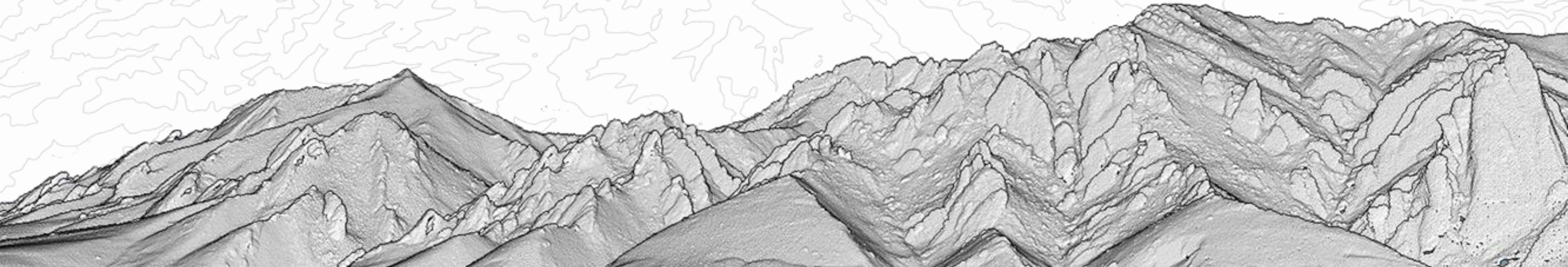
Introduction to topographic differencing

Chelsea Scott

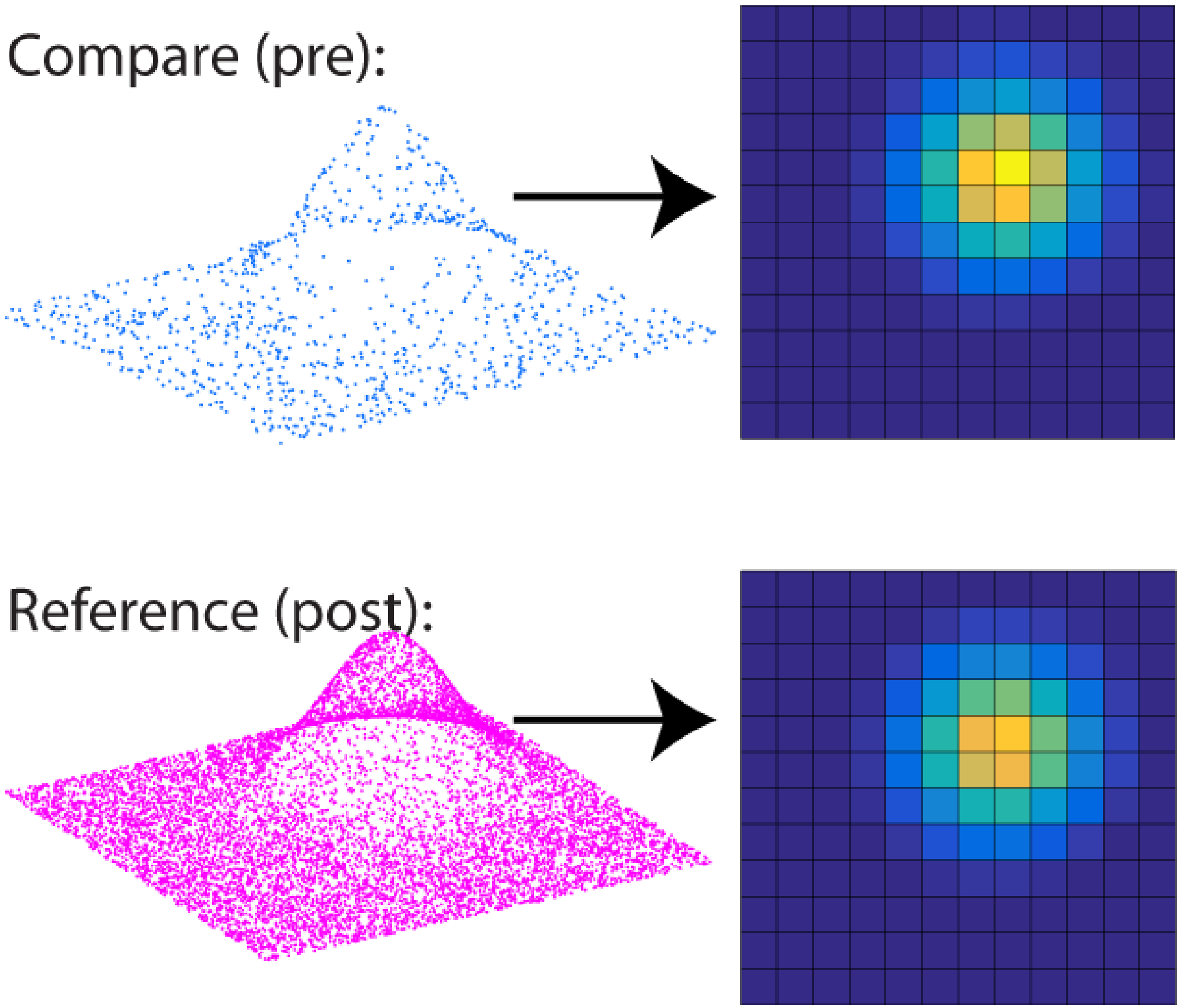
CLaSH Workshop | September 23, 2026



Outline

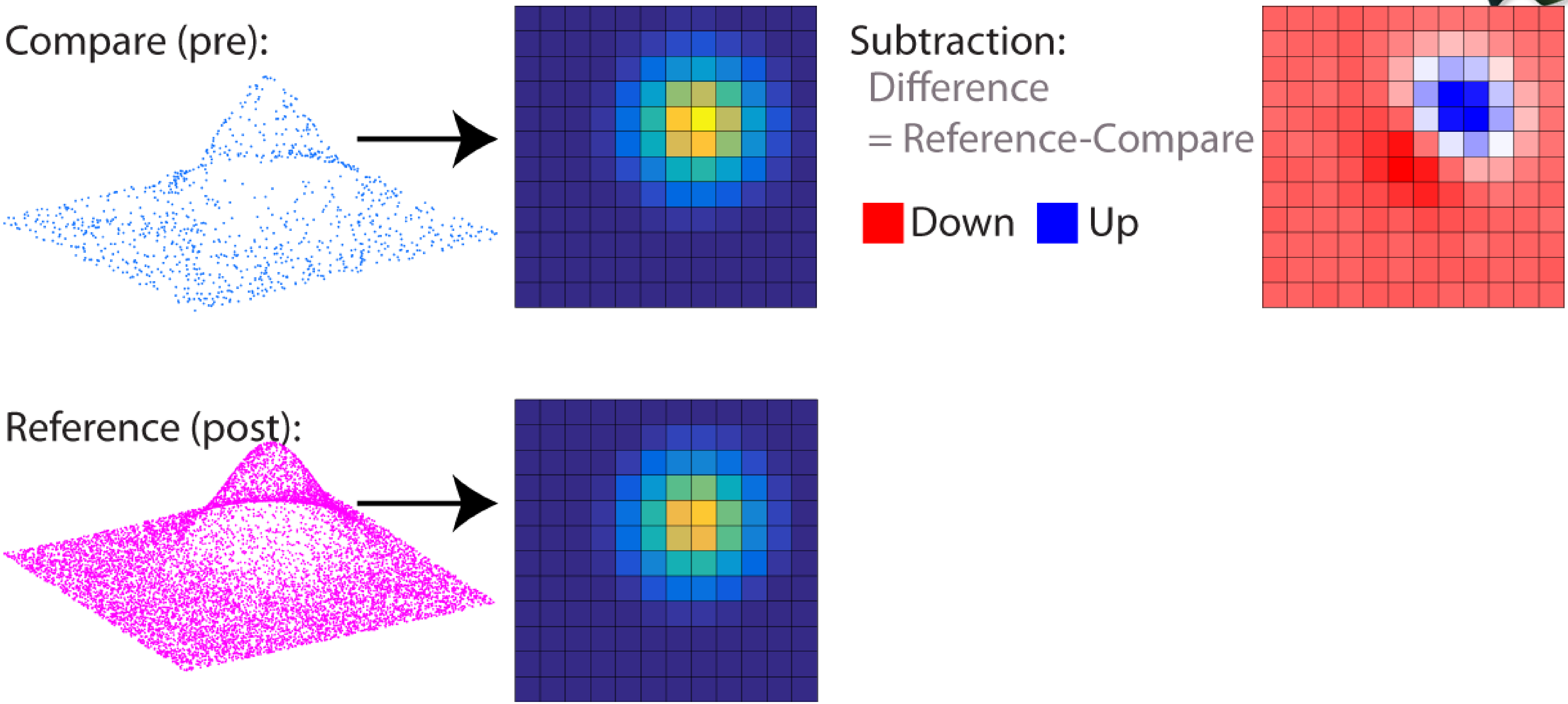
- Vertical and 3D topographic differencing
- Examples of change
- State-wide Indiana Differencing
- Vertical differencing on QGIS: Raster Math

