Measuring Fault Slip - Why and How?

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USGS
science for a changing world

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Measuring fault slip - why and how?

- Why?
  - What can details of slip variation tell us about earthquake source physics? (You may suggest or prefer other reasons …)
  - Variance and other statistical properties of slip distributions - physical relation to fundamental quantities (such as maximum slip, seismic and aseismic energy, stress drop, D_c)
  - Large slip variations, if real, could constrain rupture process models and explain high-frequency seismic energy radiation

- How?

  My bias here is that great earthquakes do differ from small ones
  - Attempt to observe slip pulses or other crack propagation phenomena
    - Real-time 'GPS Fault Slip Sensor' - to complement inertial sensors
  - Variation in slip along-strike and with depth - quantify the errors
    - Airborne Laser Swath Mapping - to observe near-fault deformation

  To observe these quantities, need to devise & develop new methods

Earthquake Scaling

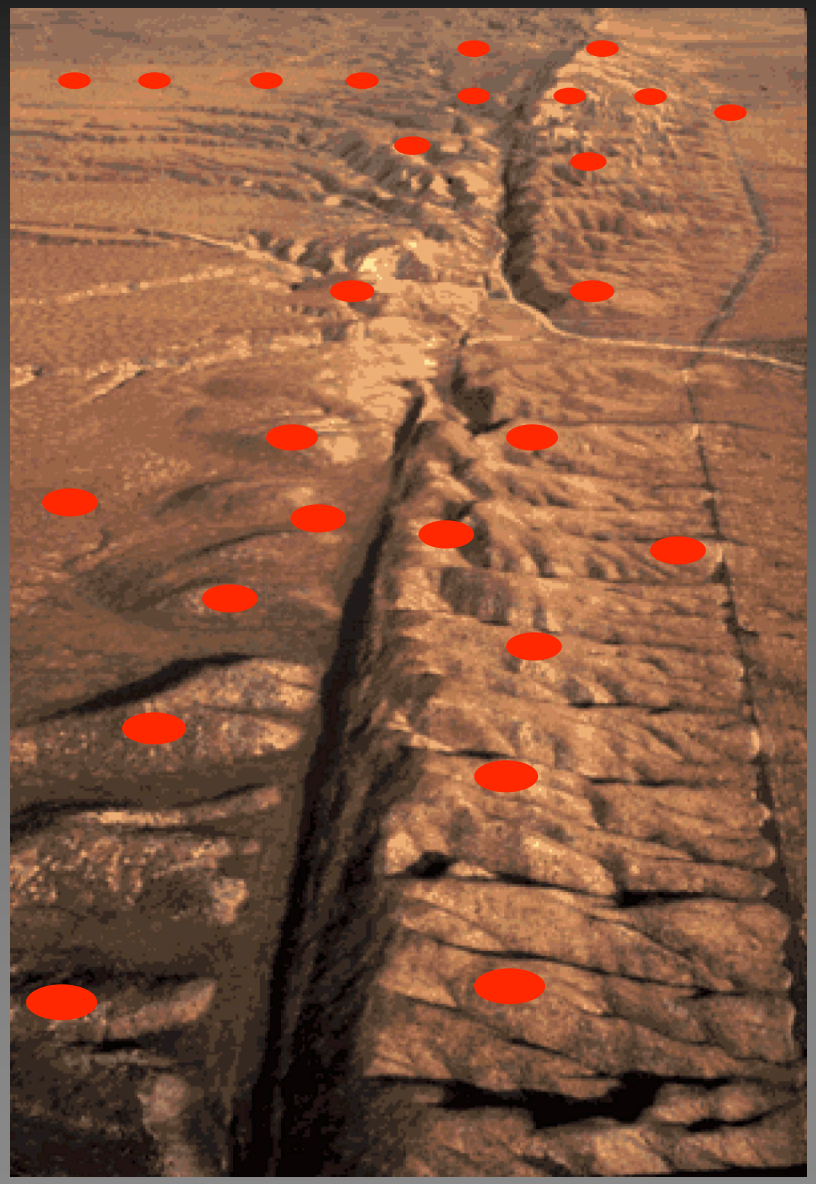
- Are stress drops constant?
  - e.g., Brune (1970, '71)
- What about L-model scaling for large events?
  - e.g., Scholz (1982, 1994) and Romanowicz (1992)
- Bi-linear scaling model
  - Hanks and Bakun (2002)
- Great continental strike-slip earthquakes are of special interest - their slip (and stress drops) may become larger with longer ruptures (up to 10 x W):
  - 1857 and 1906 SAF
  - 1905 Bulnay and 1957 Gobi-Altay
  - 1920 Haiyun
  - 1939 Erzincan
  - Kunlun & Denali

Some Questions …

- How may friction drop co-seismically?
  - Opening? What mode of crack propagation?
  - Key observation - accurate 3D particle motions close to the fault --- inertial sensors are unable to discriminate between tilt & acceleration; GPS fault slip sensors can help to observe this for future large events
- What impedes and stops rupture?
  - Roughness and variation in slip - heterogeneity of stress, as well as fault interaction and dynamic effects
  - Key observation - objective systematic measurements of slip along-strike at surface for bedrock-on-bedrock fault with large amount of slip; ALSM for Hector Mine

San Andreas fault

- 35 mm/yr slip rate;
  - >70% of plate motion
  - 1685, 1812, 1857 eq's
- Big Bend compression
  - 1971 Sylmar (M 6.7)
  - 1994 Northridge (M 6.7)
- SoCal is now heavily 'wired' - need more?
- 150+ BB CISN stations
- 250+ SCIGN stations
- Catalog; SCEC CMM3
- 'Natural laboratory'
- Likely source of most future 'Big Ones'



Before moving on …

- State-of-the-art GPS networks and technology development have become vital infrastructure for earthquake research and response:
  - Static deformation field data; source models & rapid tilt and strain mapping
  - Monitoring of large engineered structures (e.g., dams, buildings)
  - Understanding earthquake source physics - e.g., slip pulses (near-field accurate particle motions and static displacement field mapping)
- New enhancements to telemetry support wider range of applications
  - Real-time GPS sub-networks of SCIGN
    - Precise RTK positioning for surveying, AVL and GIS applications
  - InSAR, Airborne Laser Swath Mapping (ALSM) and digital photography
    - SCIGN provides ground control for airborne imaging and surveys
    - Mapping and imaging for rapid assessment of damage to buildings, lifeline infrastructure, etc. (The National Map; Homeland Security)
- Collaboration between Scientific, Surveying, GIS, Engineering and Transportation communities has mutual benefits - this is expected to help with funding our projects in the future

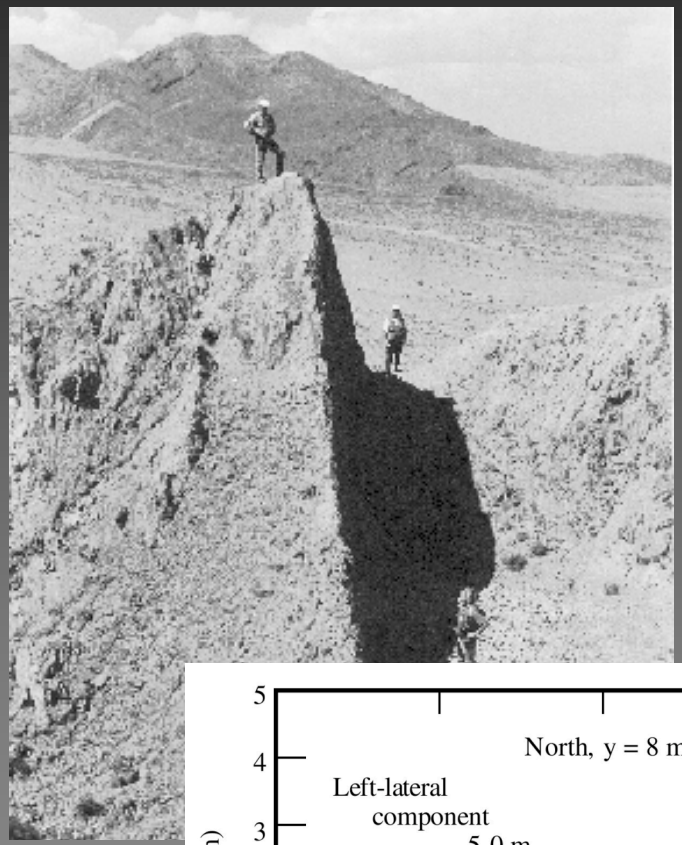
How to measure slip?

Finite-fault source models:

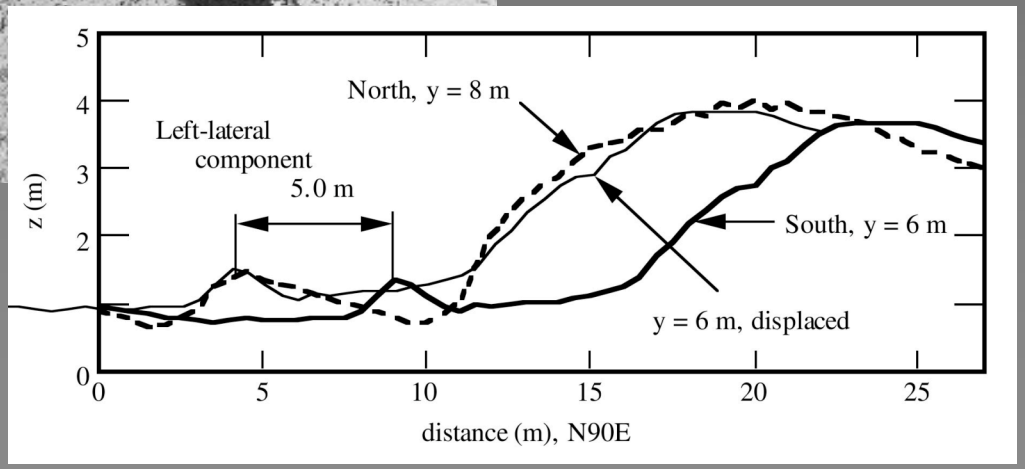
- Seismological data
  - Teleseismic and regional waveforms
  - Strong motion waveforms
- Geological data
  - Field geology - surface slip observations - relative offset data
  - Near-field deformation from imagery, e.g., air photo, SPOT
- Geodetic data
  - GPS static displacements (constrains final slip - postseismic?)
  - Strong motion waveforms (e.g., Ji et al., GRL - Sept. 2004)
  - InSAR (de-correlates near fault in existing C-band data)
  - Repeat-pass LiDAR/ALSM and direct-georeferenced imagery

New methods and data integration

- Precise topographic mapping of surface ruptures and active fault scarps
  - slip models for prehistoric events
  - rapid assessment of surface slip and damage patterns after large events
  - Requires precise integration of GPS & INS for flight navigation



