Image from NASA:
https://commons.wikimedia.org/wiki/File:Earth_Western_Hemisphere_transparent_background.png#filelinks

GIScience

Digital Terrain Analysis

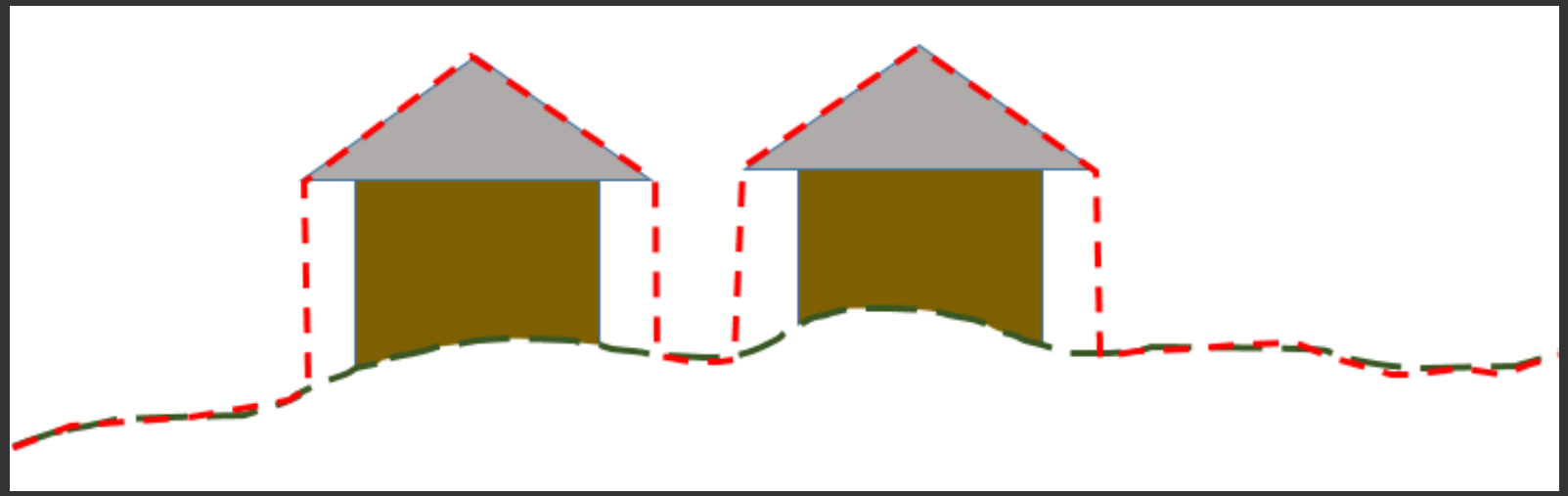
WV VIEW

AmericaView℠
Empowering Earth Observation Education
AmericaView.org - Est. 2003

Digital Terrain Data

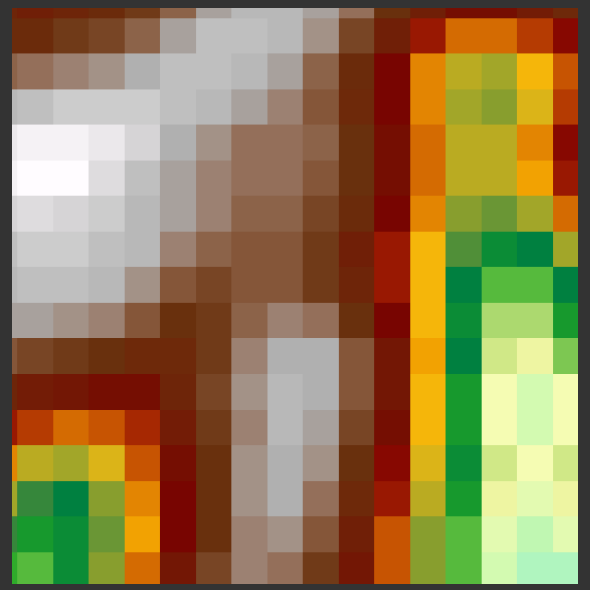
Elevation Data in a GIS

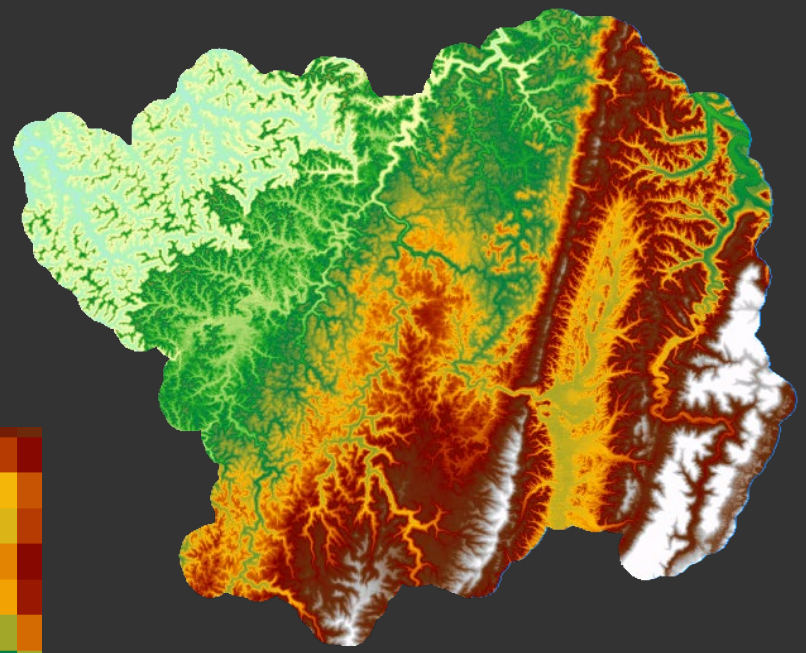
- DTM (Digital Terrain Model) = A representation of a terrain surface calculated by measuring elevation values at a series of locations
- DEM (Digital Elevation Model) = A model of the terrain surface
- DSM (Digital Surface Model) = Ground surface + objects above the ground surface



Digital Elevation Models (DEMs)