Vertical Topographic Differencing



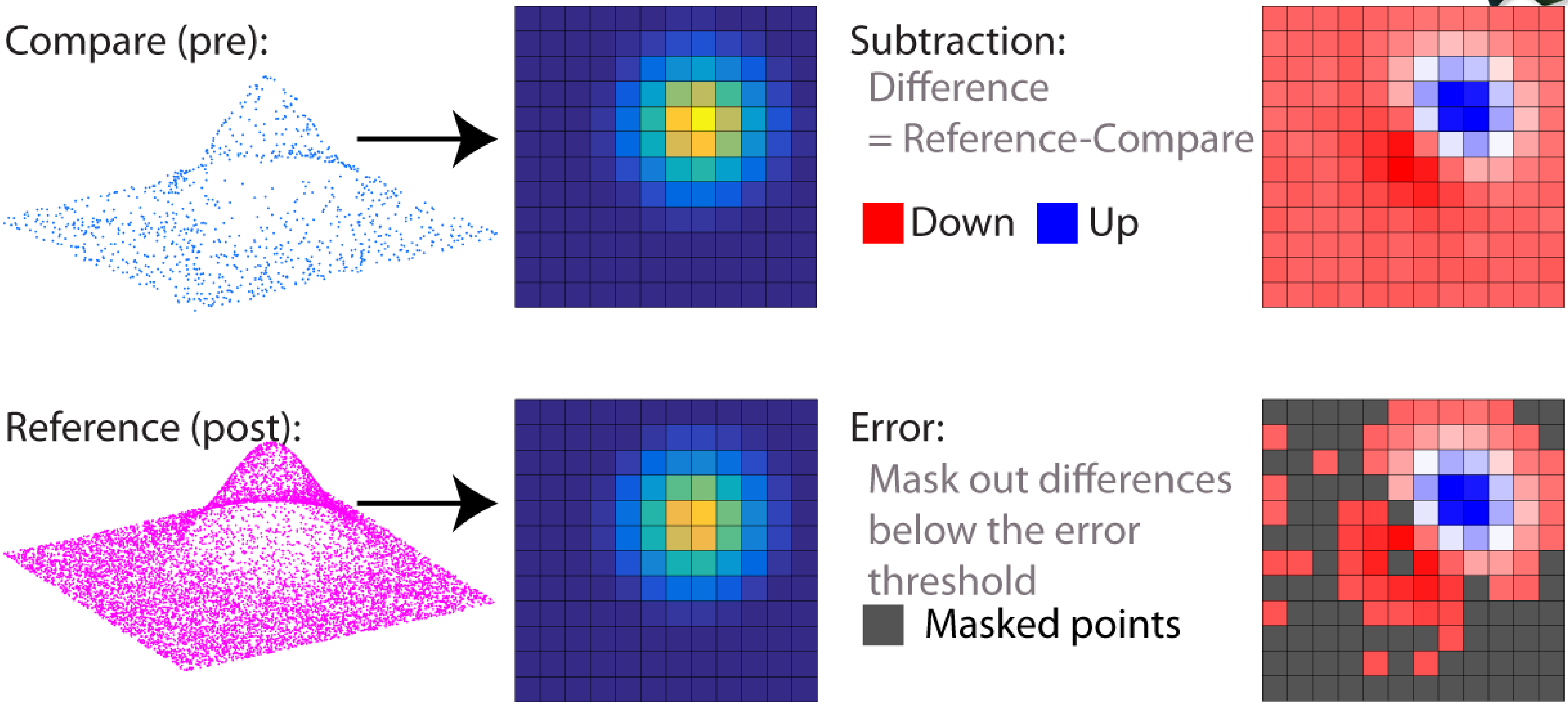
Identical grid for pre and post event topography