1957 Gobi-Altai earthquake surface rupture



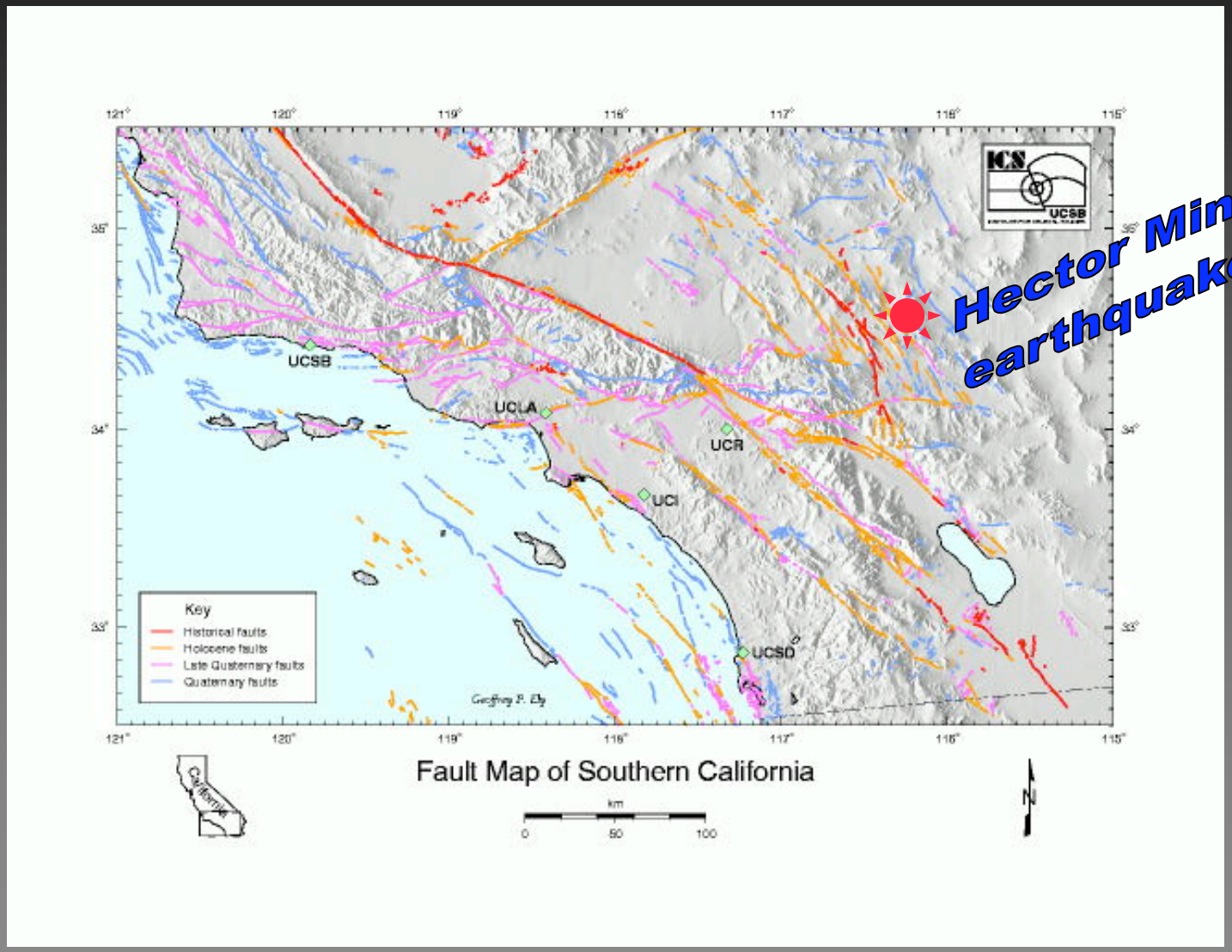
High resolution topography along surface rupture of the October 16, 1999 Hector Mine, California Earthquake (M_w7.1) from Airborne Laser Swath Mapping

Hudnut, K. W. (USGS), A. Borsa (UCSD),
C. Glennie (Aerotec, LLC) and J.-B. Minster (UCSD)

Bulletin of the Seismological Society of America
Special Issue on the Hector Mine earthquake (2002)

http://pasadena.wr.usgs.gov/office/hudnut/docs/

Active Faults in Southern California

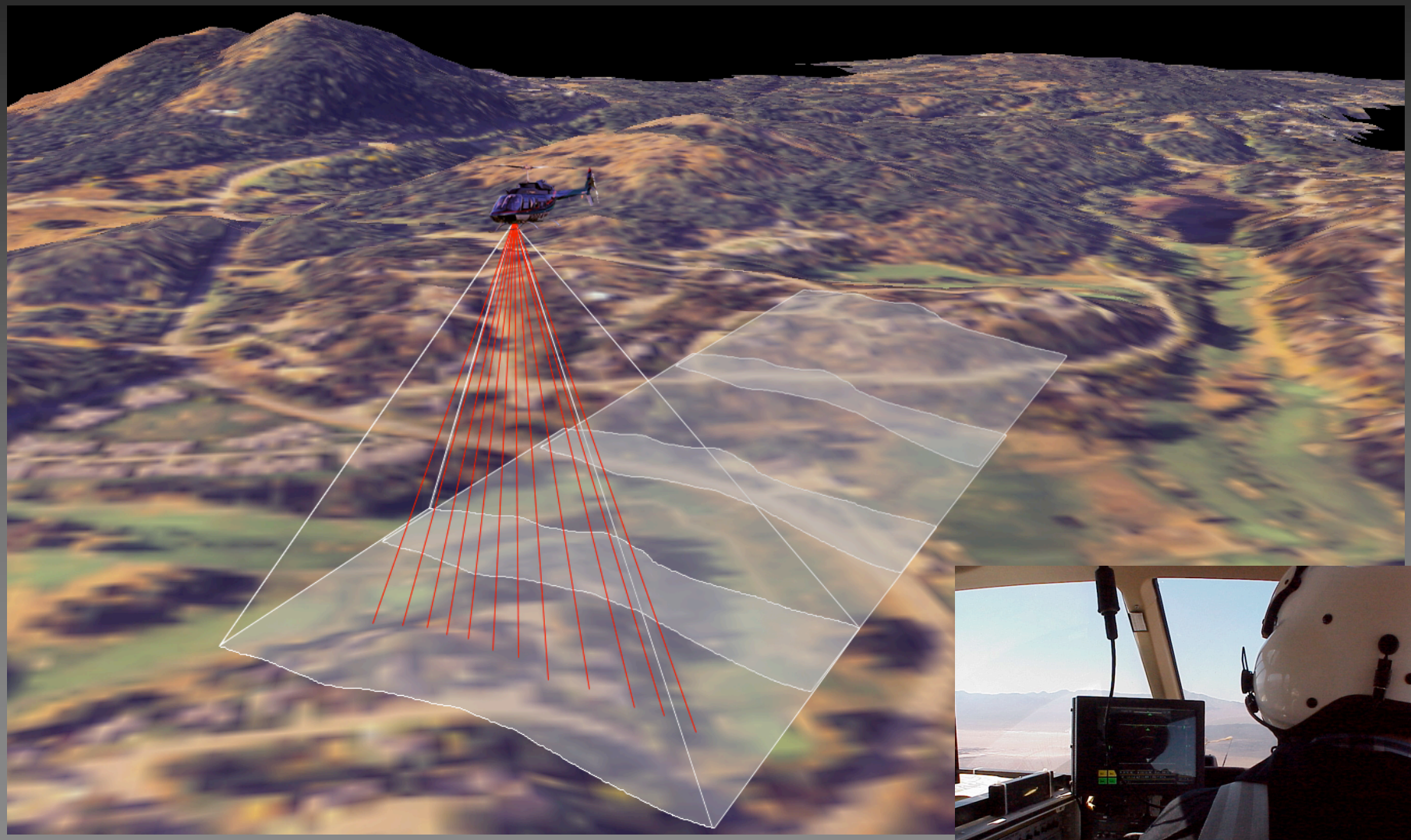


Surface Rupture

- Previously mapped, but un-named
- Lavic Lake fault in recognition of breaks through dry lake bed
- Up to 5.7 meters of right-lateral motion
- 48 km overall length of surface rupture
- Only ruptured once prior through ~50 ka alluvium

from *Treiman et al.* (BSSA 2002)

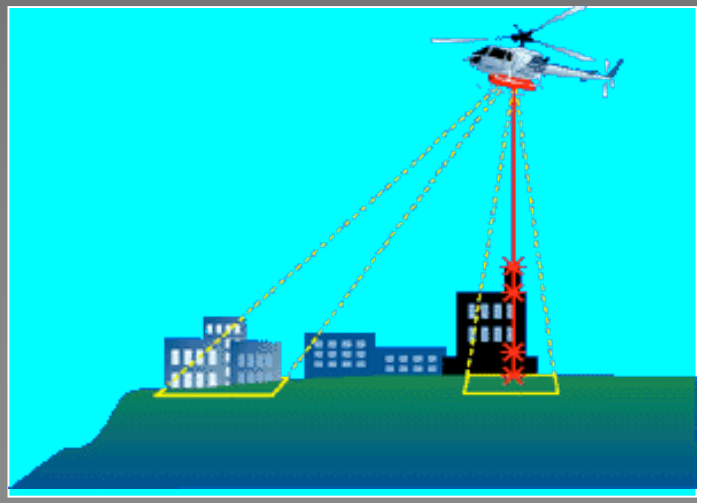
Airborne laser swath mapping (LiDAR)



ALSM (Scanning LIDAR imaging)

- Slow, precise helicopter flight line data acquisition at 200-300 m AGL.
- 6888 pps near infra-red (1064 nm) laser.
- Scan Width: +/- 20 degrees. Nominally, 180 meters full-width.
- 200 pulses across swath, ~ 80cm spacing.

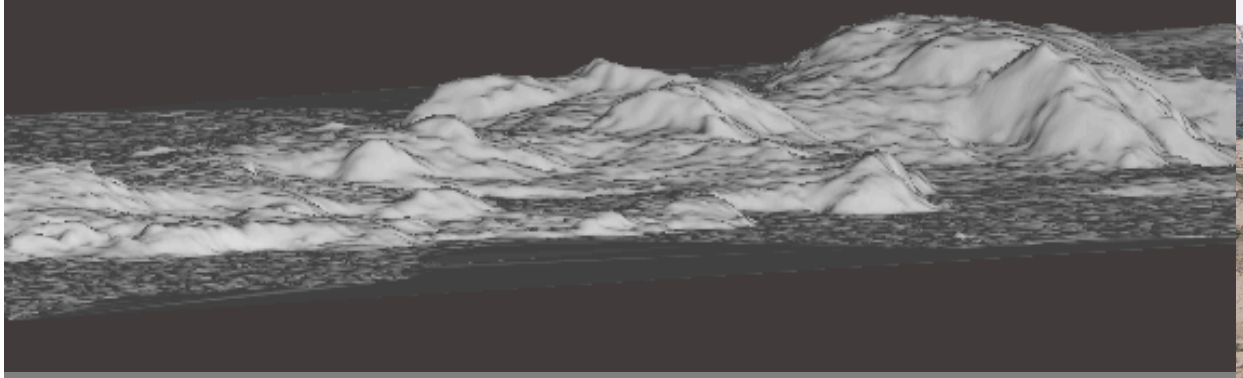
- Footprint Diameter: Nominally 40cm.
- Half-meter posting, 15cm horizontal one-sigma absolute accuracy specified.
- Integrated GPS & INS navigation and attitude determination.
- Pitch Mirror Correction: maximum +3.5/-6.5 degrees (+ forward bias).