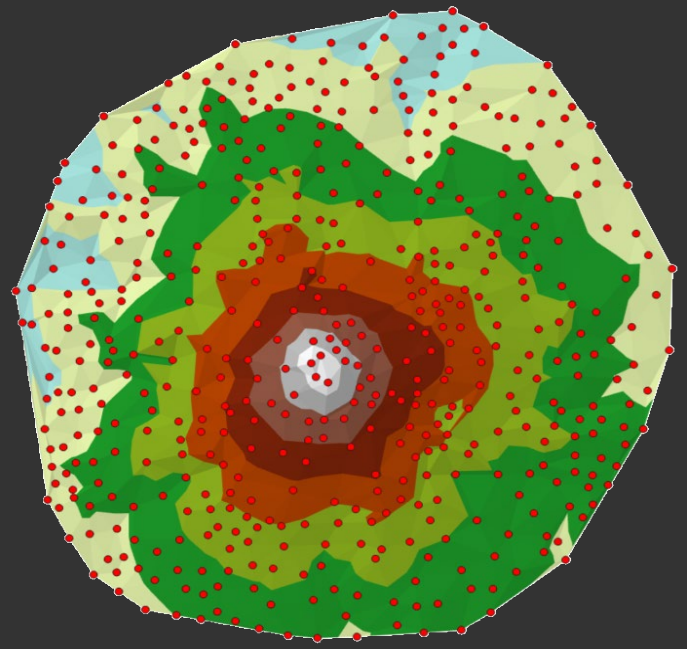
- A continuous raster-based representation of terrain
- Each pixel holds an elevation measurement in feet or meters

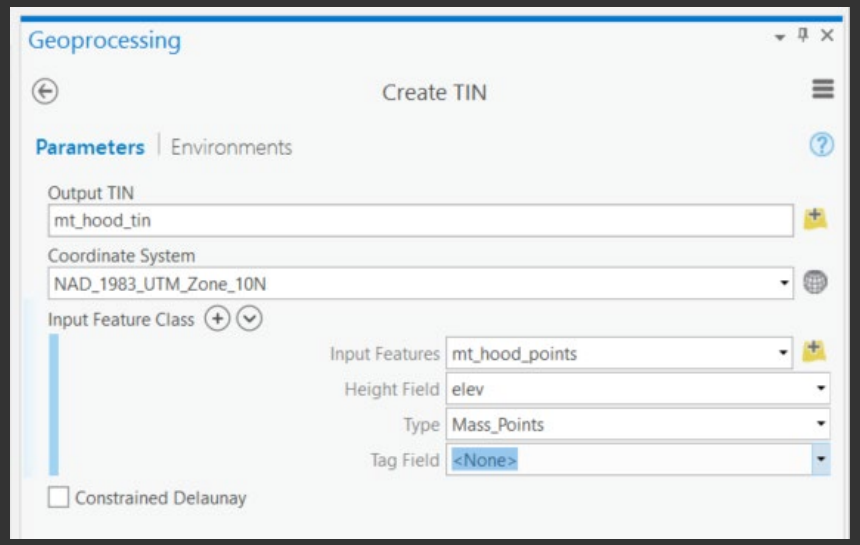


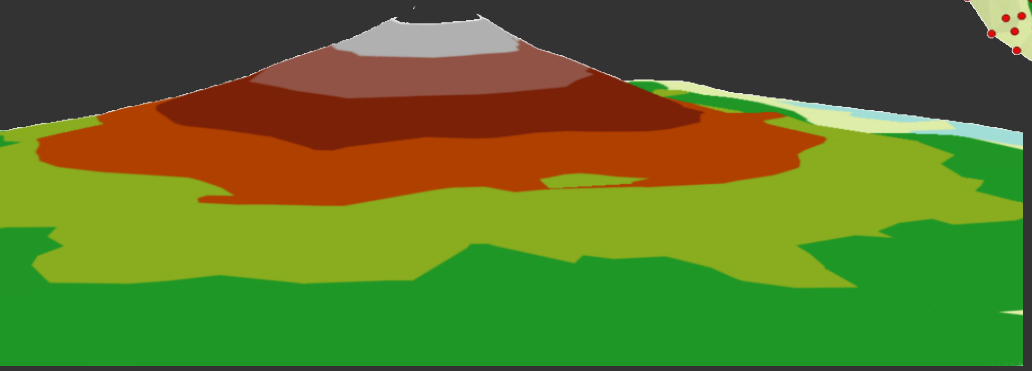


Vector Data, Not for Discrete Features

- TINs (Triangulated Irregular Network)
- Good for representing terrain data
- A space filling model