Vertical Topographic Differencing



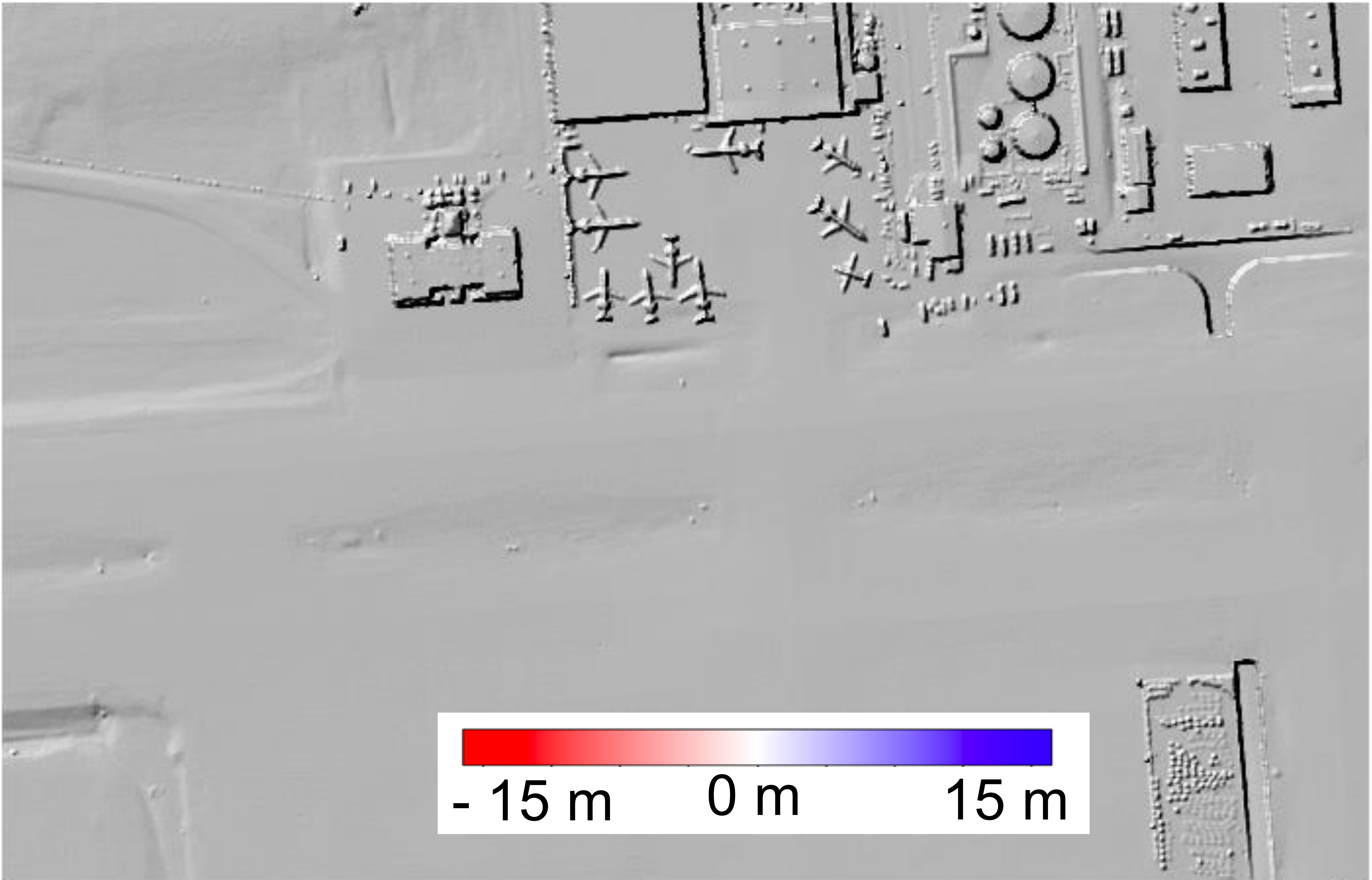
Raster subtraction

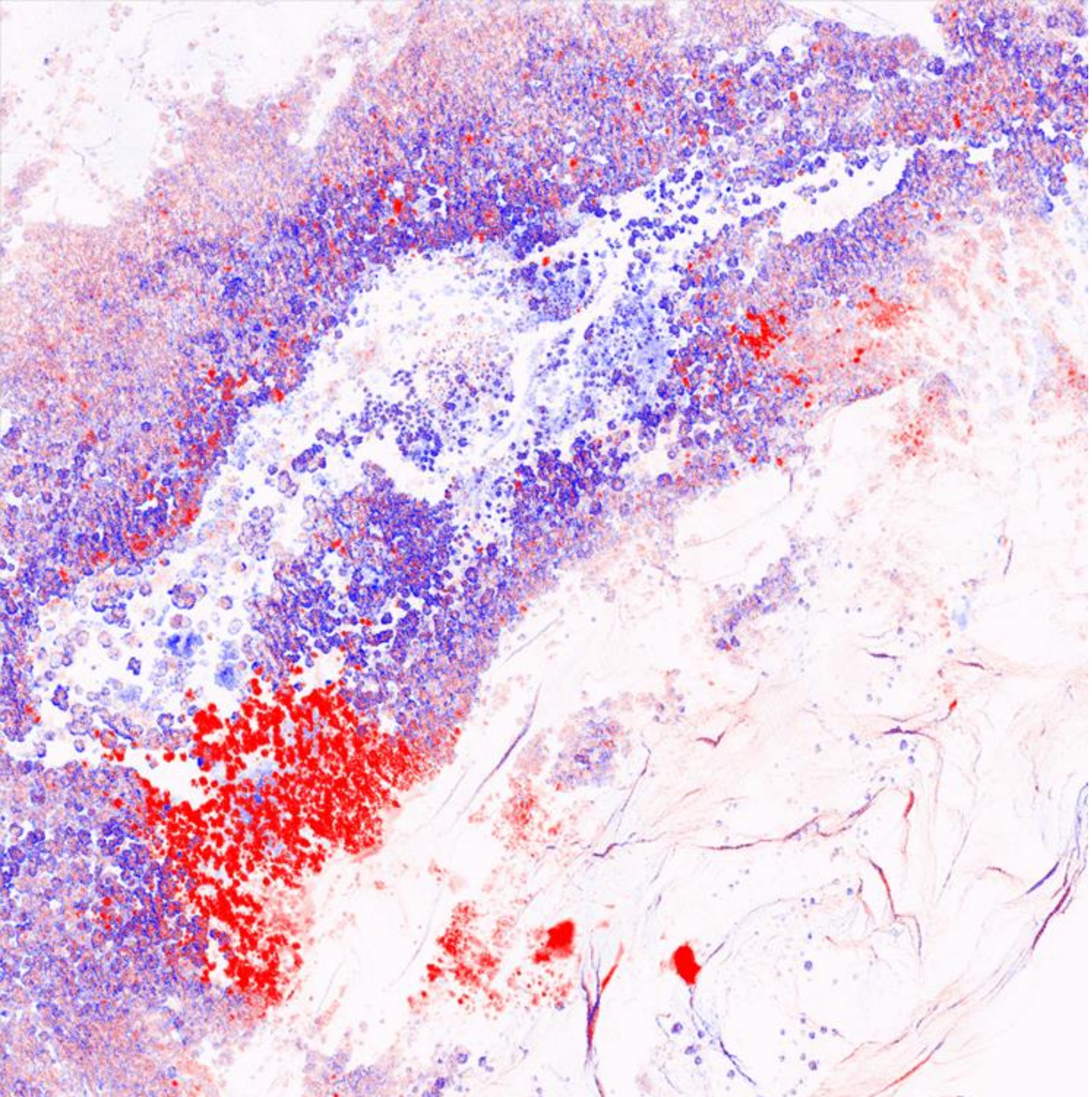
Vertical Topographic Differencing



Error Calculation: Limit of detection

Salt Lake City Airport





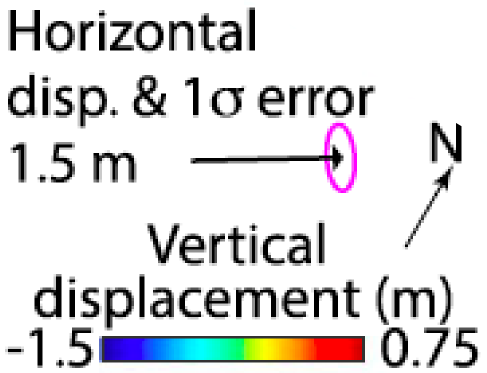
Yosemite, California

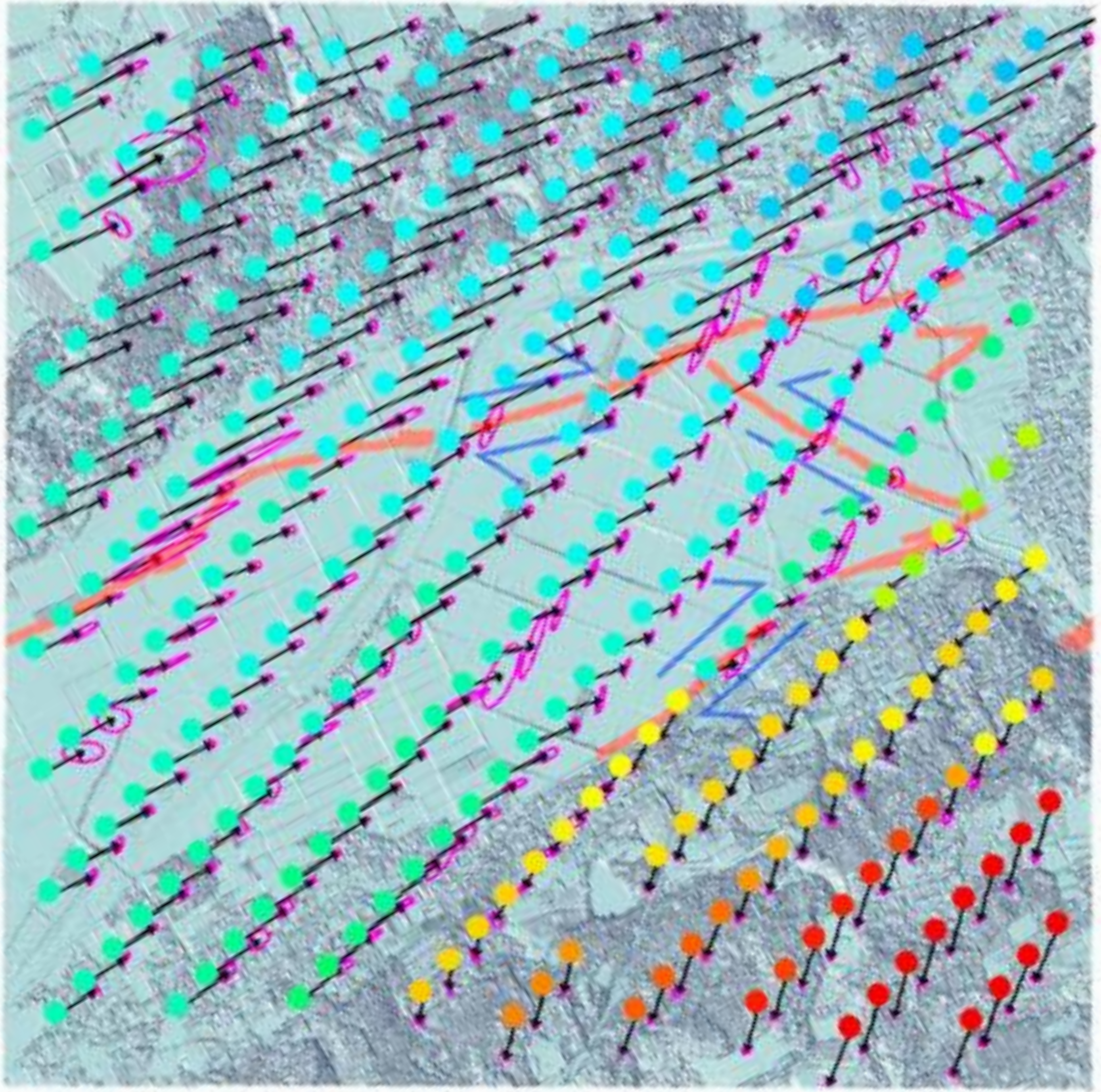
2006-2010

Salt Lake City, Utah

3D Topographic Differencing

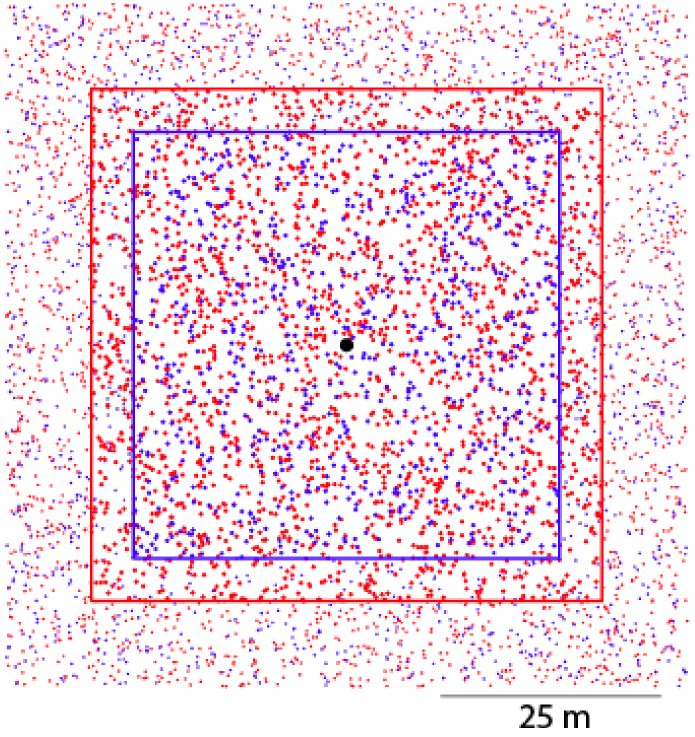
2016 M7 Kumamoto Earthquake, Japan

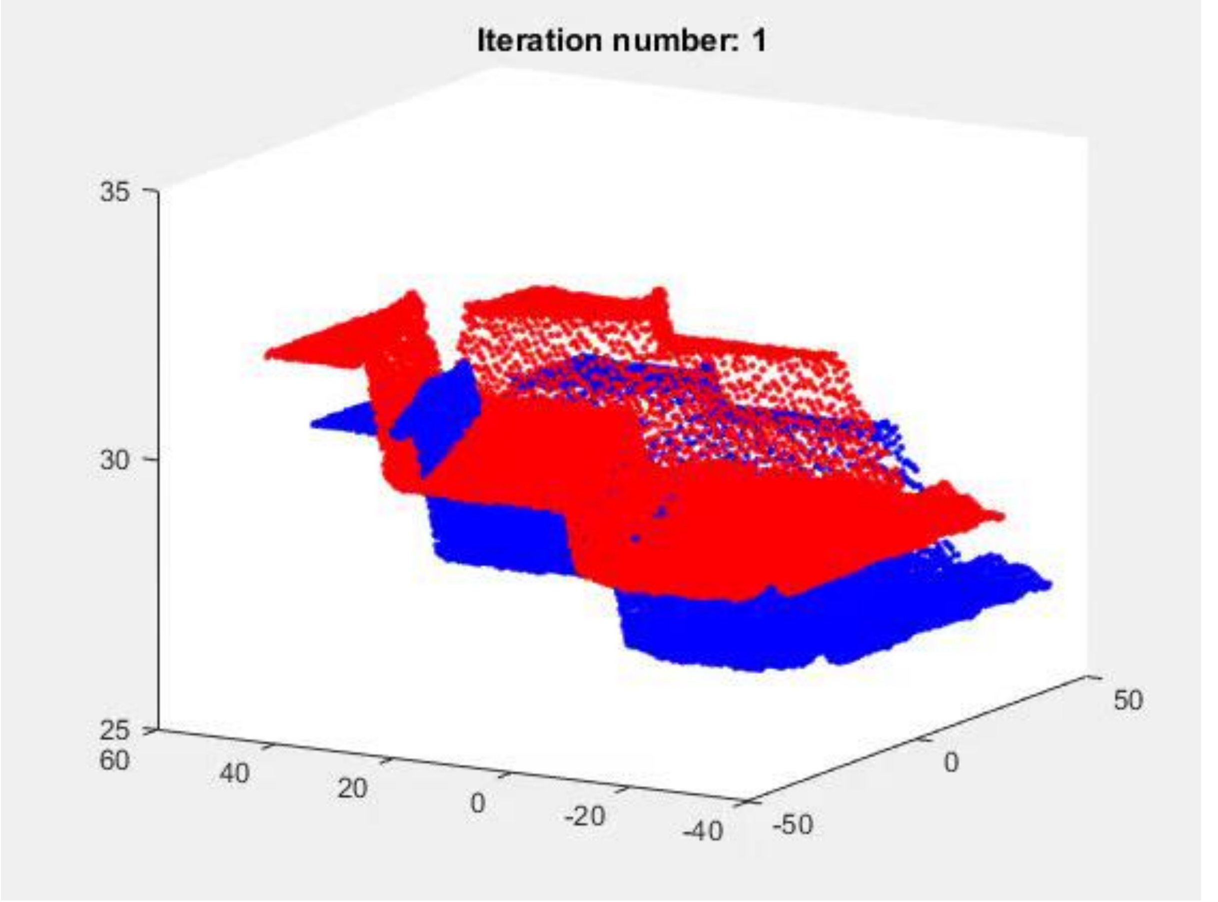




Besl and McKay (1992); Geiger et al., (2012); Nissen et al., (2012; 2014); Scott et al., (2018)

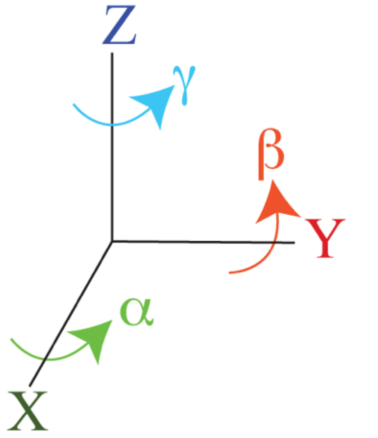
Iterative Closest Point





$$\text{Deformed point cloud} = \begin{bmatrix} 1 & -\gamma & \beta \\ \gamma & 1 & -\alpha \\ -\beta & \alpha & 1 \end{bmatrix} \begin{bmatrix} \text{Undeformed point cloud} \end{bmatrix} + \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix}$$

Rotation Translation