New methods and data integration

- precise topographic mapping of surface ruptures and active fault scarps

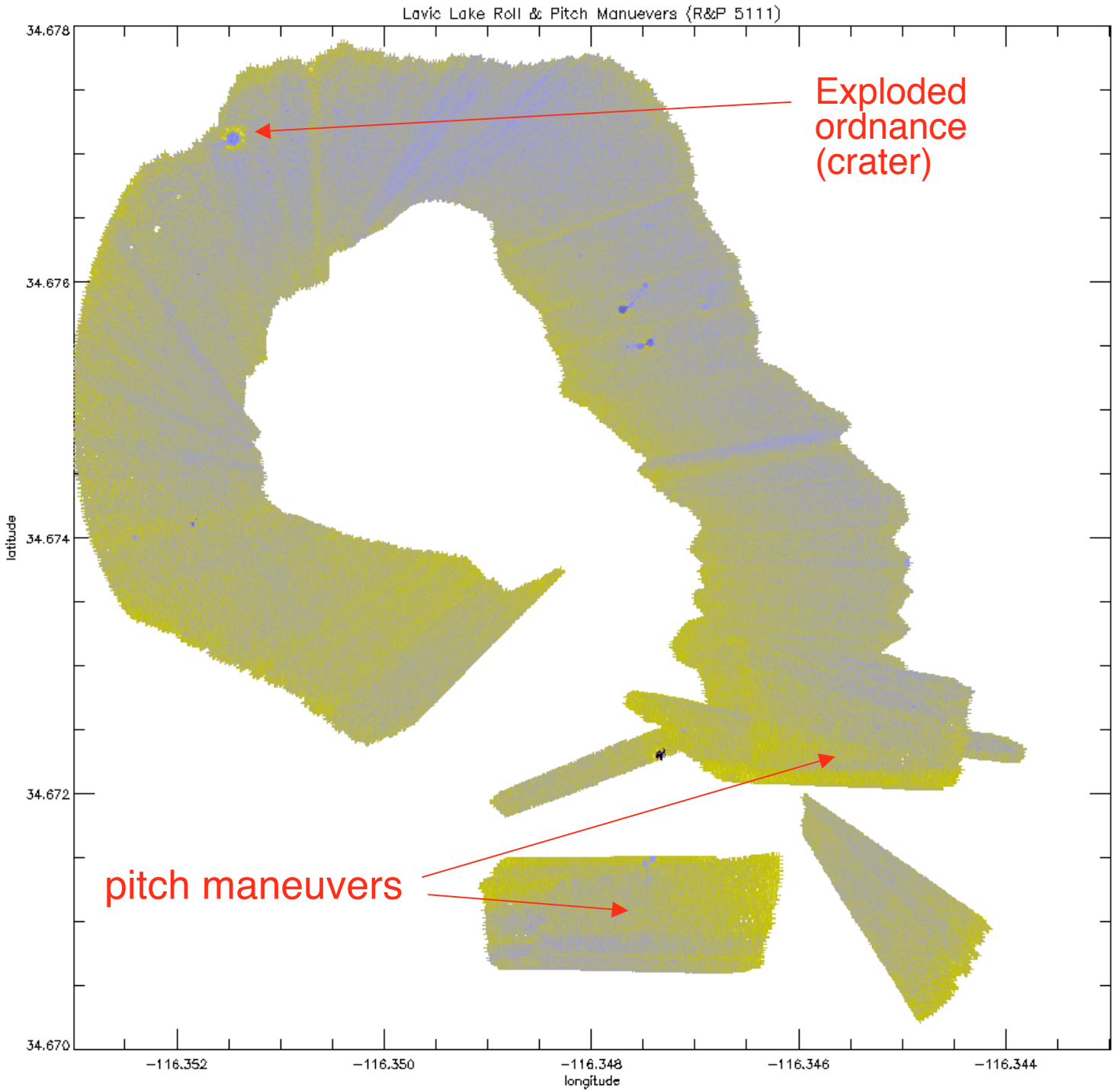
Airborne platform navigation must be highly precise and requires high-rate GPS data



- representation of actual fault ruptures recorded and preserved in unprecedented detail for use by future earthquake researchers

To assess geodetic capability of repeat-pass ALSM: calibration requirements

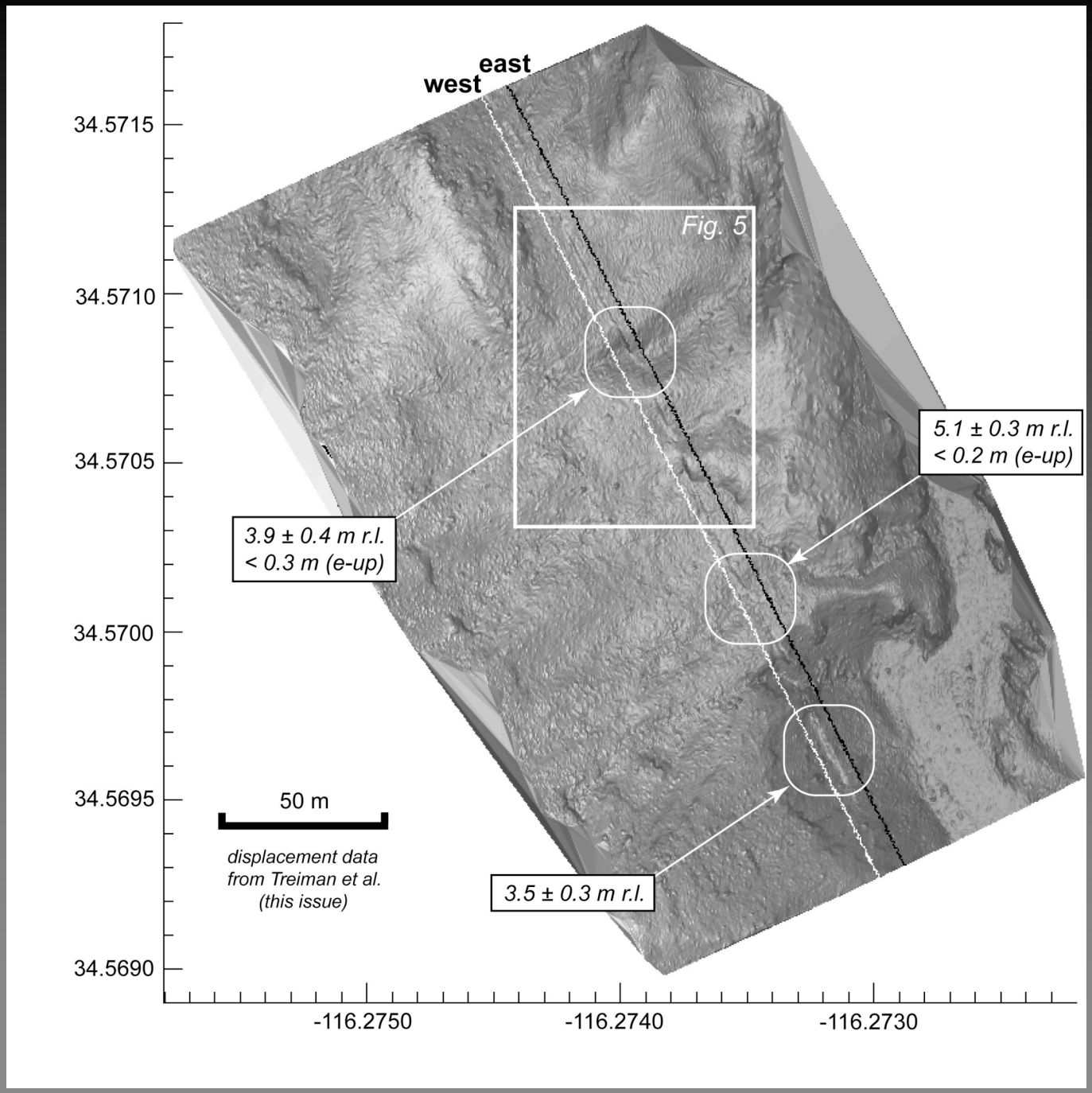
- Geometry: mount angles, scan offsets, GPS-Laser vector, GPS antenna phase center
- Delays: electronic, optical, atmospheric
- Reference point on laser platform
- Timing of various components: e.g. INS vs. GPS vs. mirror attitude sensors
- Stabilization platforms (delays, accuracy)
- Detectors (thresholds, amplitude-range “walk”)