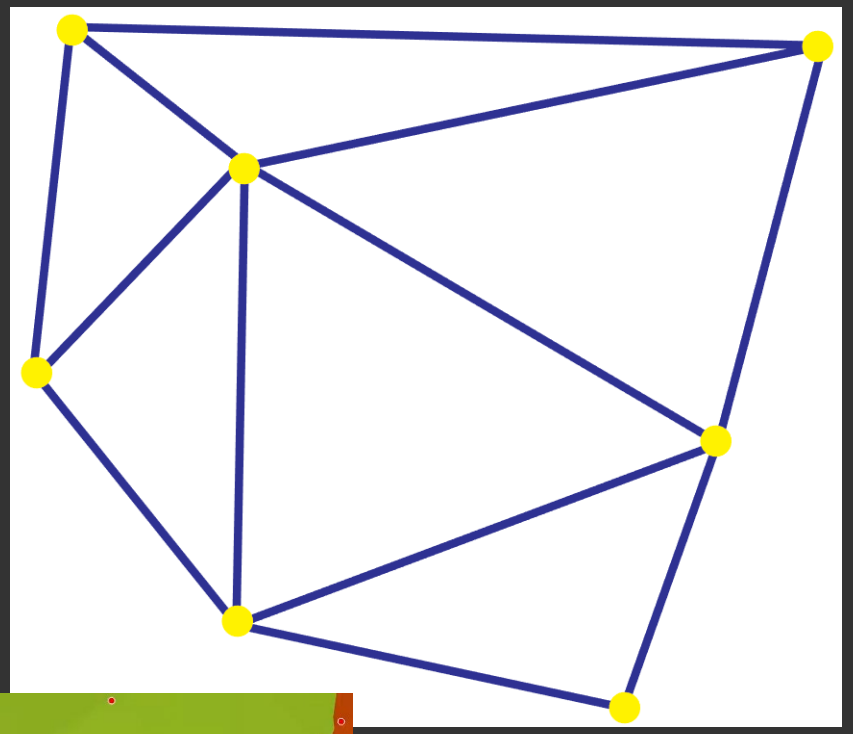


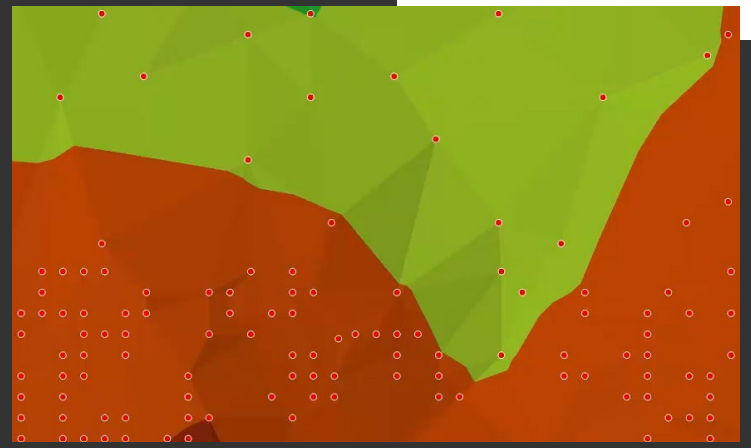




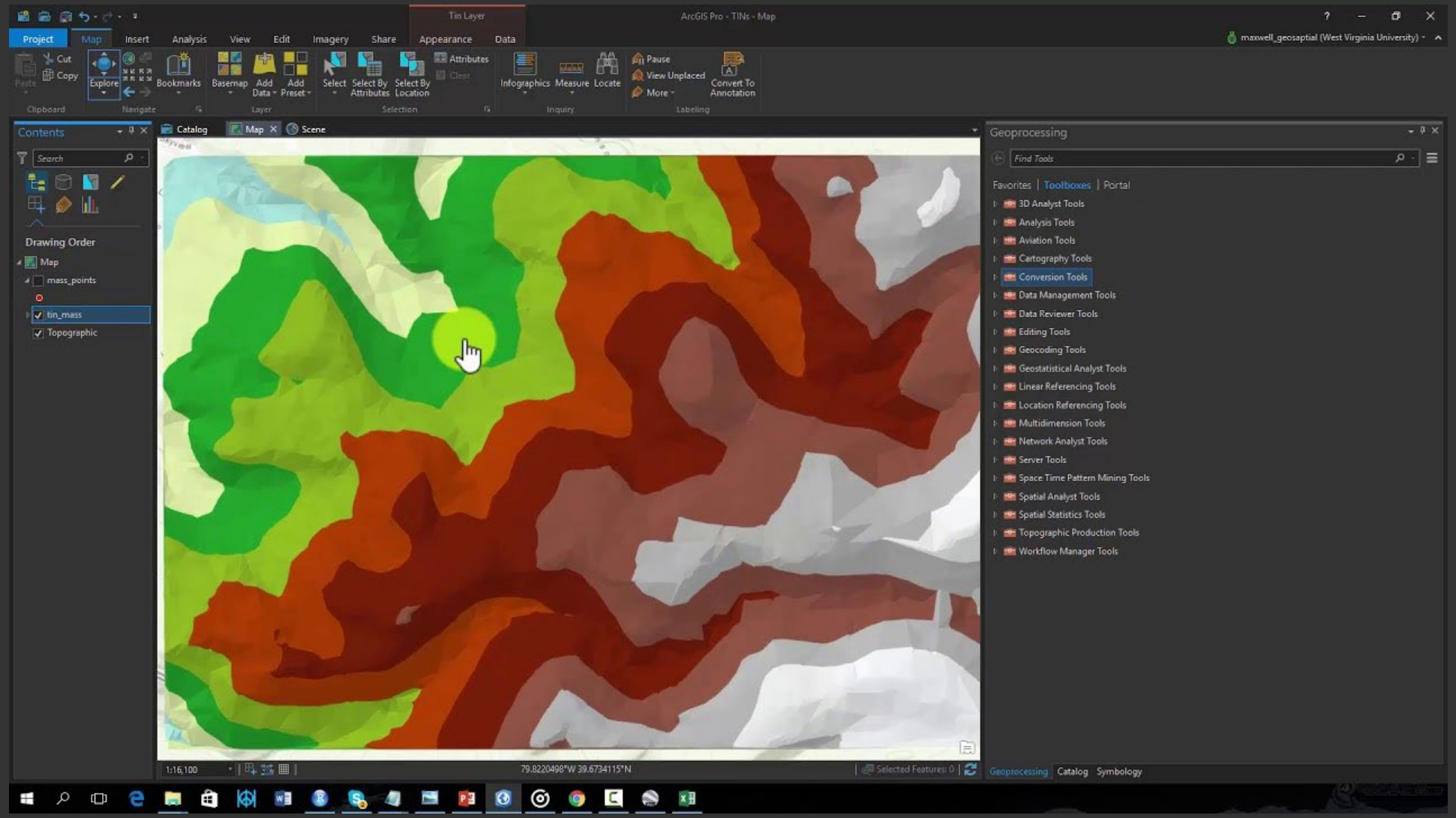
TINs

- Connecting measurement points to form a triangle (face)
- Can also include contours and/or breaklines
- Lines connecting points = edges
- Can be used to represent a terrain (or other continuous surfaces)
- Pros and cons compared to raster data