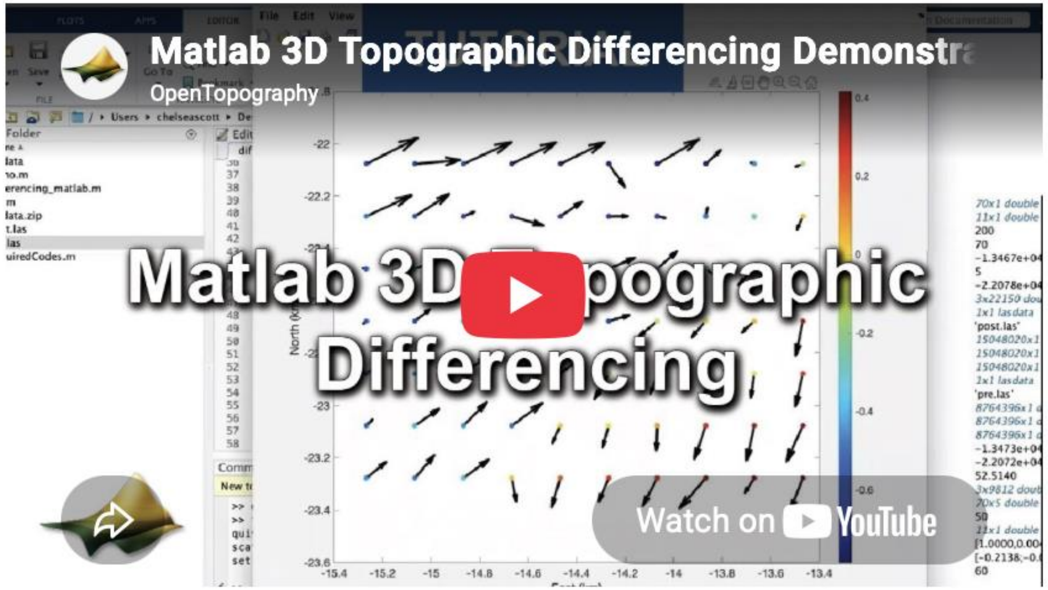


Coordinate system

3D differencing: GitHub code & video

GitHub Code Repositories:

- Topographic differencing error analysis workflow Jupyter notebook and supporting Python modules for a geostatistically-grounded workflow to quantify spatial uncertainty in lidar-derived topographic differencing.
- Matlab code for performing a windowed implementation of the Iterative Closest Point (ICP) algorithm using additional Matlab functions for ICP and reading las files. Lidar data from the 2016 Kumamoto, Japan, earthquake lidar are available here. This tutorial is designed to be relatively straightforward.



https://github.com/opentopography

Vertical vs. 3D Differencing?

Vertical- Change is mostly vertical

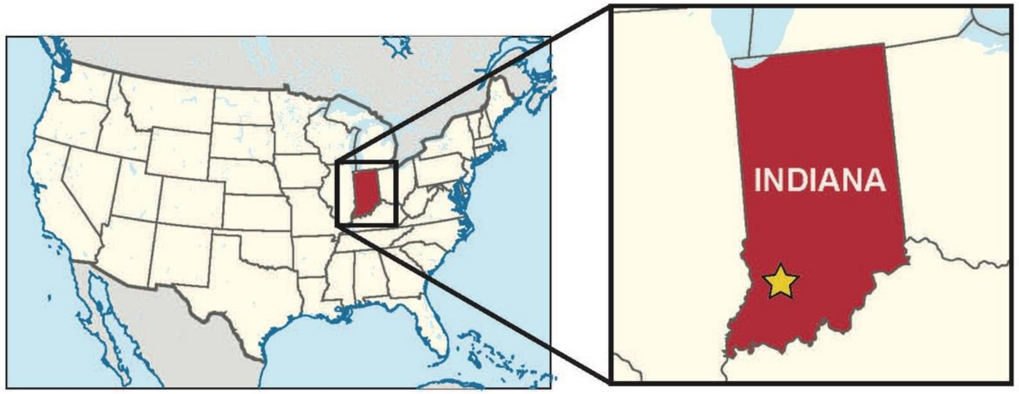
Examples: erosion and depositional along rivers, coastal processes, earthquakes, landslides, cliff collapse, volcanic eruptions, urban growth, forest changes