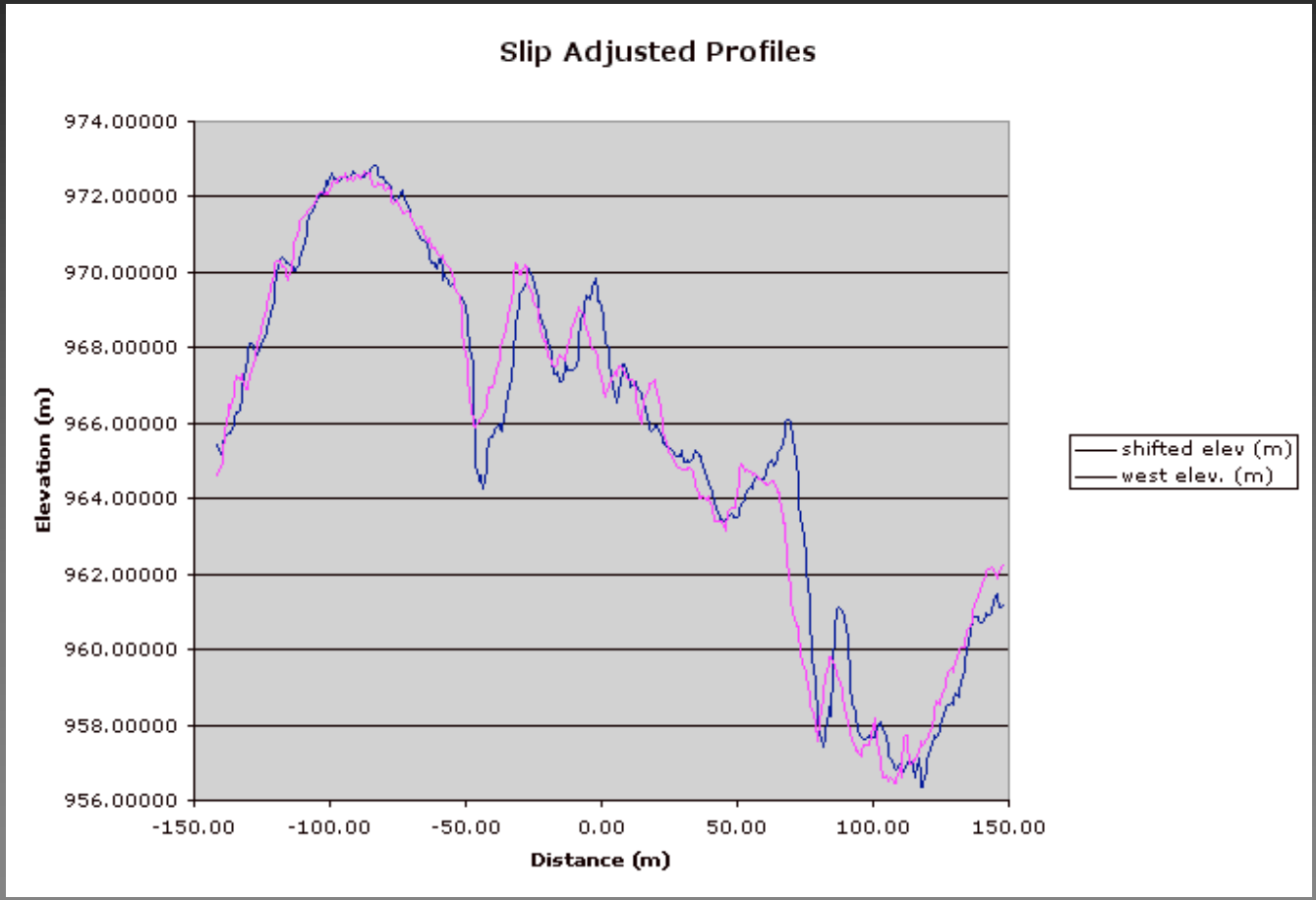
Lavic Lake Roll & Pitch Maneuvers

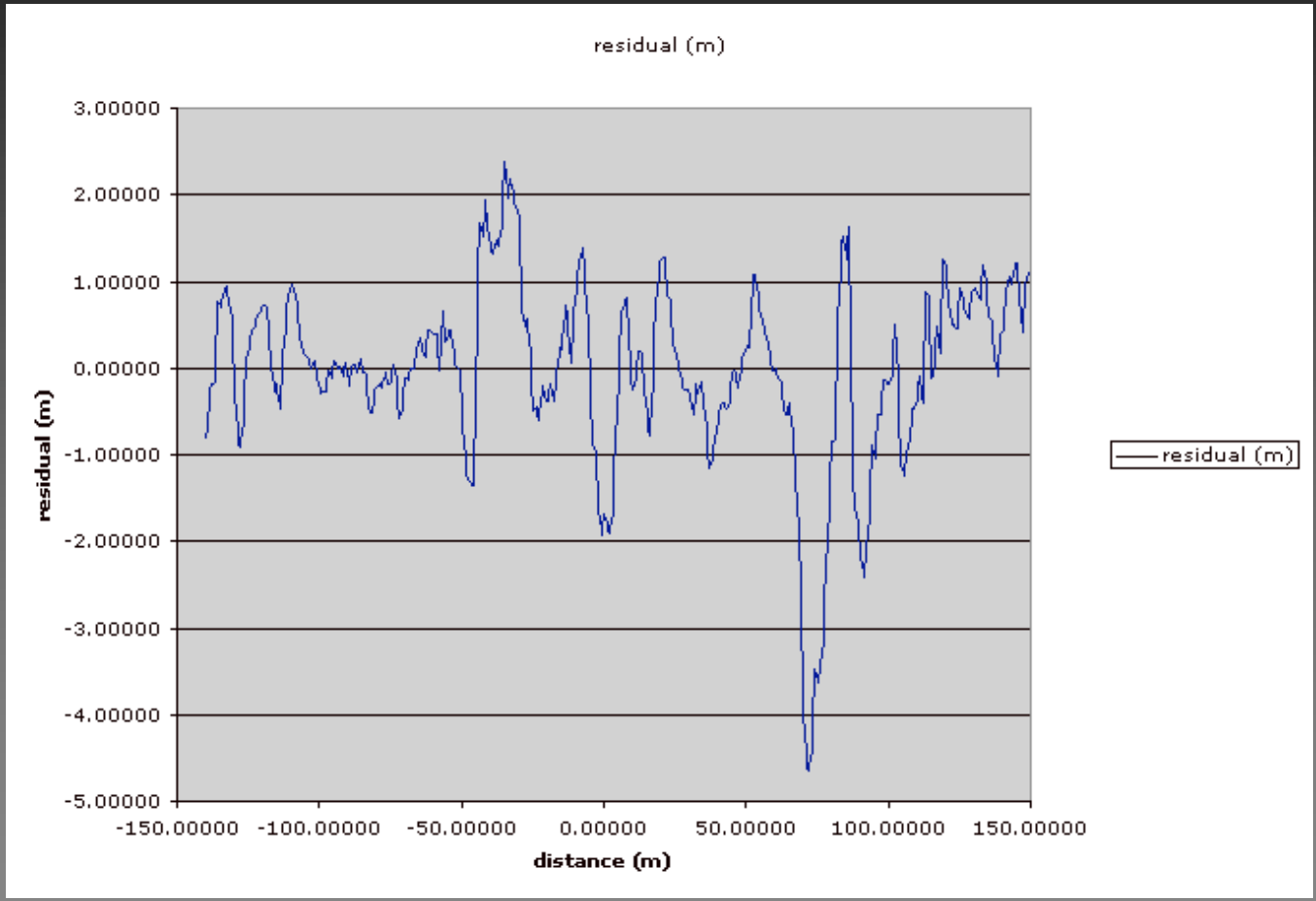
Maximum slip section of the 1999 Hector Mine eq. surface rupture

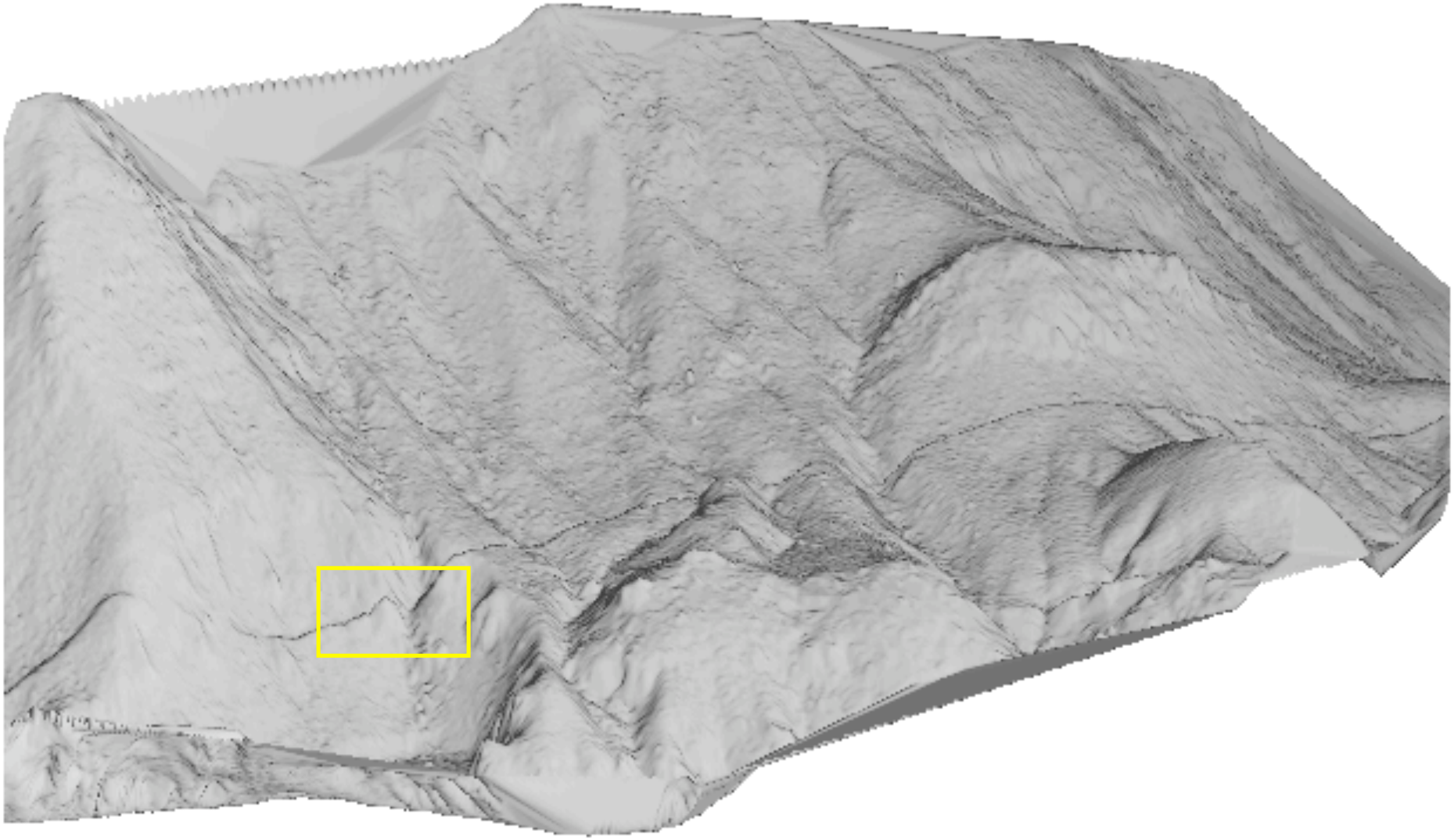
Photo by Keith Stark (SCIGN)



Estimating slip on 'max. slip' segment of the fault


Slip Adjusted Profiles
974.00000
972.00000
970.00000
968.00000
966.00000
964.00000
962.00000
960.00000
958.00000
956.00000
Elevation (m)
-150.00
-100.00
-50.00
0.00
50.00
100.00
150.00
Distance (m)
shifted elev (m)
west elev. (m)


residual (m)
3.00000
2.00000
1.00000
0.00000
-1.00000
-2.00000
-3.00000
-4.00000
-5.00000
residual (m)
-150.00000
-100.00000
-50.00000
0.00000
50.00000
100.00000
150.00000
distance (m)
residual (m)



Geological quantification and questions

- Tectonic interpretation of strain release in great earthquakes from their surface rupture
  - Basic documentation of surface rupture
    - e.g., Kurushin et al. (1997) study of 1957 Gobi-Altay eq.
- How does slip vary along-strike?
  - e.g., need to assess variance and error in slip rate estimates from paleoseismic methods
    - e.g., Barka et al. (2002) and Rockwell et al. (2002) extensive studies of 1999 eq.'s in Turkey and similar studies of Hector Mine earthquake (BSSA 2002)
  - is high-frequency energy radiated from fault?
- Does slip vary from one earthquake to the next?
  - can detailed topographic mapping of geomorphic features along the fault be modeled by repeats of exactly the same slip in successive earthquakes, or must slip vary in order to explain the topography?
  - slip variation models for earthquake recurrence strongly influence seismic hazard analyses – assumptions made in these analyses necessarily simplify faulting processes, with societal repurcussions

Airborne Camera Systems & GPS-aided Inertial Technology for Direct Geopositioning along the San Andreas Fault System