Video: TINs


Tin Layer
ArcGIS Pro - TINs - Map
Project
Map
Insert
Analysis
View
Edit
Imagery
Share
Appearance
Data
maxwell_geosaptial (West Virginia University)
Cut
Copy
Paste
Explore
Bookmarks
Basemap
Add Data
Add Preset
Select
Select By Attributes
Select By Location
Attributes
Clear
Infographics
Measure
Locate
Pause
View Unplaced
More
Convert To Annotation
Clipboard
Navigate
Layer
Selection
Inquiry
Labeling
Contents
Search
Drawing Order
Map
mass_points
tin_mass
Topographic
Catalog
Map
Scene
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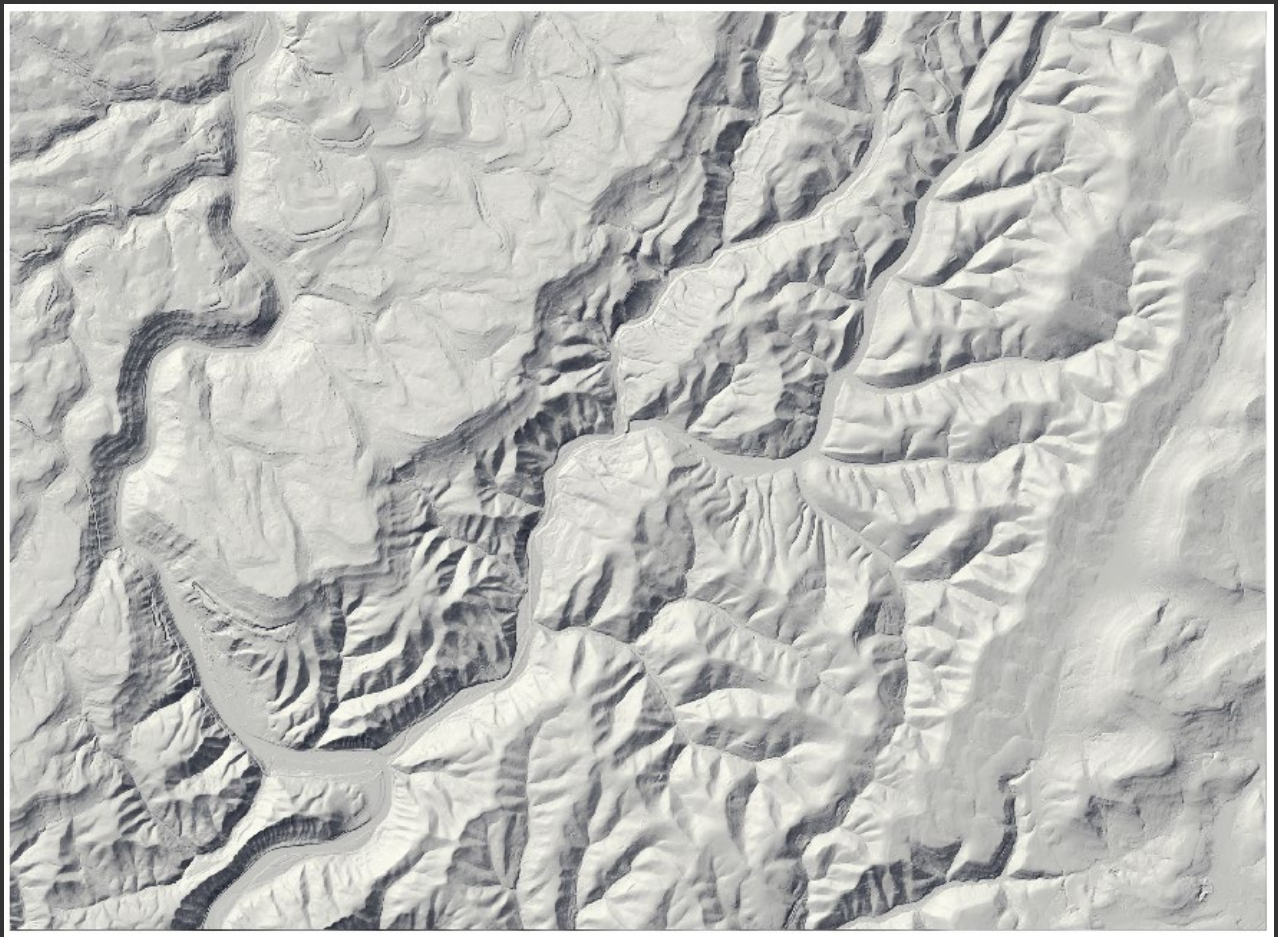
79.8220498°W 39.6734115°N
Selected Features: 0
Geoprocessing
Find Tools
Favorites
Toolboxes
Portal
3D Analyst Tools
Analysis Tools
Aviation Tools
Cartography Tools
Conversion Tools
Data Management Tools
Data Reviewer Tools
Editing Tools
Geocoding Tools
Geostatistical Analyst Tools
Linear Referencing Tools
Location Referencing Tools
Multidimension Tools
Network Analyst Tools
Server Tools
Space Time Pattern Mining Tools
Spatial Analyst Tools
Spatial Statistics Tools
Topographic Production Tools
Workflow Manager Tools
Geoprocessing
Catalog
Symbology

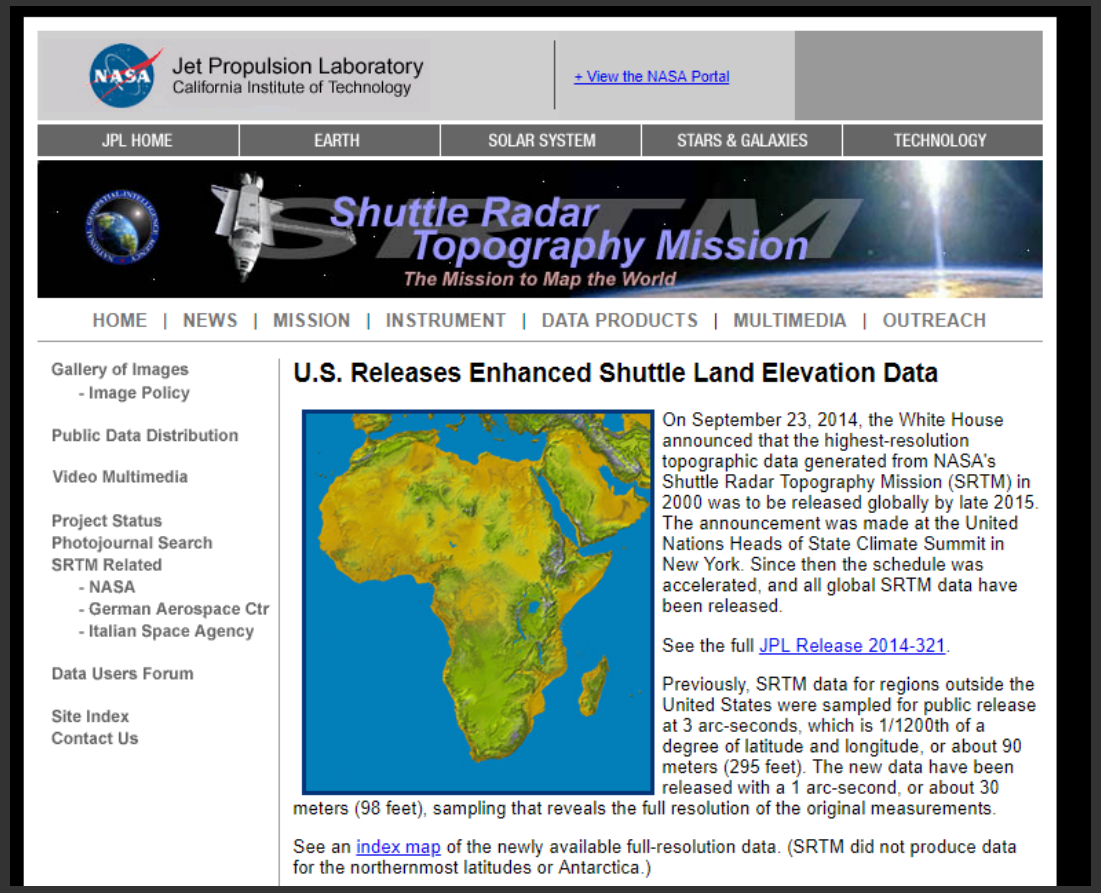
What are the sources of terrain data

1. Contour Lines and hypsography data
2. Photogrammetry
3. Radar (Radio Detection and Ranging)
4. LiDAR (Light Detection and Ranging)
5. GPS
6. Structure from Motion