3D: landscape shifts laterally

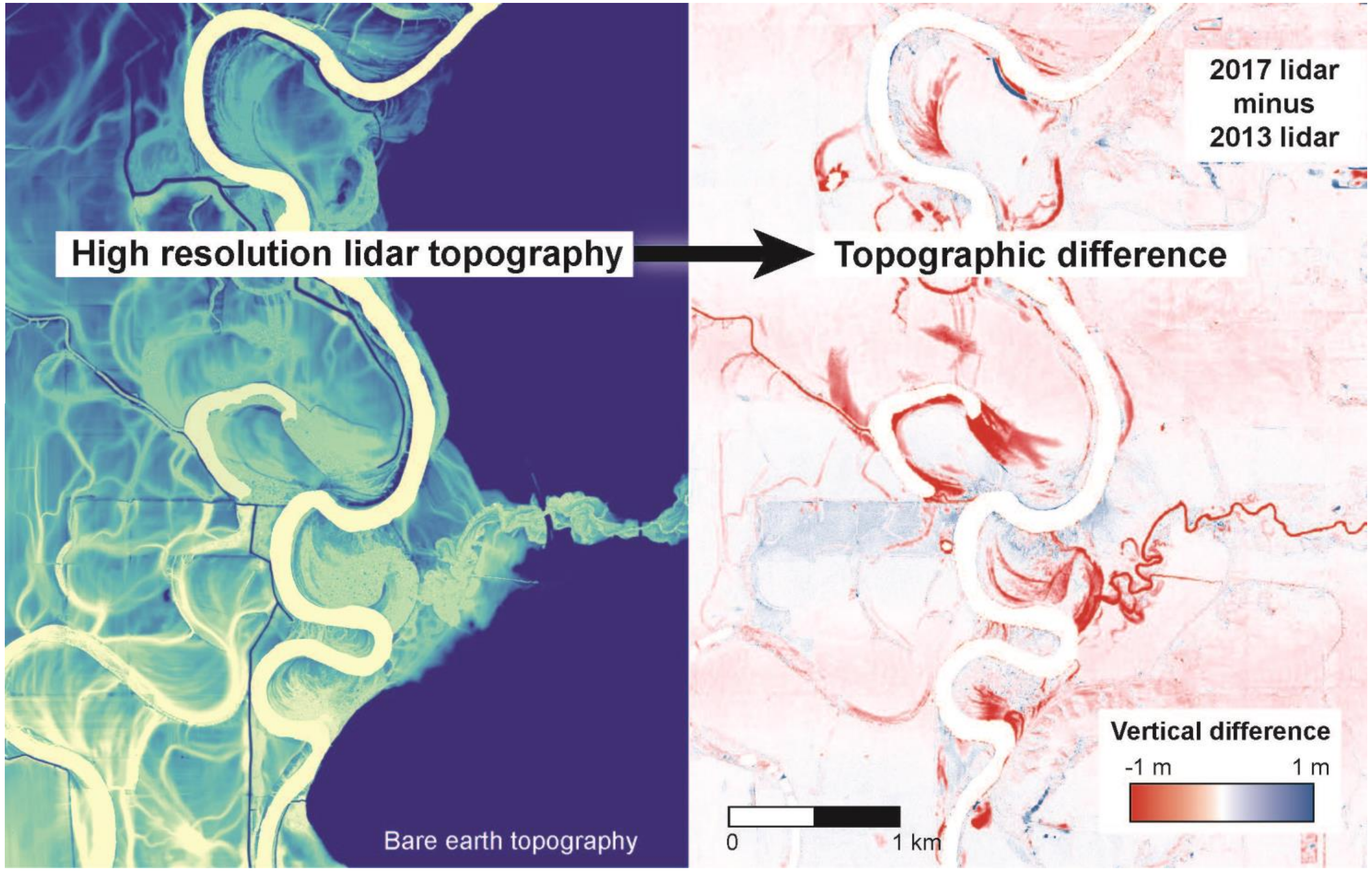
Examples: tectonic fault motion (earthquake or creeping fault), creeping landslide, sand dune migration

Recommend starting with vertical differencing: Meter-scale results capture errors & vertical change of & around feature of interest

Statewide Topographic Differencing of Indiana



Scott, C. P., Beckley, M., Phan, M., Zawacki, E., Crosby, C., Nandigam, V., & Arrowsmith, R. (2022). **Statewide USGS 3DEP Lidar Topographic Differencing Applied to Indiana, USA**. *Remote Sensing*, *14*(4). https://doi.org/10.3390/rs14040847



Statewide Topographic Differencing of Indiana

Motivation:

Large-scale topography processing

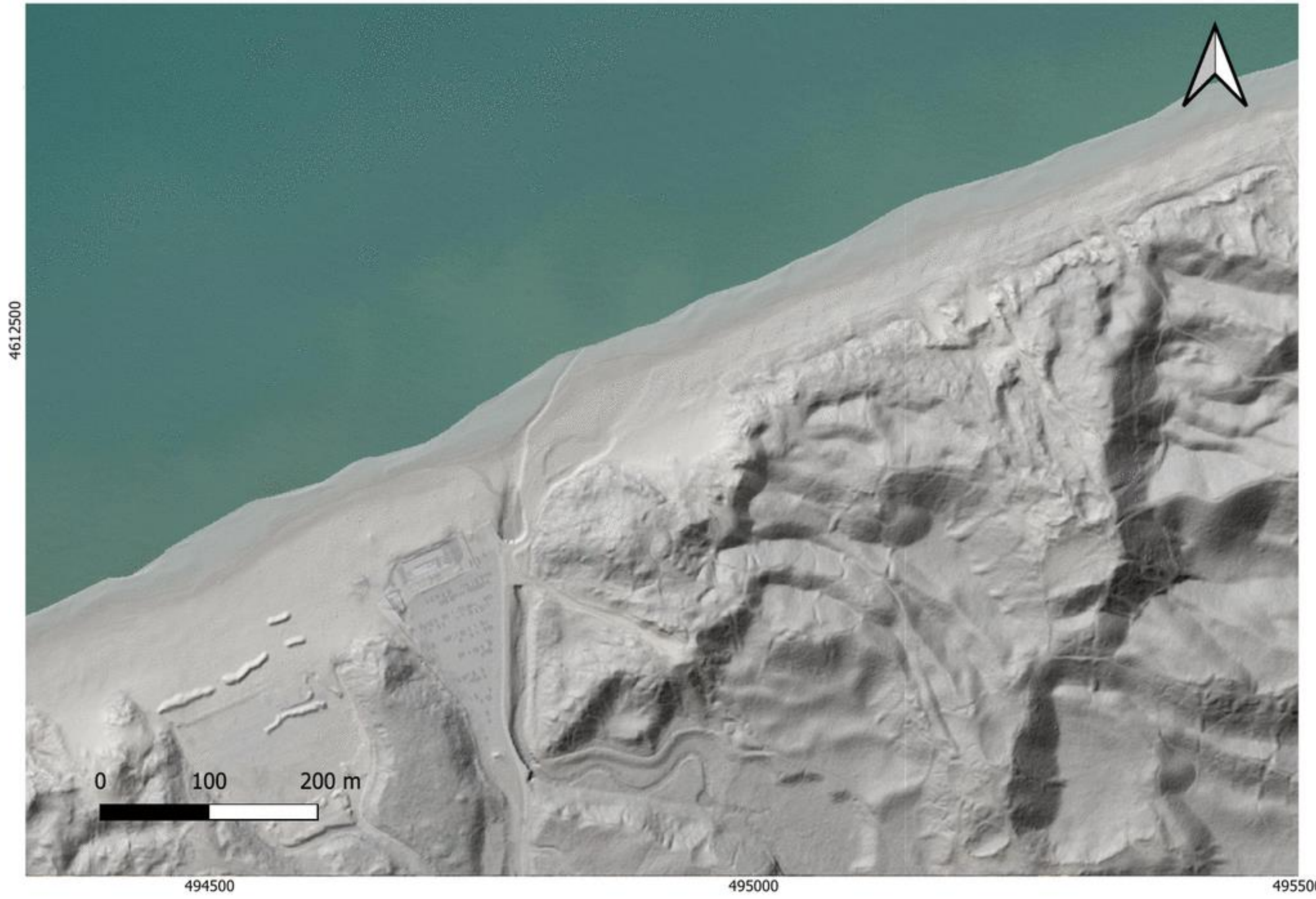
What does a decade of change look like across a state?

Why Indiana:

Two statewide datasets

Anticipated interesting change

Data-hosting partnership between OT and Indiana



Indiana Dunes National Park

Statewide Topographic Differencing Challenges

Big data: Indiana is 10^2-10^3 larger than the area of large past differencing studies

