 5.1
The 2011 Iwaki earthquake (Mw 6.7), Japan

ALOS interferogram (ascending track)

The Iwaki earthquake produced two sub-parallel surface ruptures along the SW-dipping Yunotake and Idosawa faults. The Idosawa rupture is spanned by repeat LiDAR in an area where InSAR data are largely incoherent.

InSAR model from Fukushima et al. (2013), BSSA
The 2011 Iwaki earthquake (Mw 6.7), Japan

The Iwaki earthquake produced two sub-parallel surface ruptures along the SW-dipping Yunotake and Idosawa faults. The Idosawa rupture is spanned by repeat LiDAR in an area where InSAR data are largely incoherent.
Post-event data:

1 m Bare Earth DEM, Aero Asahi Corp.

The 2011 Iwaki earthquake (Mw 6.7), Japan

ALOS interferogram (ascending track)

The Iwaki earthquake produced two sub-parallel surface ruptures along the SW-dipping Yunotake and Idosawa faults. The Idosawa rupture is spanned by repeat LiDAR in an area where InSAR data are largely incoherent.
Field measurements by Tadashi Maruyama

In many places, only a small proportion of the slip makes it to the surface. Indicative of slip at ~200-600 m depth.
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This is a common phenomenon for thrust faults that rupture upwards through unconsolidated sediment.
In many places, only a small proportion of the slip makes it to the surface. This is a common phenomenon for thrust faults that rupture upwards through unconsolidated sediment.
y-axis rotations in windows which contain surface faulting
these rotations are present even in areas with low scarp heights, suggesting fault slip is lost in the very near surface (less than 50 m), perhaps to bedding plane slip or warping.
ICP LiDAR differencing: strengths and weaknesses

**Synthetic Aperture Radar Interferometry (InSAR)**

InSAR measures deformation in the satellite line of sight. **Pixel matching** usually only measures horizontal displacements.

*ICP can resolve displacements and rotations in 3-D.*

**Pixel matching** can be applied to LiDAR imagery, but requires gridding (rasterization) of the point clouds, resulting in information loss.

*ICP works on the original point clouds.*

InSAR is good at measuring **far-field deformation** but often break down close to surface faulting

*LiDAR is typically focused along active faults, so ICP will be useful for obtaining near-field deformation*