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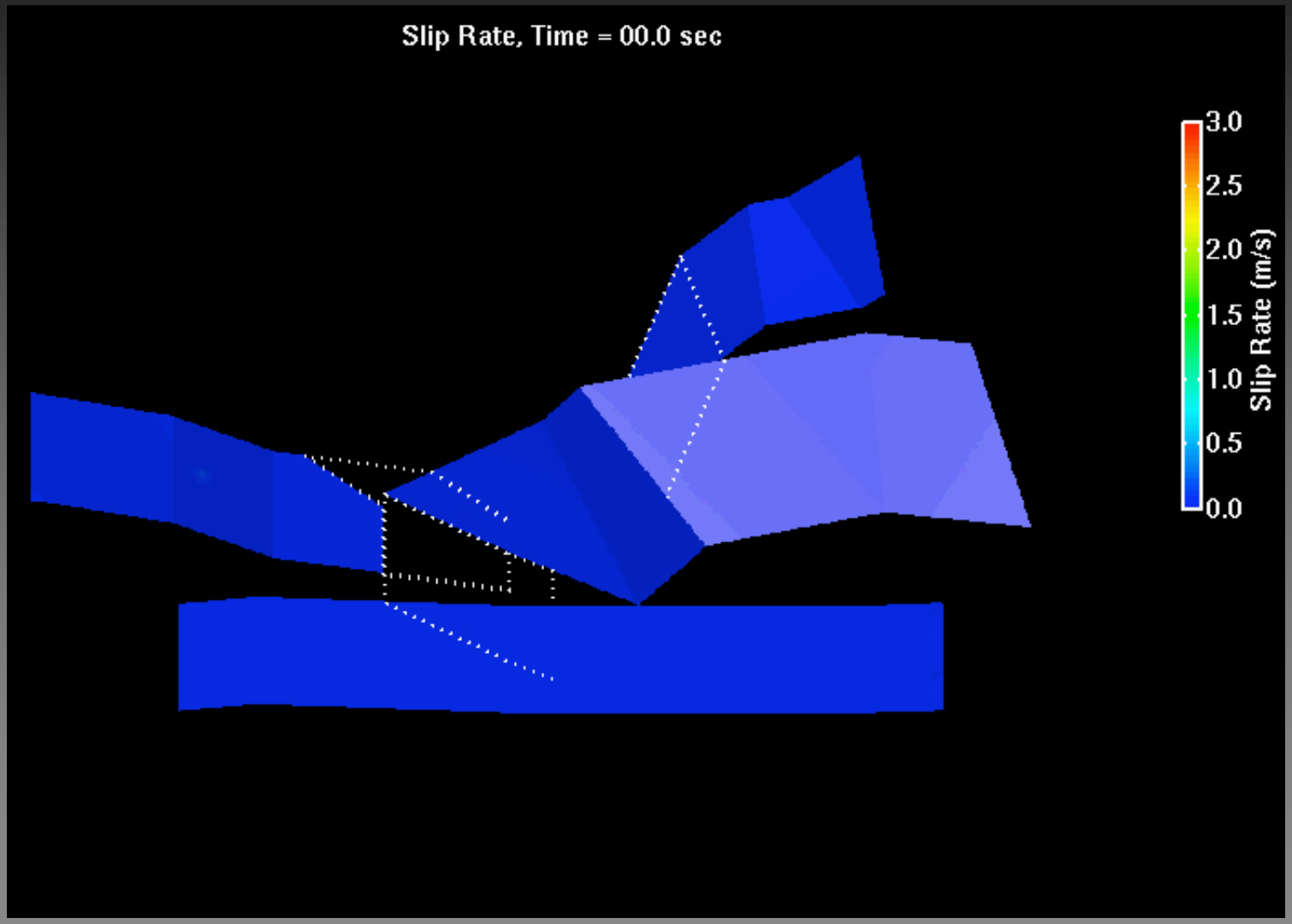
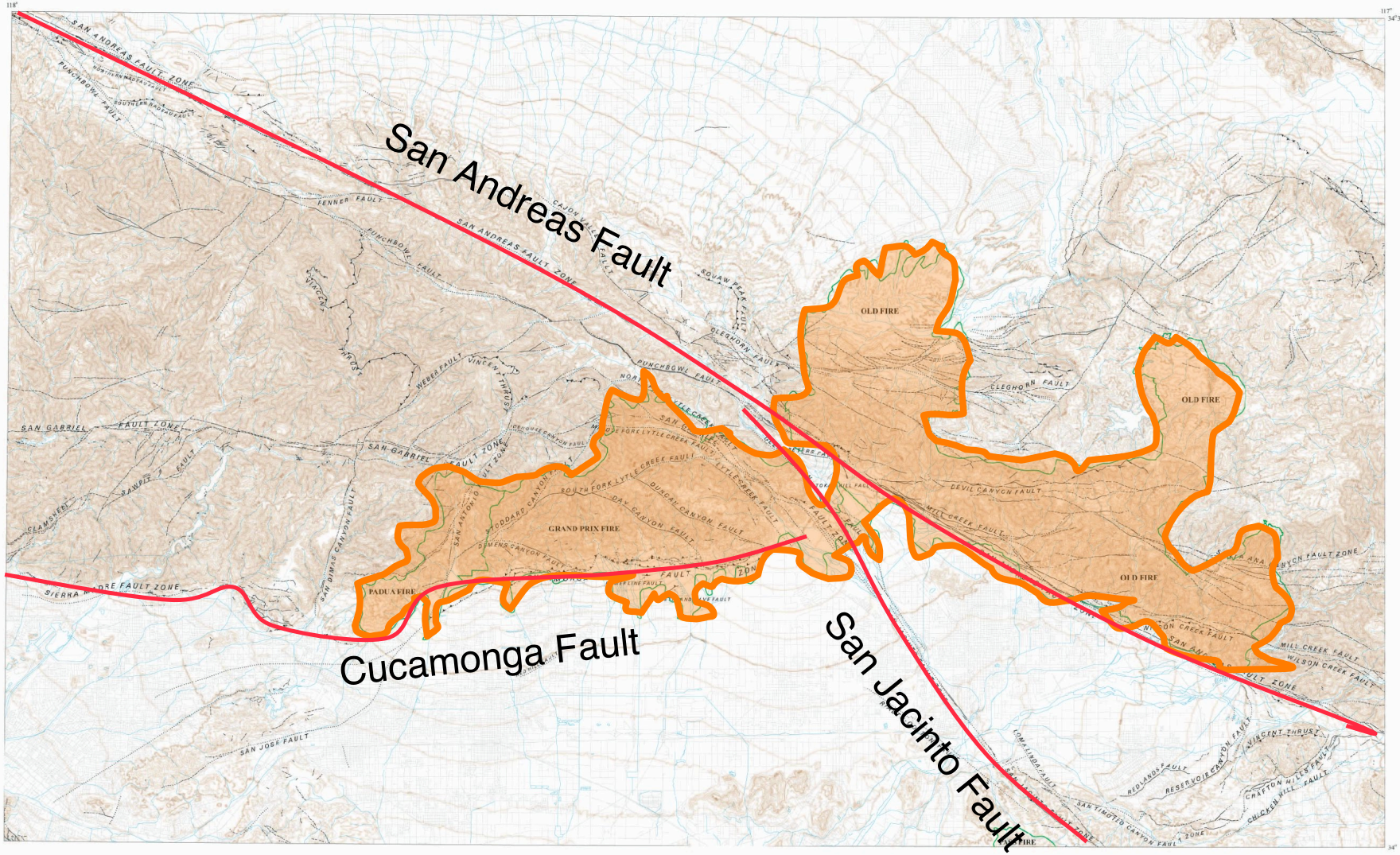
U.S. Geological Survey

U.S. Department of the Interior
U.S. Geological Survey

SJF event with jumping



Brad Aagaard, USGS - from *Anderson et al.*, Science (2003)



2003 Fire Perimeters within the San Bernardino 30' x 60' quadrangle, southern California

Compiled by the Southern California Areal Mapping Project (SCAMP)
Riverside, California

SCALE 1:100,000

CONTOUR INTERVAL 40 METERS

Wildfire Perimeters provided by USFS

Courtesy of Rachel Alvarez, SCAMP

Courtesy of Ray Weldon

Background: *Digital Sensor System*

DSS Camera	Contax
Lens	Zeiss
Focal Length	55.0000 mm
Frame/format Size	36.83 mm x 36.70 mm
Solid State CCD, full frame	4,092 x 4,077 pixels
Pixels per frame	16,683,084
Pixel spacing	9 microns (center to center)
Pixel size	9 x 9 microns
GSD Optimum	10 cm (4 in)