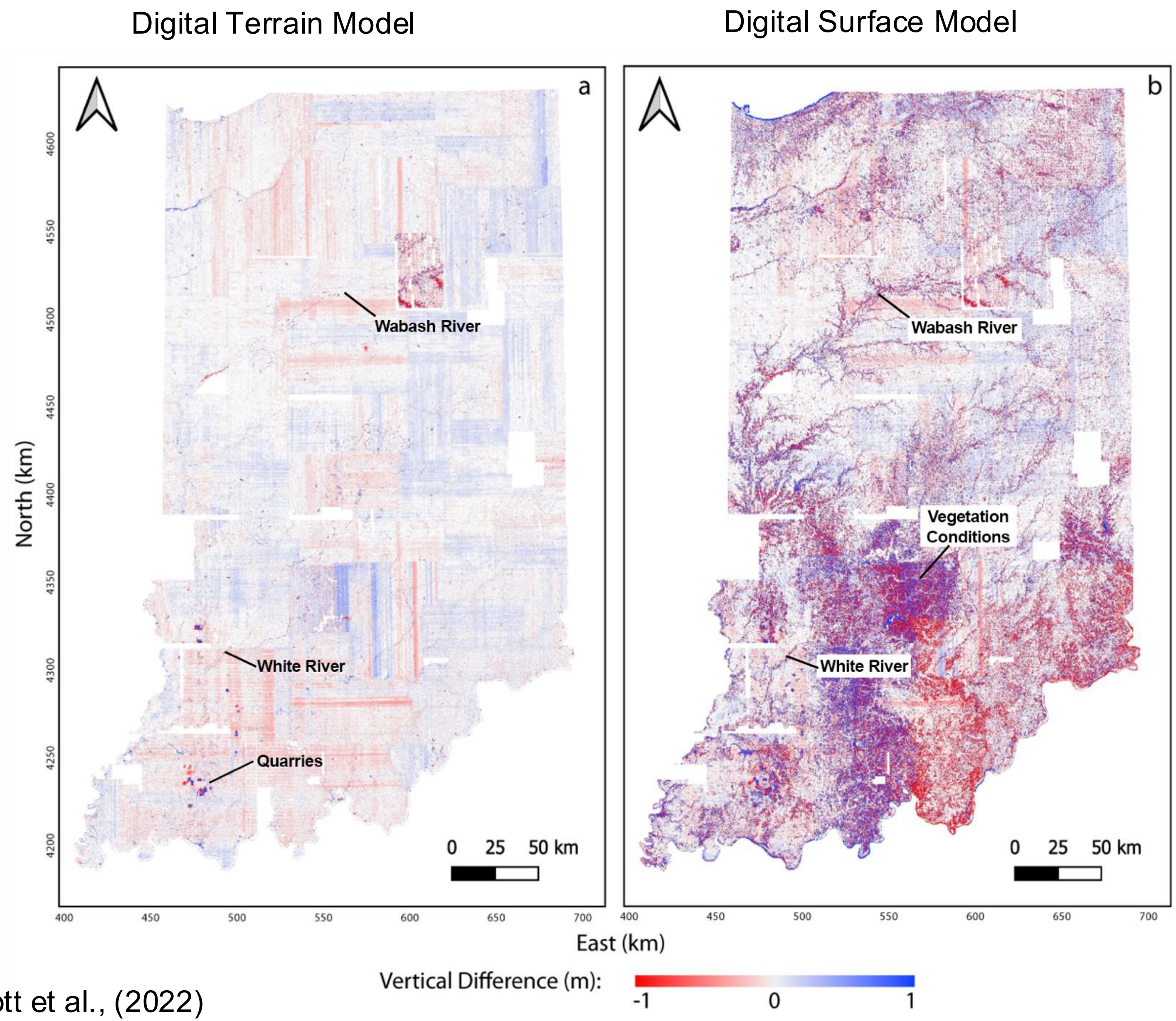
Computation:

- Need high performance computing (HPC) resources
- Memory needs, especially for point cloud to raster/grid
- Final products are ~4 TB

Noise: Sources? Correct at the state-scale?

Visualize the results?

Indiana Topographic Differencing



Scott et al., (2022)

Fluvial and riparian

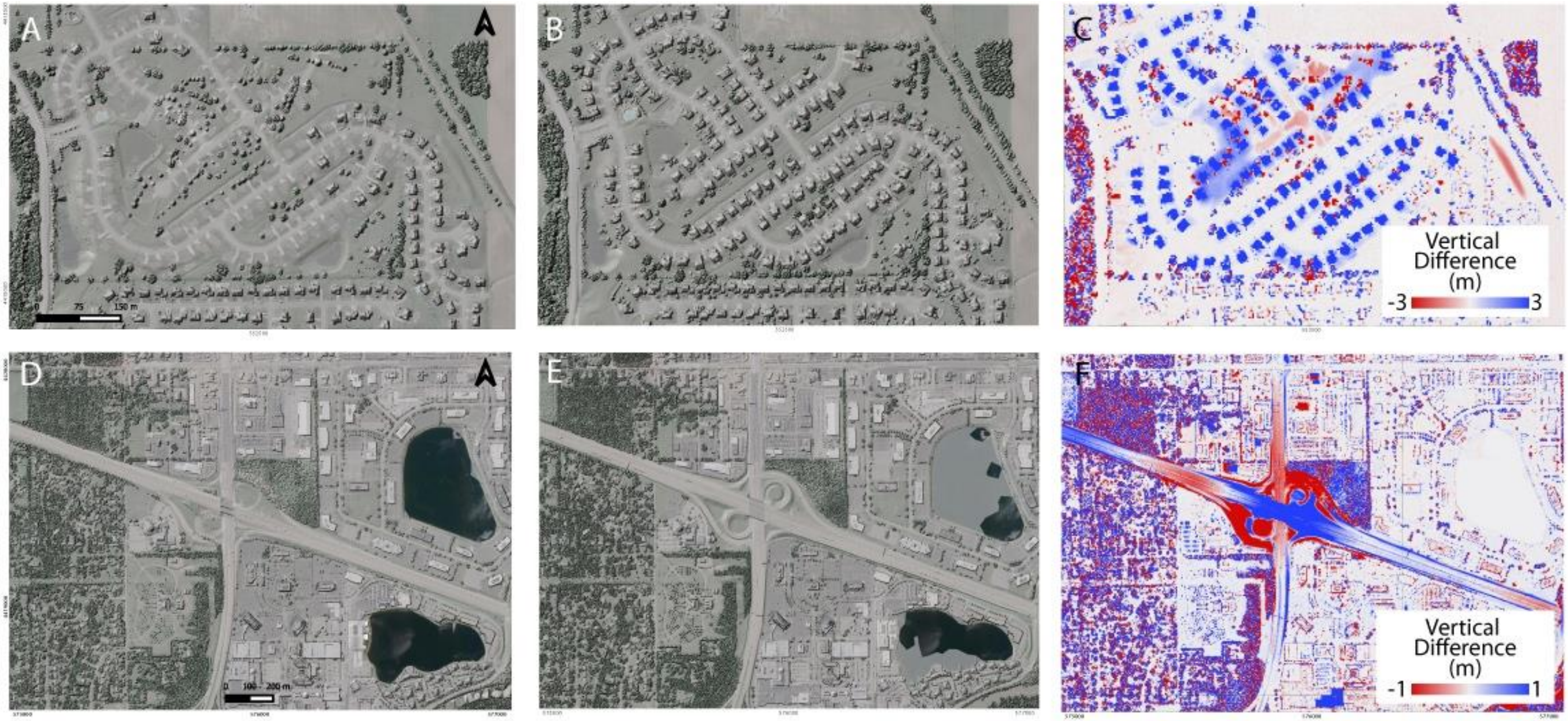
Vegetation (correlations with season of data acquisition)

Quarries and mining

Flight alignment errors

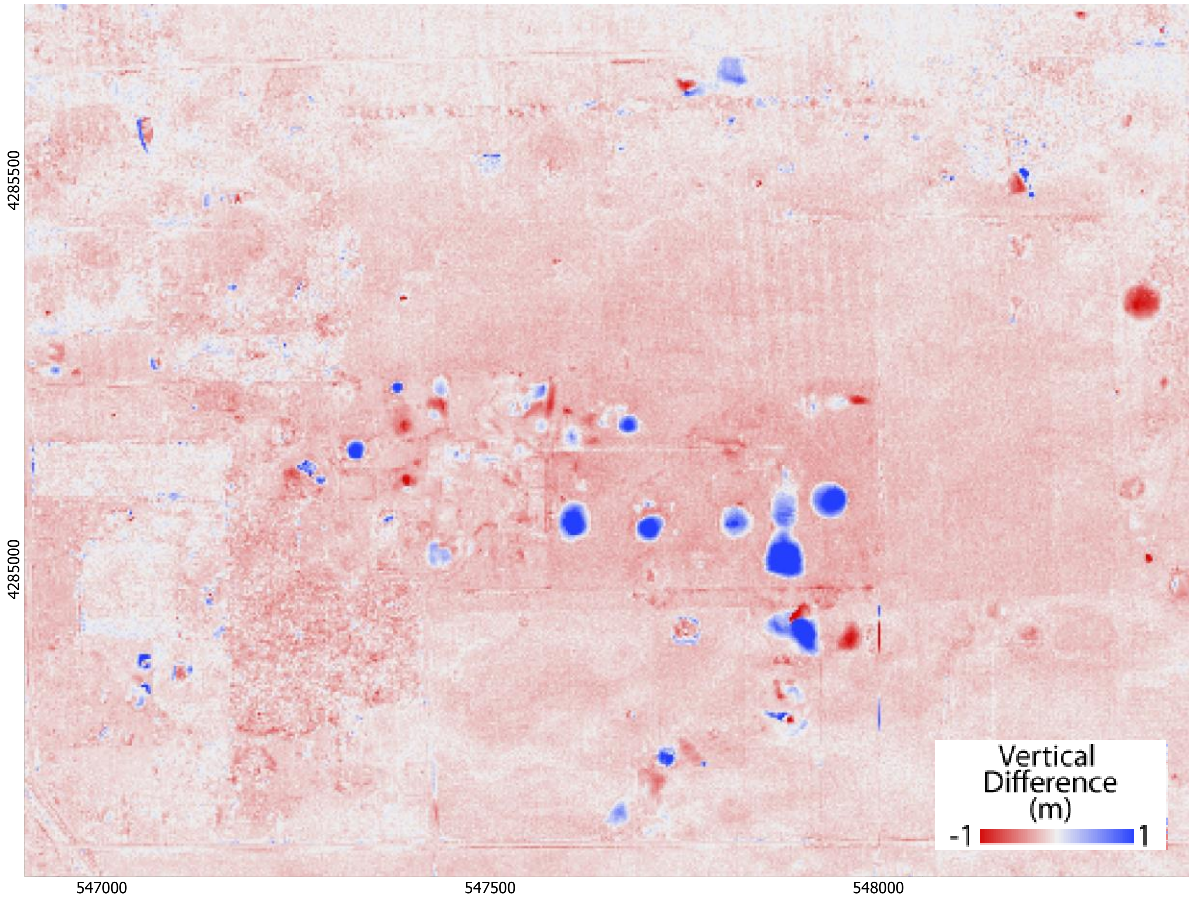
Browsable map:
portal.opentopography.org/indiana