Radio Detection and Ranging (RaDAR)

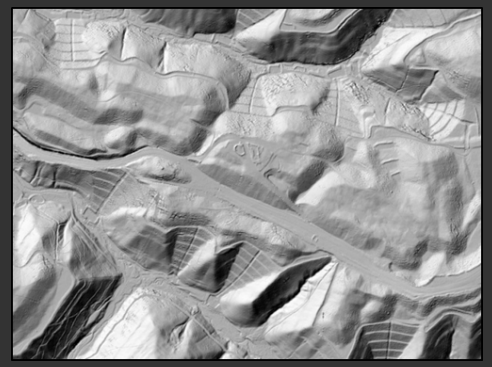
- SRTM (Shuttle Radar Topography Mission)
- February 2000
- 11 day mission
- Mapped 80% of world at 90 m resolution
- 30 meter over US

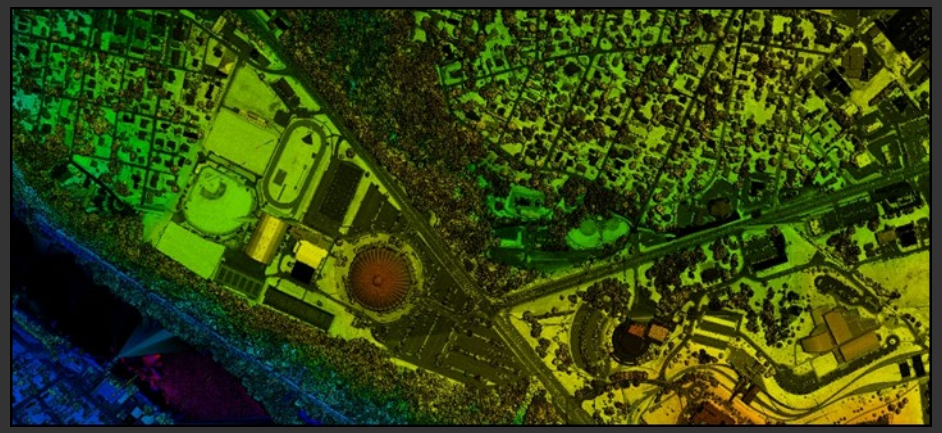


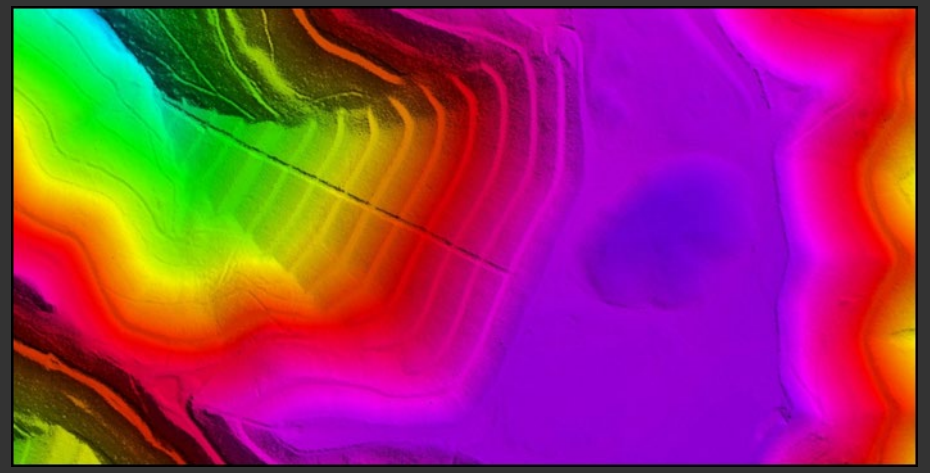
https://www2.jpl.nasa.gov/srtm/

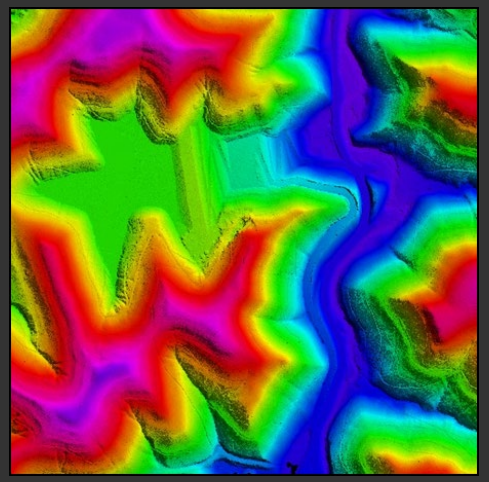
Light Detection and Ranging (LiDAR)

- Use laser pulses
- Often collected from a aircraft
- Provides multiple returns per each laser pulse
- High resolution (sub meters)
- High accuracy (+/- 10 cm)