POS-AV Platform

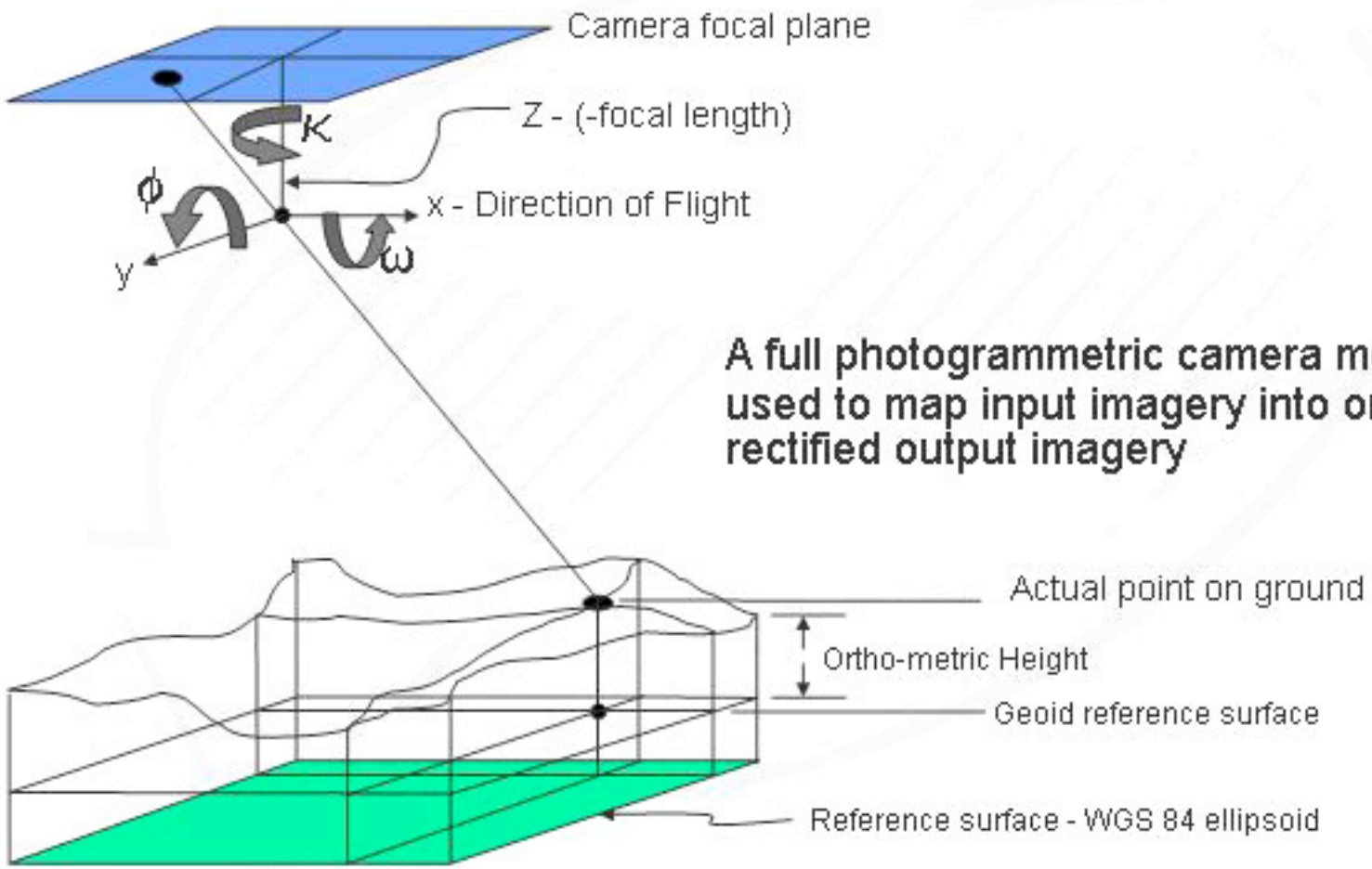
IMU

Courtesy of Applanix

Emerge integrated GPS/inertial system and Applanix POS-AV Platform

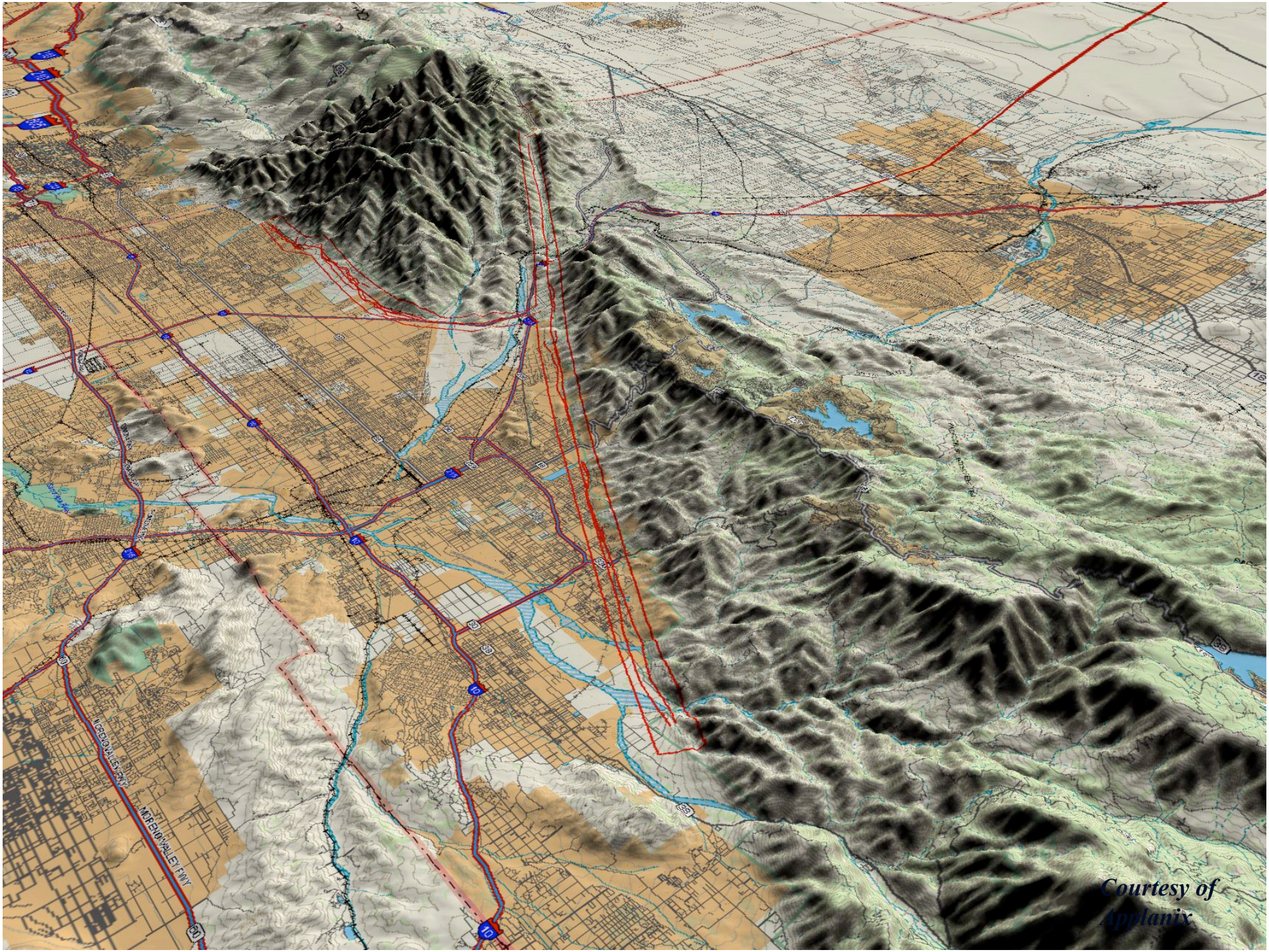
Close-up view of Emerge Integrated GPS/inertial system
Camera port hole under the aircraft

Spatial Pixel Relationships

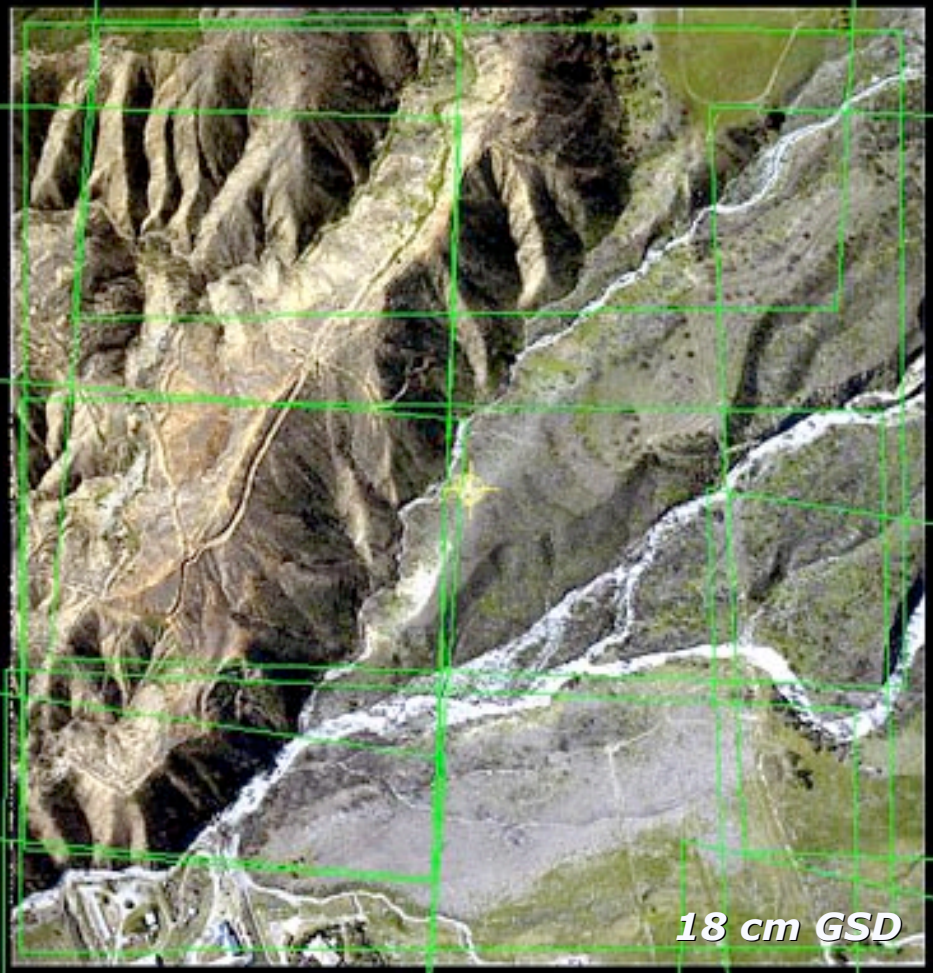


A full photogrammetric camera model is used to map input imagery into ortho-rectified output imagery

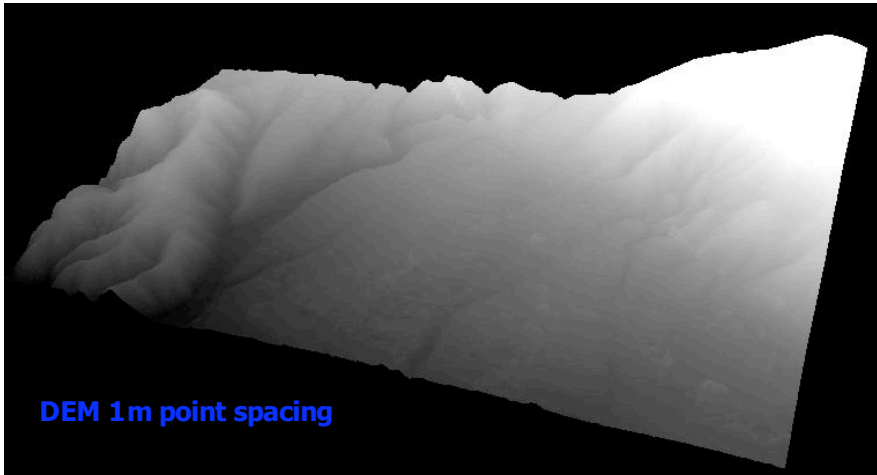
EMERGE

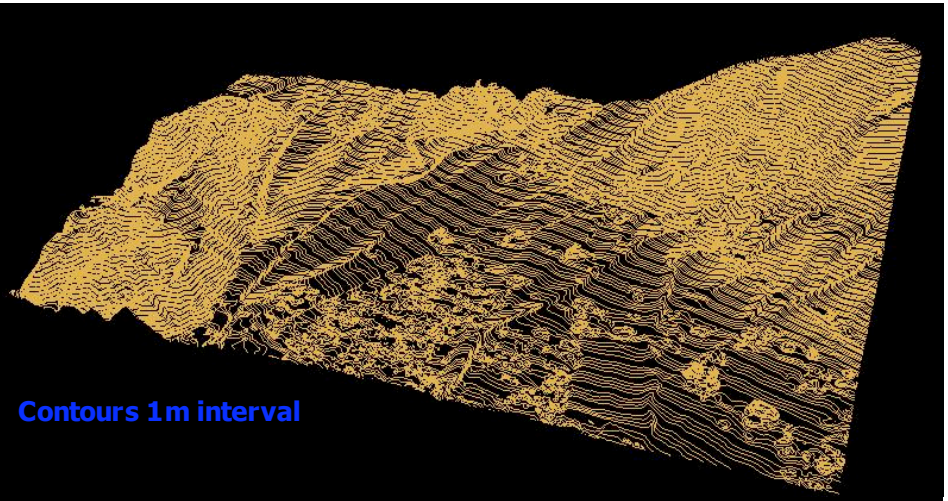

MORENO VALLEY FWY
MORENO VALLEY FWY
Courtesy of
Applanix

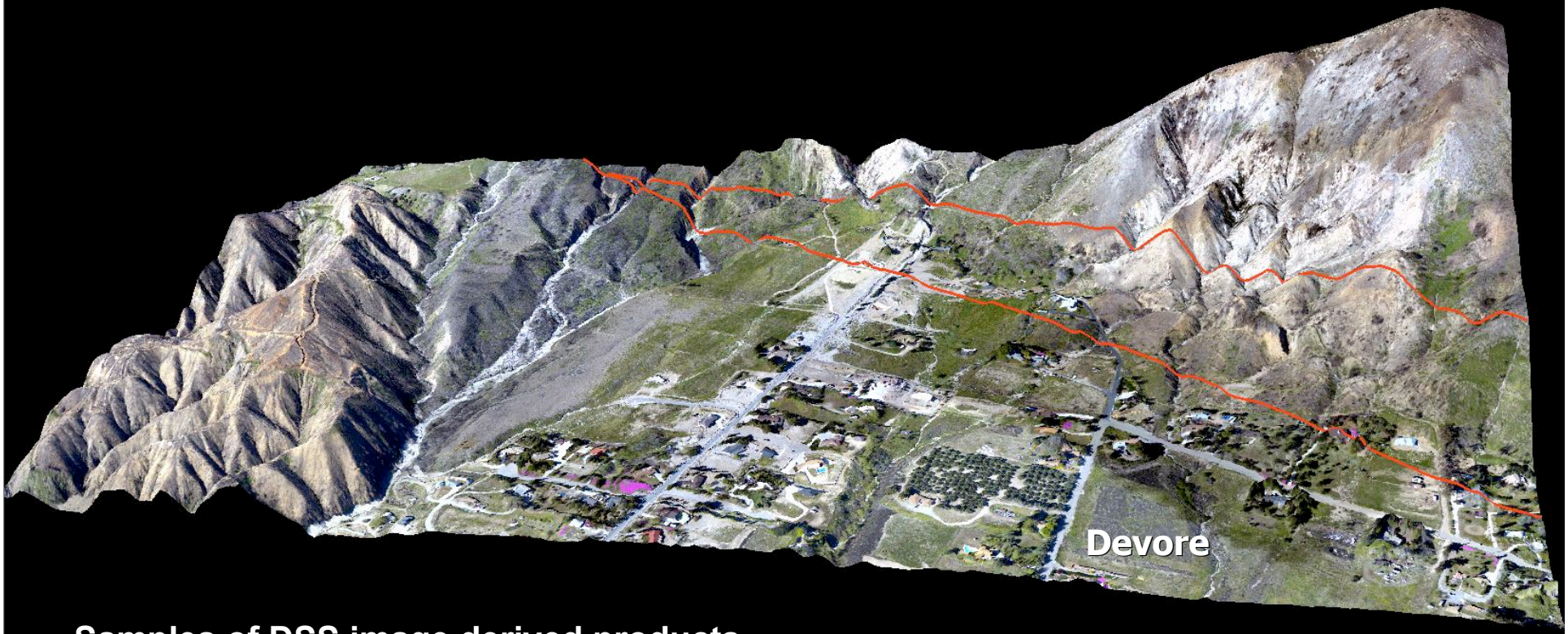
A DEM can be developed from a stereo model of two overlapping frames, but 60 – 80% end lap and 30% side lap is required for mosaicking a DEM project area



DEM mosaic coverage derived from DSS data flown at an altitude of 1,067 m (3,500 ft)