Construction in Indianapolis



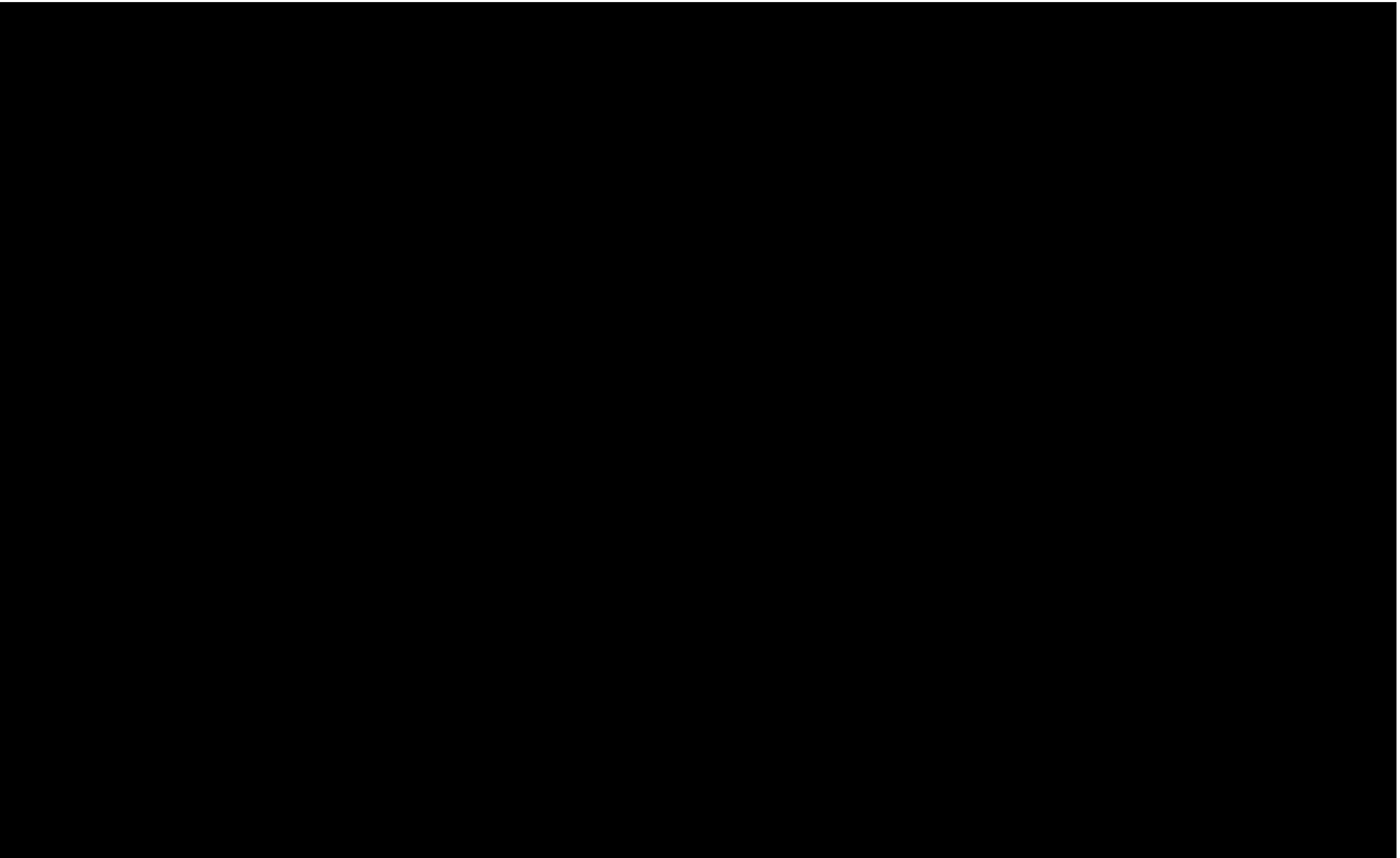
Scott et al., (2022)

Sinkholes

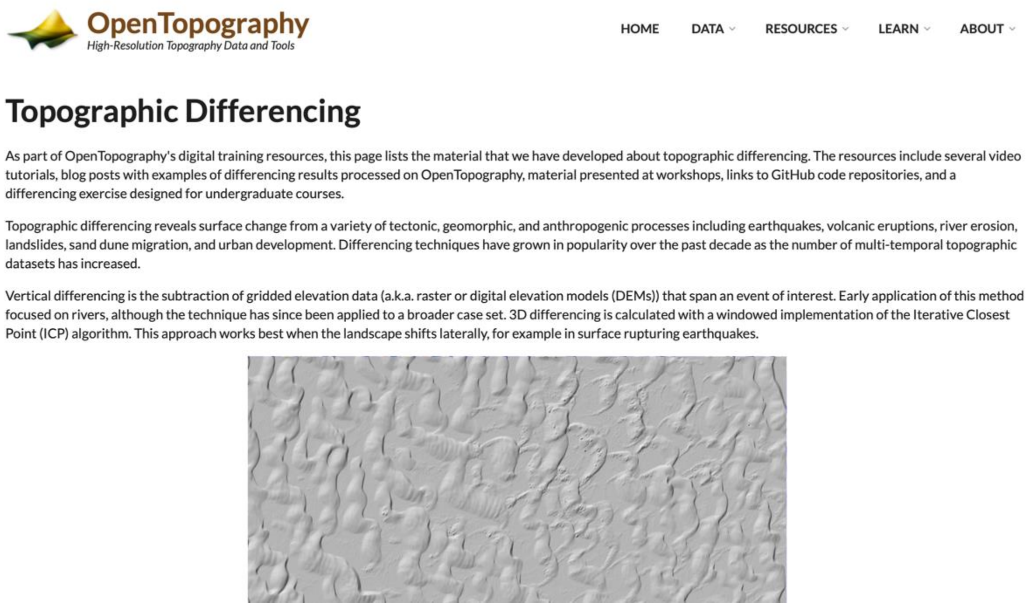


Scott et al., (2022)

Visualize: https://portal.opentopography.org/indiana



Resources: Self-paced Learning


OpenTopography
High-Resolution Topography Data and Tools

HOME DATA RESOURCES LEARN ABOUT

Topographic Differencing

As part of OpenTopography's digital training resources, this page lists the material that we have developed about topographic differencing. The resources include several video tutorials, blog posts with examples of differencing results processed on OpenTopography, material presented at workshops, links to GitHub code repositories, and a differencing exercise designed for undergraduate courses.

Topographic differencing reveals surface change from a variety of tectonic, geomorphic, and anthropogenic processes including earthquakes, volcanic eruptions, river erosion, landslides, sand dune migration, and urban development. Differencing techniques have grown in popularity over the past decade as the number of multi-temporal topographic datasets has increased.

Vertical differencing is the subtraction of gridded elevation data (a.k.a. raster or digital elevation models (DEMs)) that span an event of interest. Early application of this method focused on rivers, although the technique has since been applied to a broader case set. 3D differencing is calculated with a windowed implementation of the Iterative Closest Point (ICP) algorithm. This approach works best when the landscape shifts laterally, for example in surface rupturing earthquakes.

https://opentopography.org/learn/differencing

Blog posts with differencing examples and error discussion

Video tutorials: Differencing on OT, 3D differencing on Matlab

Conference presentations

Github links to differencing code

Undergraduate differencing exercise

Resources: Peer-reviewed Open Access Publications

Software Contribution

GEOSPHERE

GEOSPHERE, v. 17, no. 4

https://doi.org/10.1130/GES02259.1

12 figures; 2 tables

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Measuring change at Earth's surface: On-demand vertical and three-dimensional topographic differencing implemented in OpenTopography

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ABSTRACT

Topographic differencing measures landscape change by comparing multitemporal high-resolution topography data sets. Here, we focused on two types of topographic differencing: (1) Vertical differencing is the subtraction of digital elevation models (DEMs) that span an event of interest. (2) Three-dimensional (3-D) differencing measures surface change by registering point clouds with a rigid deformation. We recently released topographic differencing in OpenTopography where users perform on-demand vertical and 3-D differencing via an online interface. OpenTopography is a U.S. National Science Foundation–funded facility that provides access to topographic data and processing tools. While topographic differencing has been applied in numerous research studies, the lack of standardization, particularly of 3-D differencing, requires the customization of processing for individual data sets and hinders the community's ability to efficiently perform differencing on the growing archive of topography data. Our paper focuses on streamlined techniques with which to efficiently difference data sets with varying spatial resolution and sensor type (i.e., optical vs. light detection and ranging [lidar]) and over variable landscapes. To optimize on-demand differencing, we considered algorithm choice and displacement resolution. The optimal resolution is controlled by point density, landscape characteristics (e.g., leaf-on vs. leaf-off), and data set quality. We provide processing options derived from metadata that allow users to produce optimal high-quality results, while experienced users can fine tune the parameters to suit their needs. We anticipate that the differencing tool will expand access to this state-of-the-art technology, will be a valuable educational tool, and will serve as a template for differencing the growing number of multitemporal topography data sets.