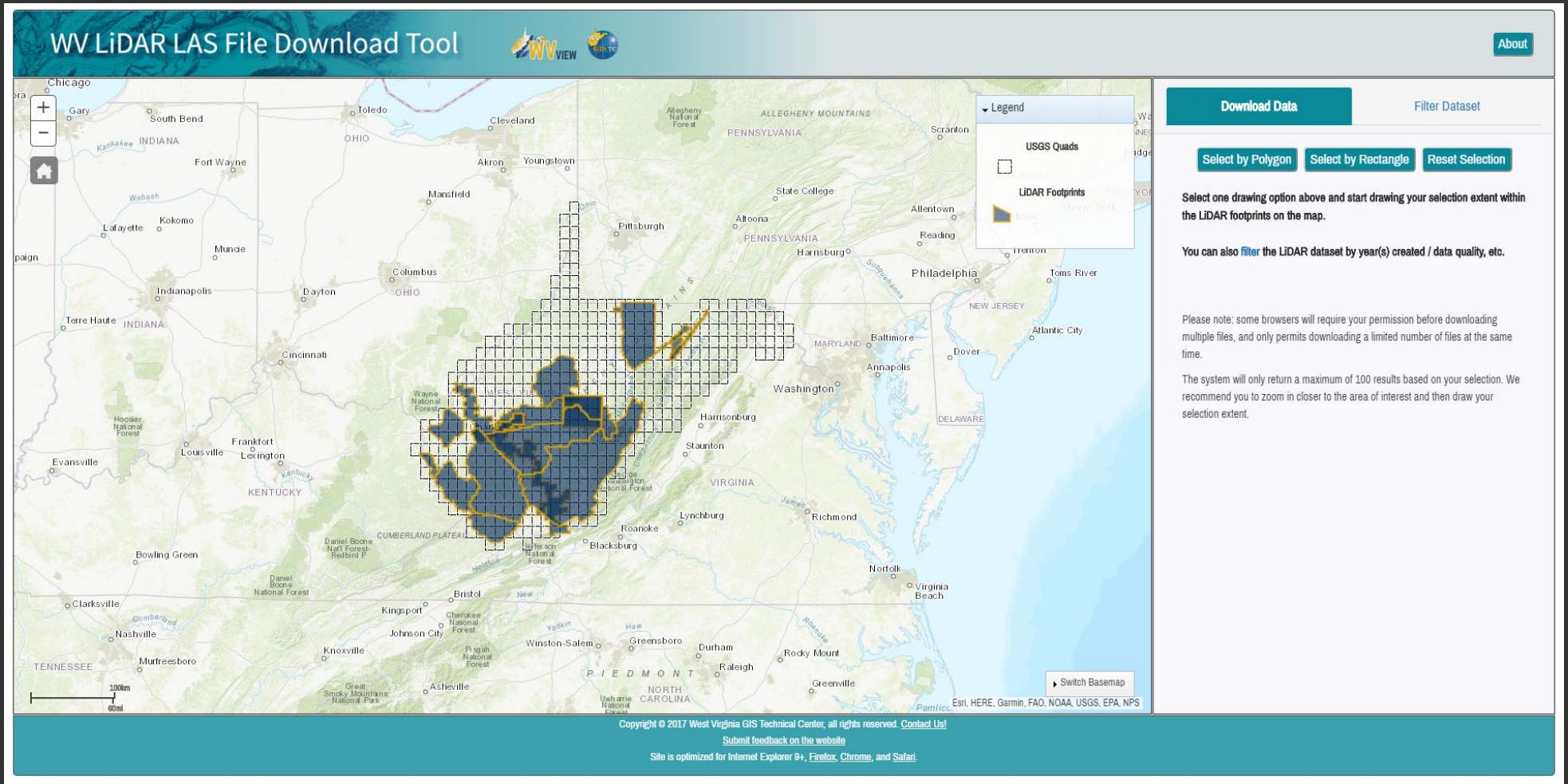






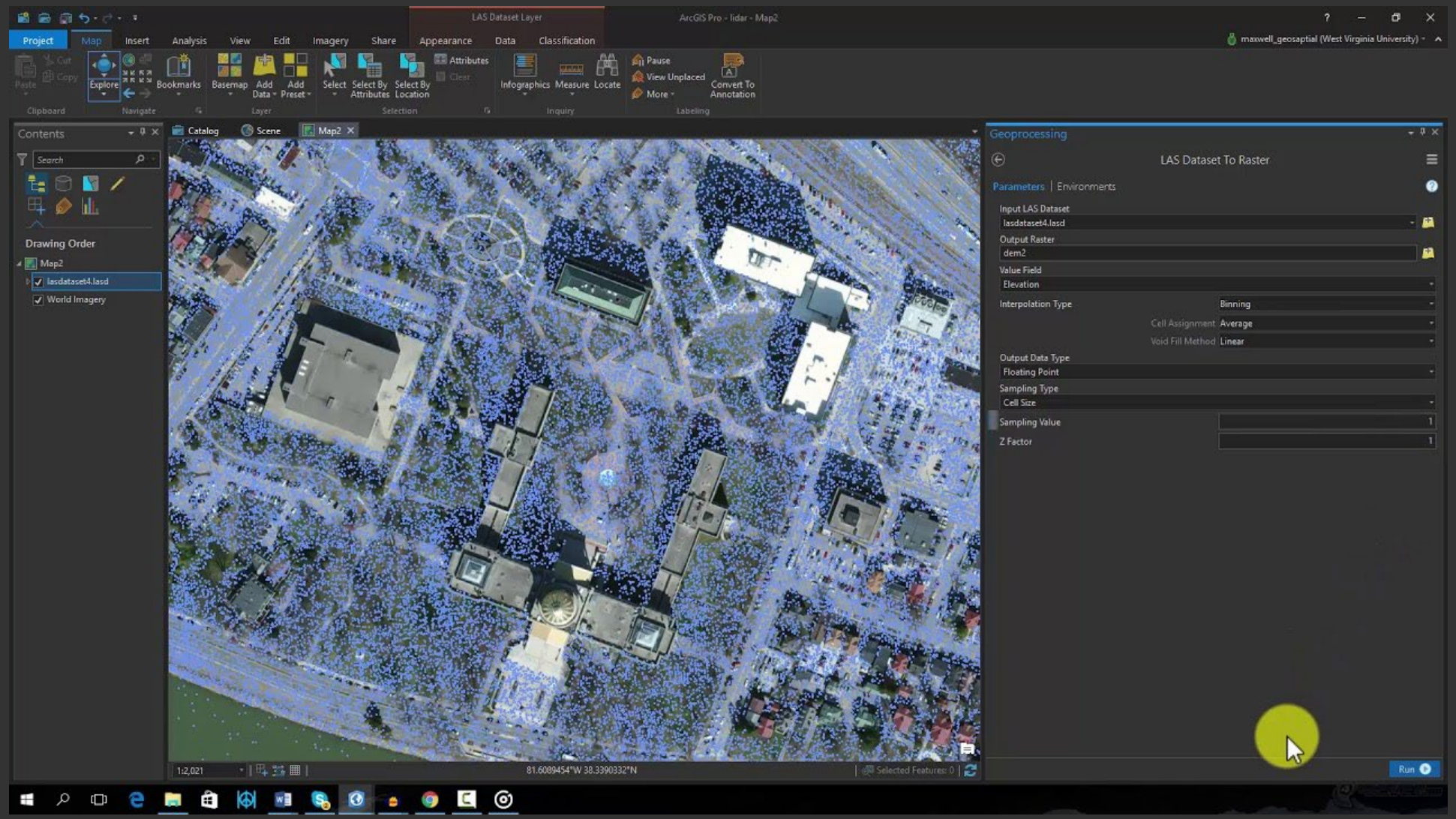


LiDAR in West Virginia



http://www.wvgis.wvu.edu/lidar/

Video: LiDAR


LAS Dataset Layer
ArcGIS Pro - lidar - Map2
Project
Map
Insert
Analysis
View
Edit
Imagery
Share
Appearance
Data
Classification
maxwell_geosaptial (West Virginia University)
Explore
Bookmarks
Basemap
Add Data
Add Preset
Select
Select By Attributes
Select By Location
Attributes
Infographics
Measure
Locate
Pause
View Unplaced
More
Convert To Annotation
Clipboard
Navigate
Layer
Selection
Inquiry
Labeling
Contents
Search
Drawing Order
Map2
lasdataset4.lasd
World Imagery
Catalog
Scene
Map2
Geoprocessing
LAS Dataset To Raster
Parameters
Environments
Input LAS Dataset
lasdataset4.lasd
Output Raster
dem2
Value Field
Elevation
Interpolation Type
Binning
Cell Assignment
Average
Void Fill Method
Linear
Output Data Type
Floating Point
Sampling Type
Cell Size
Sampling Value
1
Z Factor
1
Run
1:2,021
81.6089454°W 38.3390332°N