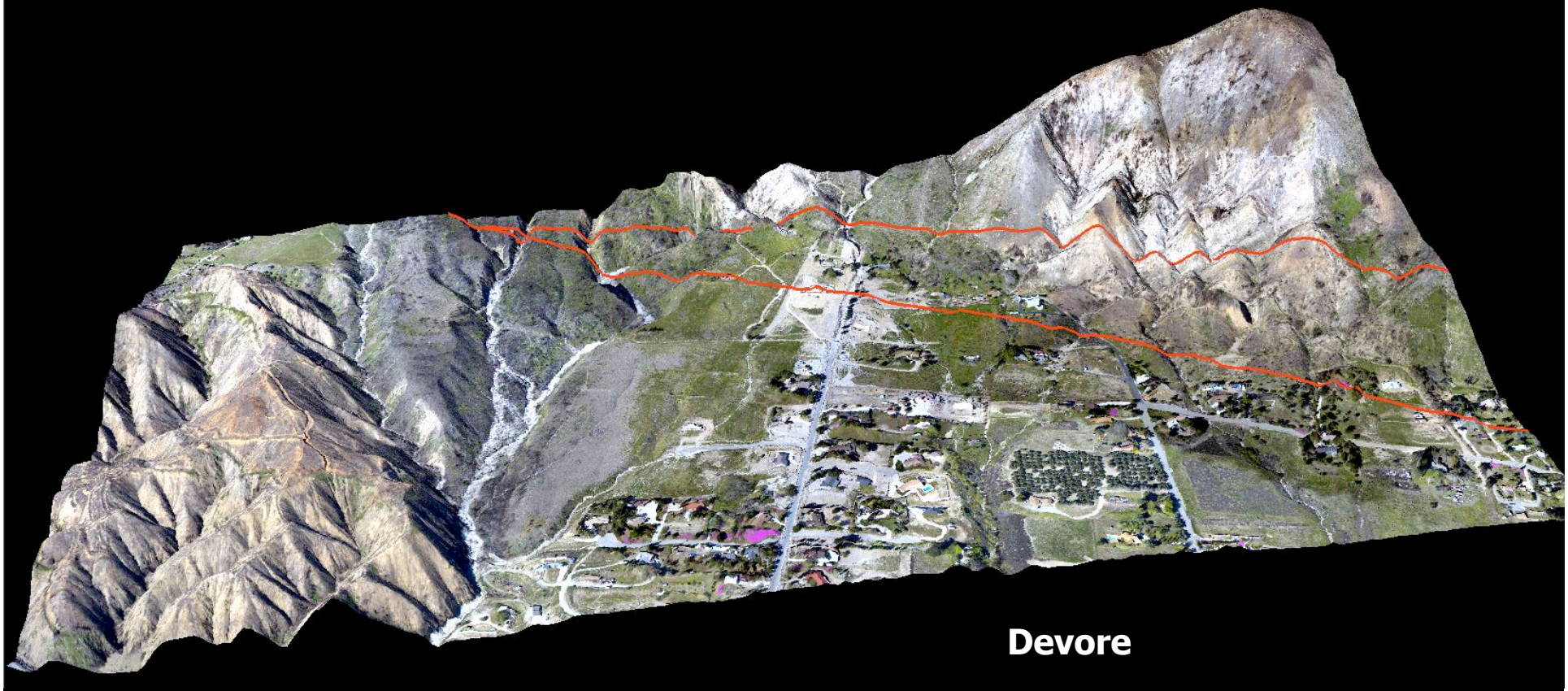




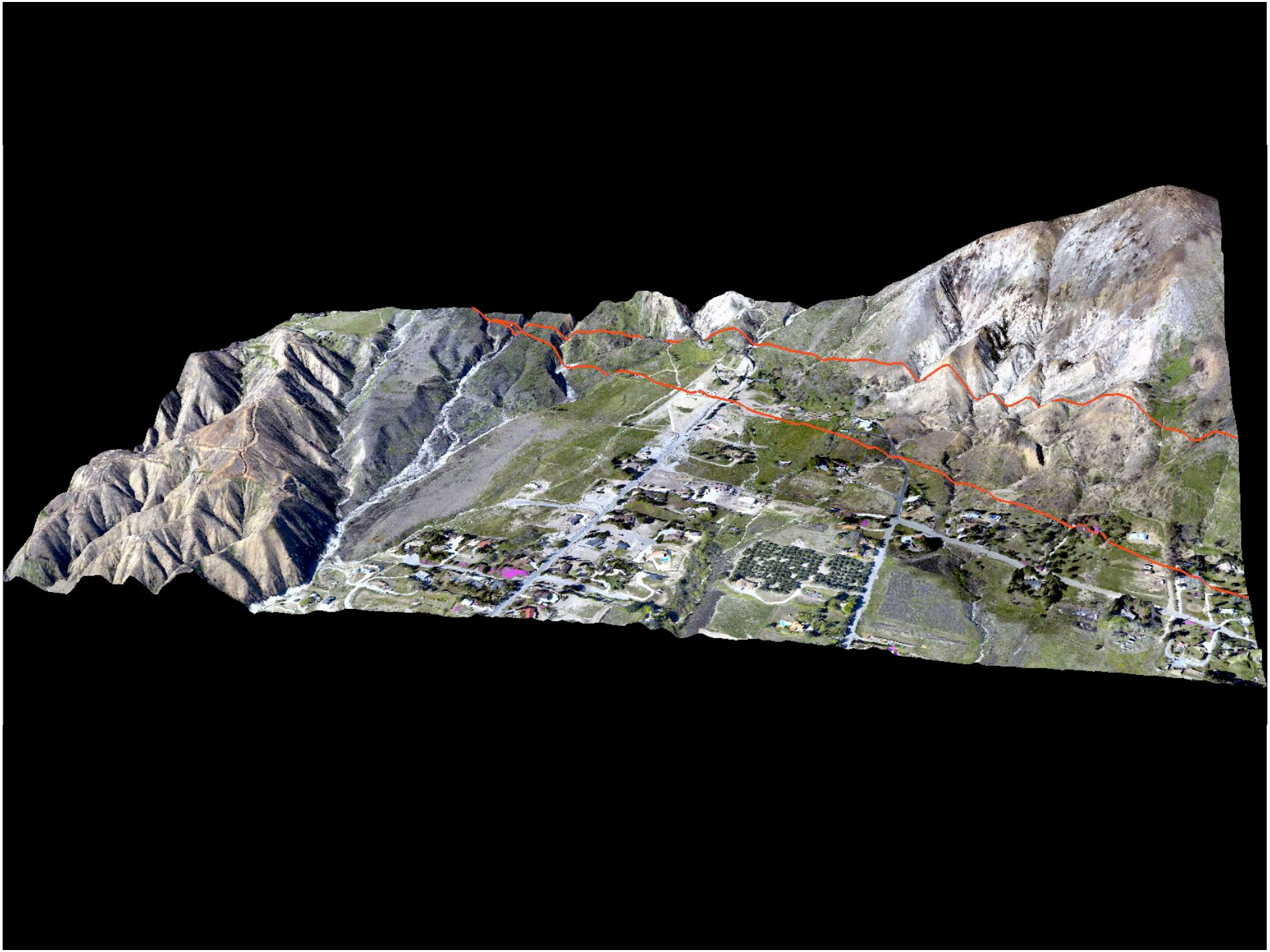


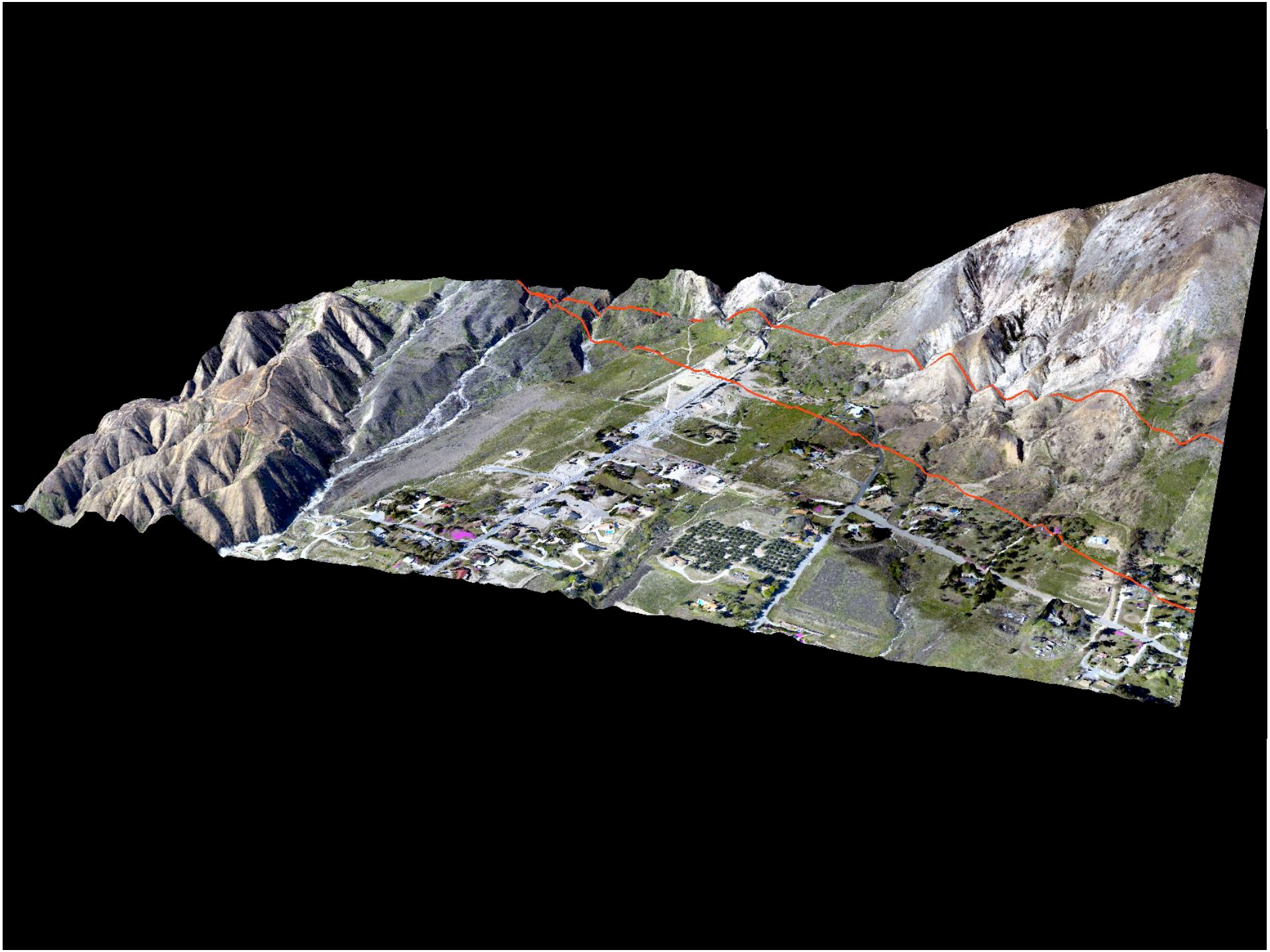
Samples of DSS image derived products

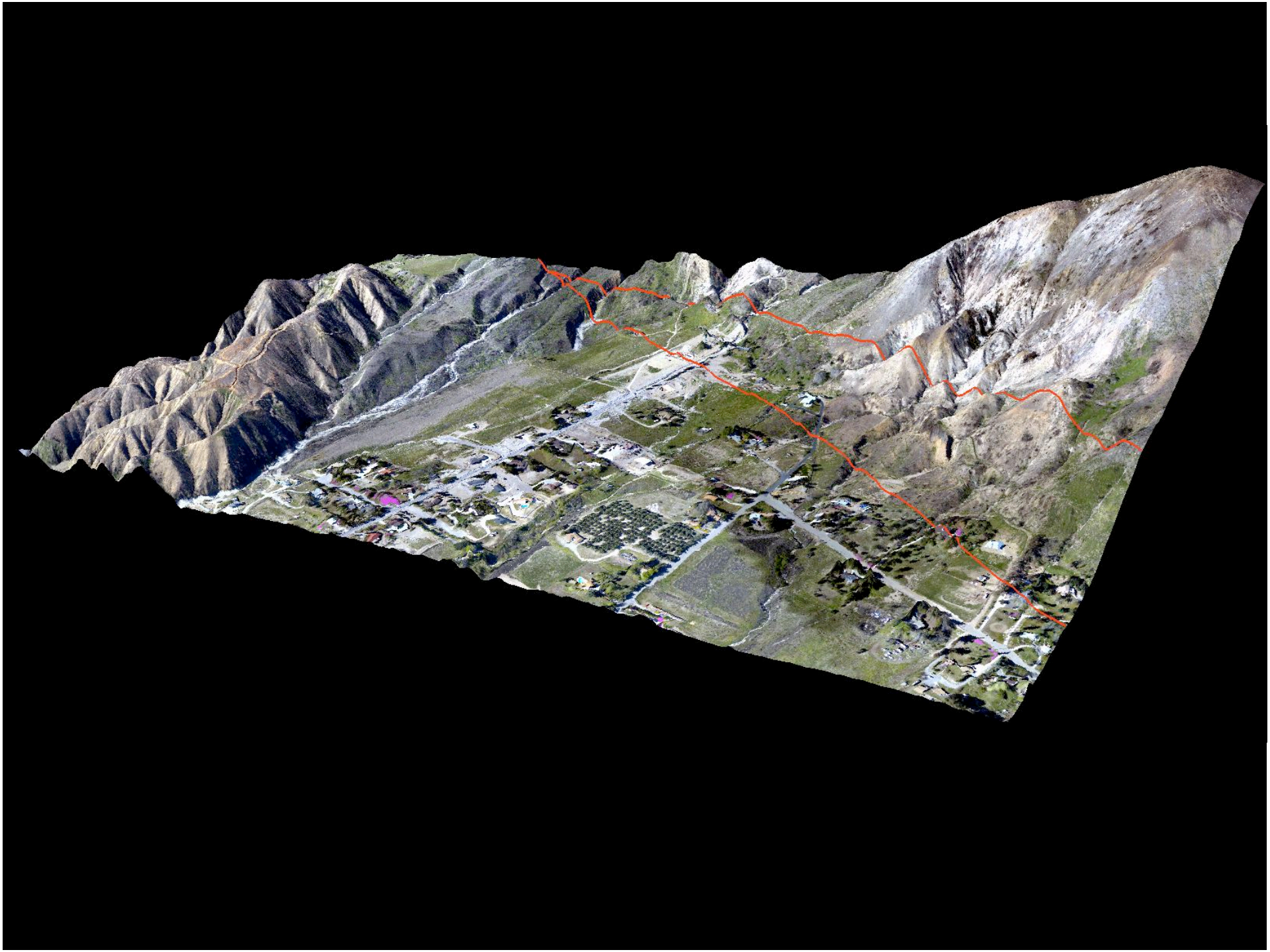
ArcGIS 3-D Perspective



Note: By default ArcGIS adjusts resolution to reduce data volume and improve speed of display



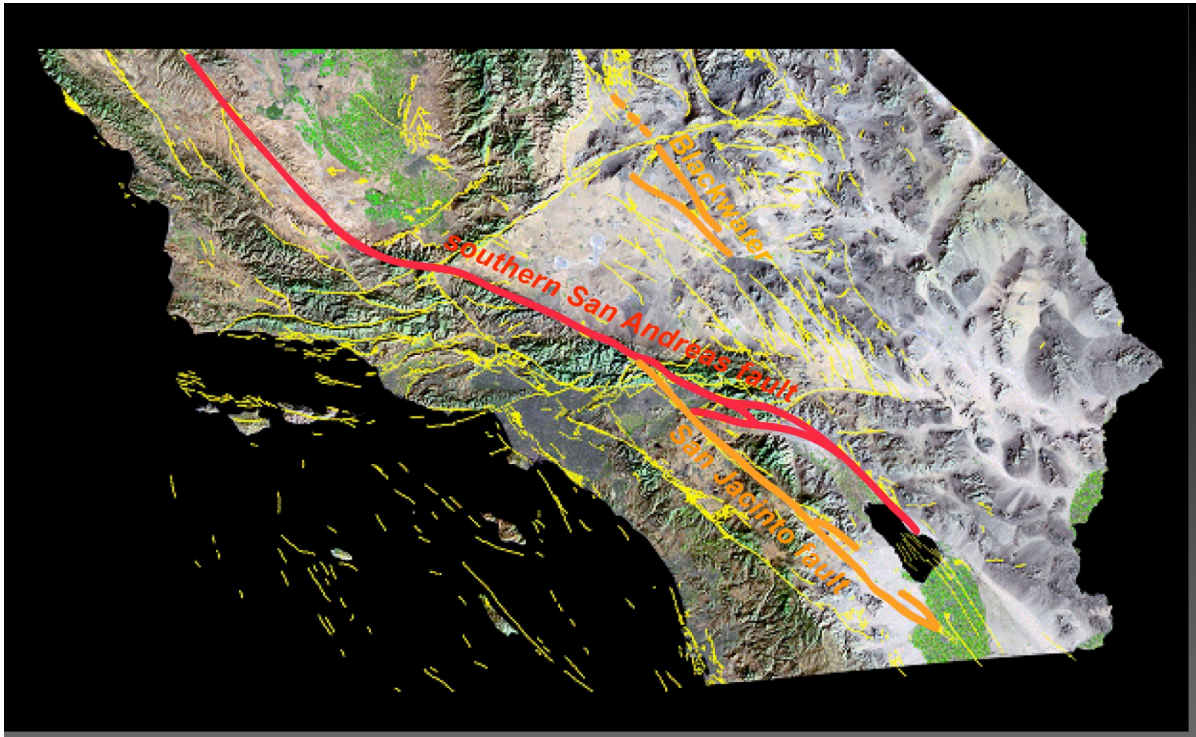




DSS Assessment Findings & Recommendations

- With some limitation at the highest resolution the Digital Sensor System has the potential of providing near real-time mapping of the San Andreas and other fault systems
- More research is recommended to further improve overall geopositional accuracy and the navigational photogrammetric process
- For now a combination of airborne GPS/INS imaging and LiDAR/ALSM is recommended to minimize potential vertical positional accuracy limitations
- How do other airborne digital cameras compare with the Applanix-Emerge Digital Sensor System?
  - *Stereo images from airborne camera systems are similar in scope but rise in cost as the level of accuracy and high-spatial resolution increases*

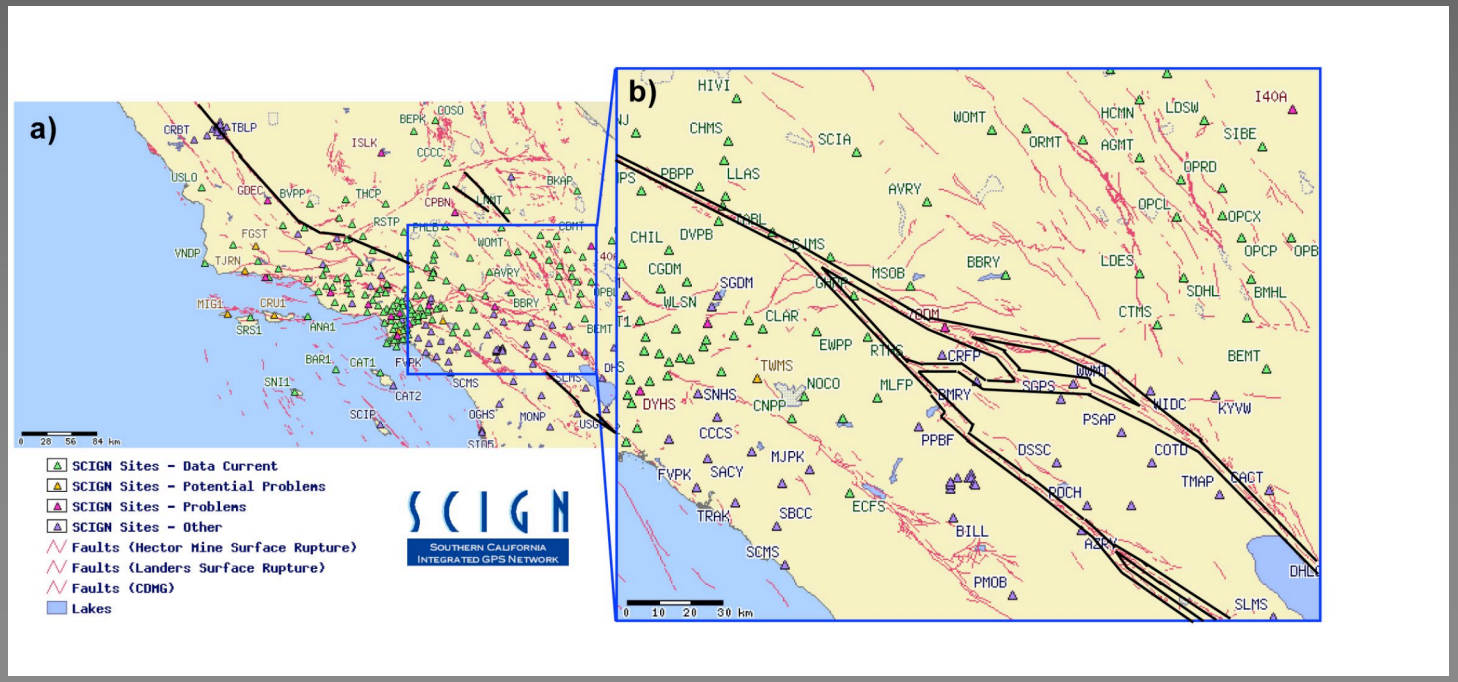
USGS



Laser Scan of the San Andreas

NSF-Funded NCALM Project:
Prof. Mike Bevis, PI (OSU)
- NCALM 'SOP' refinements for GeoEarthScope deployment
- Combine ALSM & Direct GeoRef

Requires high-rate (1 Hz) GPS data from SCIGN sites along fhe fault & special care with GPS-INS



Conclusions - and some open questions

- Airborne LIDAR imaging (ALSM) and Direct Georeferencing Digital Photogrammetry (e.g., DSS) offer high-resolution and accurate imagery for geomorphology and fault zone studies, even over inaccessible or vegetated areas
    - Commercial operations can be reliable and affordable on well-specified targets with carefully designed deployments (for ALSM, digital photogrammetry, or both in combination)
    - CAL-VAL maneuvers are essential for geodetic-quality mapping of geomorphic features
    - Turning ALSM into a geodetic-quality tool requires careful calibration and considerable analysis
  - Slip estimation:
    - has been initially developed demonstrated
    - new and improved methods are being developed
    - systematic measurement along the surface rupture will be done and then compared with geologic estimates, InSAR and other methods
    - quantitative assessment of slip variation along-strike
      - dynamic faulting models – is high-frequency energy radiating from the fault?
      - is slip variation really this extreme? Need to check so as to either verify (or not) …
  - Quantitative geomorphology
    - Model tectonic landform evolution
      - Did topographic features form as a result of exactly repeated slip distributions?
      - Can topography be explained by only certain combinations of slip in past events?