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INTRODUCTION

Topographic differencing measures landscape change from urban growth, flooding (Wheaton et al., 2009; Izumida et al., 2017), coastal processes (Brock et al., 2001; Bull et al., 2010), earthquakes and creeping faults (Oskin et al., 2012; Nissen et al., 2012, 2014; Clark et al., 2017; Scott et al., 2018a; Wedmore et al., 2019; Barnhart et al., 2019; Scott et al., 2020), volcanic eruptions (Albino et al., 2015), and landslides (Lucieer et al., 2014), among other events. Interest in this technique is growing as more regions are surveyed with multitemporal topography data. Vertical differencing is the subtraction of raster-based digital elevation models (DEMs) and can be performed on original raster topography or grids generated from point cloud data, as shown in Figure 1. Three-dimensional (3-D) differencing resolves the best rigid deformation during an event of interest and is performed with a windowed implementation of the iterative closest point (ICP) algorithm (Besl and McKay, 1992; Chen and Medioni, 1992), as illustrated in Figure 2.

The 3-D differencing method, in particular, often requires an expert to dedicate substantial effort to customize processing, and there is little standard methodology or documentation available. As multitemporal topography coverage increases, more data types with variable characteristics are differenced, and results are used to respond to natural disasters and study phenomena altering Earth's surface. In this paper, we describe our implementation of on-demand vertical and 3-D differencing on topography data available via OpenTopography (opentopography.org). A major challenge in 3-D differencing is to select the appropriate differencing algorithm and the resolution of derived displacements, which depend on data resolution, noise, and landscape characteristics. We compared several differencing algorithms and incorporated metadata (e.g., point density) into the default processing settings. Our workflow quickly produces quality differencing results and offers default options that can be further tailored for individual data sets by more advanced users. Deployment of these tools in OpenTopography expands access to state-of-the-art technology for scientists, geospatial professionals, and students. Additionally, our tools can become a reference that contributes to the standardization of topographic differencing, which is lacking in the geosciences.

OpenTopography is a U.S. National Science Foundation–funded facility that enables discovery and access of high-resolution topography data sets and provides on-demand processing tools. OpenTopography is built on a scalable-system–oriented architecture that supports a range of downstream processing tools that derive common science products from hosted raw data (Krishnan et al., 2011). As of October 2020, the 341 point cloud data sets hosted by OpenTopography cover more than

https://doi.org/10.1130/GES02259.1

remote sensing

MDPI

Article

Statewide USGS 3DEP Lidar Topographic Differencing Applied to Indiana, USA

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Abstract: Differencing multi-temporal topographic data (radar, lidar, or photogrammetrically derived point clouds or digital elevation models—DEMs) measures landscape change, with broad applications for scientific research, hazard management, industry, and urban planning. The United States Geological Survey's 3D Elevation Program (3DEP) is an ambitious effort to collect light detection and ranging (lidar) topography over the United States' lower 48 and Interferometric Synthetic Aperture Radar (IfSAR) in Alaska by 2023. The datasets collected through this program present an important opportunity to characterize topography and topographic change at regional and national scales. We present Indiana statewide topographic differencing results produced from the 2011–2013 and 2016–2020 lidar collections. We discuss the insights, challenges, and lessons learned from conducting large-scale differencing. Challenges include: (1) designing and implementing an automated differencing workflow over 94,000 km^2 of high-resolution topography data, (2) ensuring sufficient computing resources, and (3) managing the analysis and visualization of the multiple terabytes of data. We highlight observations including infrastructure development, vegetation growth, and landscape change driven by agricultural practices, fluvial processes, and natural resource extraction. With 3DEP and the U.S. Interagency Elevation Inventory data, at least 37% of the Contiguous 48 U.S. states are already covered by repeat, openly available, high-resolution topography datasets, making topographic differencing possible.

Keywords: lidar; topographic change; USGS 3DEP; Indiana; vertical differencing

https://doi.org/10.3390/rs14040847

Differencing on QGIS: Raster Math

Dataset acquired **first**:

- DEM(t_1)
- Pre
- Compare

Dataset acquired **second**:

- DEM(t_2)
- Post
- Reference

Differencing equation

Three different ways to write out:

$\Delta z = DEM(t_2) - DEM(t_1)$

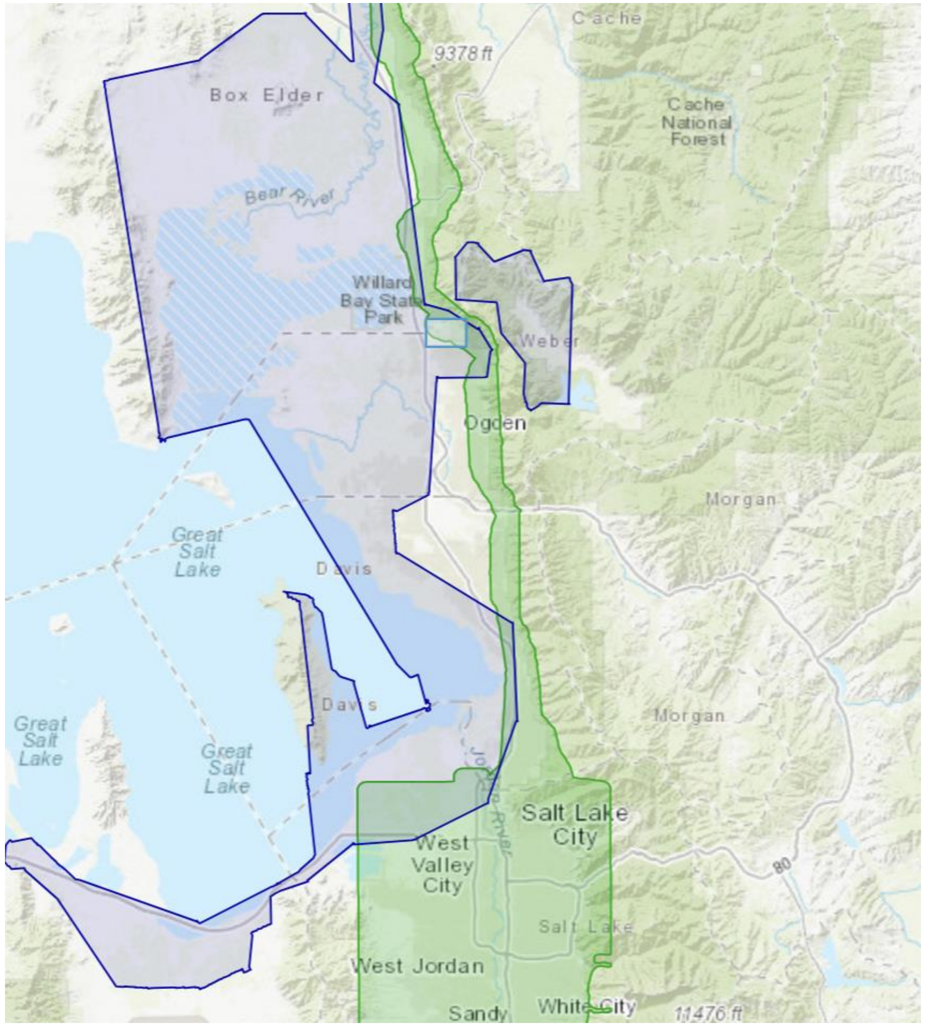
Change = Post - Pre

Change = Reference – Compare

Results:

Up: +

Down: -



	Reference dataset:	Compare dataset:
Dataset:	State of Utah Acquired Lidar Data - Wasatch Front	Utah Geological Survey Lidar
Survey Date:	10/18/2013 - 05/31/2014	09/23/2011 - 10/27/2011
Horizontal Coordinates:	NAD83 (2011) / UTM Zone 12N Meters [EPSG: 26912]	NAD83 (CORS96) / UTM Zone 12N Meters [EPSG: 26912]
Vertical Coordinates:	NAVD88 (GEOID 12A) [EPSG: 5703]	NAVD88 (GEOID 09) [EPSG: 5703]
Units:	meter	meter

Differencing

Digital Elevation Model (DEM): Changes to the bare-earth, vegetation, buildings

$$\Delta z_{DEM} = DEM(t_2) - DEM(t_1)$$

Digital Terrain Model (DTM): Changes to the bare-earth

$$\Delta z_{DTM} = DTM(t_2) - DTM(t_1)$$