Selected Features: 0

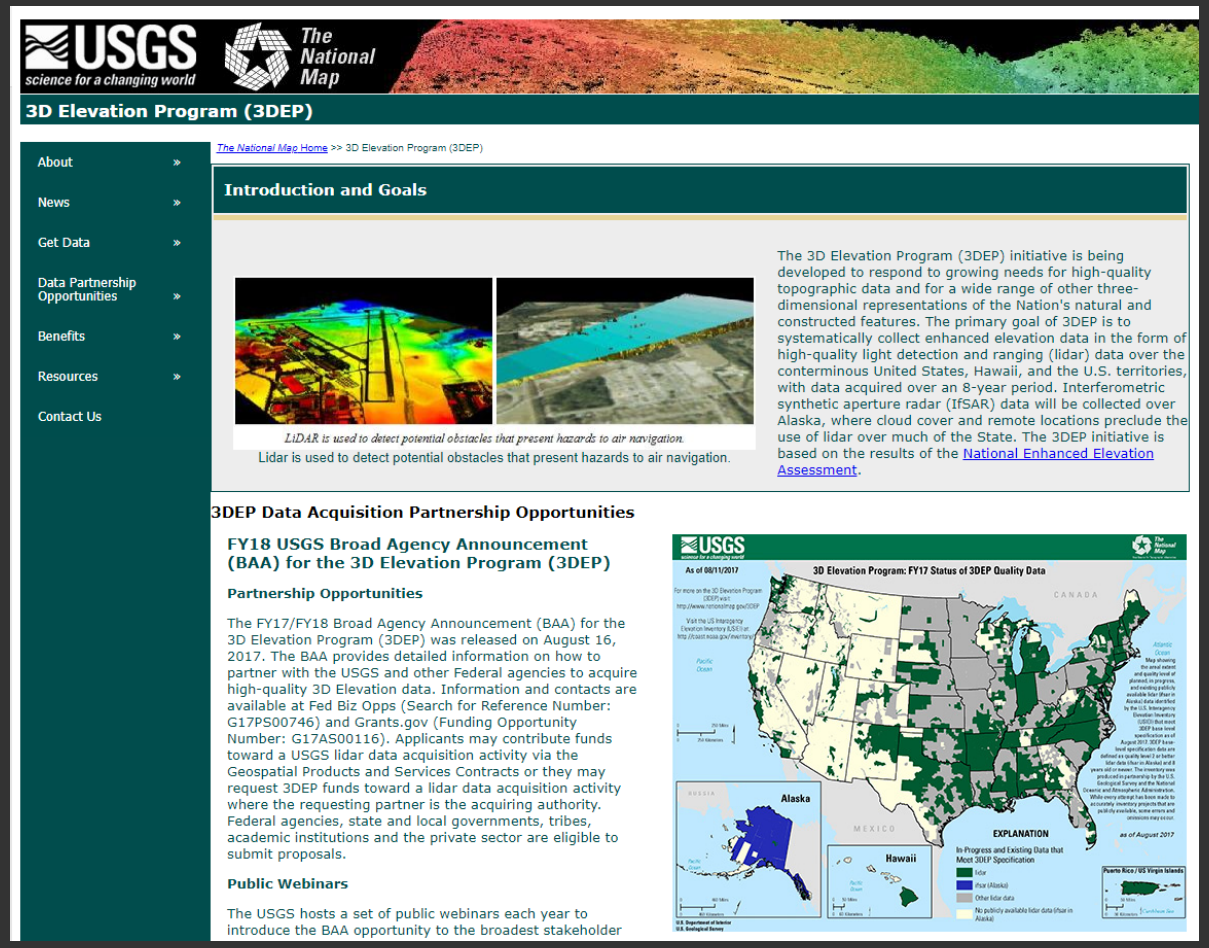
Structure from Motion (SfM)

- Terrain data created from overlapping drone imagery

Image provided by NRAC

USGS 3DEP Program

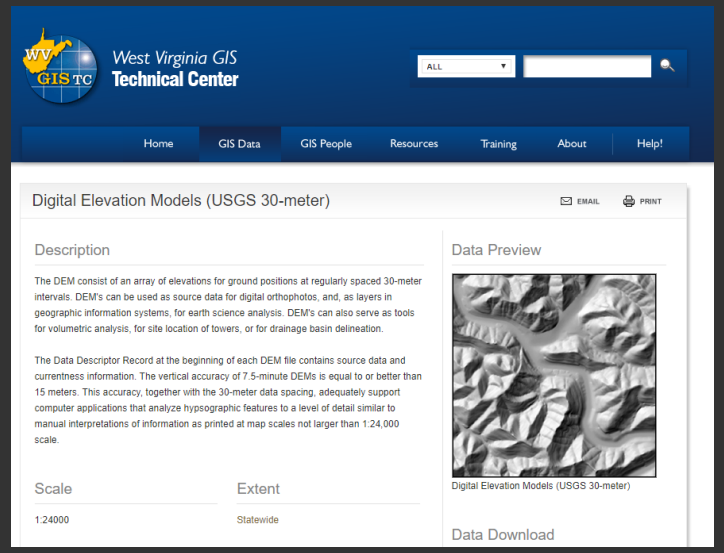
- Free elevation data download
- Draws from a variety of data sources
- A replacement for the National Elevation Dataset (NED)
- This is still developing



https://nationalmap.gov/3DEP/

National Elevation Dataset (NED)

- US data
- 30 m (1 arc-second)
- 10 m (1/3 arc-second)
- 3 m (1/9 arc-second)



http://wvgis.wvu.edu/data/dataset.php?ID=28

National Elevation Dataset (NED)

The National Elevation Dataset (NED) is the primary elevation data product of the USGS. The NED is a seamless dataset with the best available raster elevation data of the conterminous United States, Alaska, Hawaii, and territorial islands. The NED is updated on a nominal two month cycle to integrate newly available, improved elevation source data. All NED data are public domain.

The NED is derived from diverse source data that are processed to a common coordinate system and unit of vertical measure. NED data are distributed in geographic coordinates in units of decimal degrees, and in conformance with the North American Datum of 1983 (NAD 83). All elevation values are in meters and, over the conterminous United States, are referenced to the North American Vertical Datum of 1988 (NAVD 88). The vertical reference will vary in other areas.

NED data are available nationally (except for Alaska) at resolutions of 1 arc-second (about 30 meters) and 1/3 arc-second (about 10 meters), and in limited areas at 1/9 arc-second (about 3 meters). In most of Alaska, only lower resolution source data are available. As a result, most NED data for Alaska are at 2-arc-second (about 60 meters) grid spacing. Part of Alaska is available at the 1- and 1/3-arc-second resolution, and plans are in development for a significant improvement in elevation data coverage of the state.

The NED serves as the elevation layer of The National Map, and provides basic elevation information for earth science studies and mapping applications in the United States. Scientists and resource managers use NED data for global change research, hydrologic modeling, resource monitoring, mapping and visualization, and many other applications.

NED subset image *(Grand Canyon)*

https://lta.cr.usgs.gov/NED

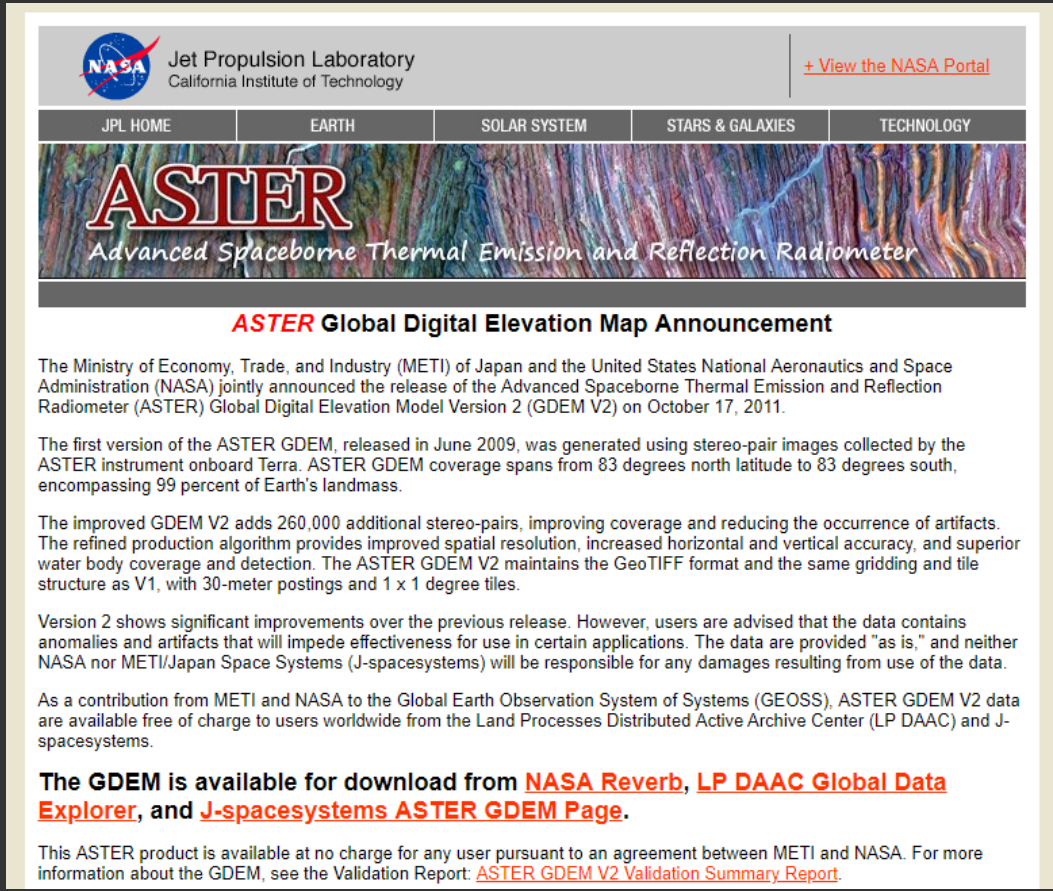
WV Statewide Addressing and Mapping Board (WVSAMB) 3 m Data

- Photogrammetric DEM
- 2003
- 3 m data

http://wvgis.wvu.edu/data/dataset.php?ID=261

ASTER Global Digital Elevation

- Photogrammetric
- Derived from the Advanced Spaceborne Thermal Emission Reflectance Radiometer (ASTER) onboard Terra
- Global coverage
- 30 m



Jet Propulsion Laboratory
California Institute of Technology

+ View the NASA Portal

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ASTER
Advanced Spaceborne Thermal Emission and Reflection Radiometer

ASTER Global Digital Elevation Map Announcement

The Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA) jointly announced the release of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 2 (GDEM V2) on October 17, 2011.

The first version of the ASTER GDEM, released in June 2009, was generated using stereo-pair images collected by the ASTER instrument onboard Terra. ASTER GDEM coverage spans from 83 degrees north latitude to 83 degrees south, encompassing 99 percent of Earth's landmass.

The improved GDEM V2 adds 260,000 additional stereo-pairs, improving coverage and reducing the occurrence of artifacts. The refined production algorithm provides improved spatial resolution, increased horizontal and vertical accuracy, and superior water body coverage and detection. The ASTER GDEM V2 maintains the GeoTIFF format and the same gridding and tile structure as V1, with 30-meter postings and 1 x 1 degree tiles.

Version 2 shows significant improvements over the previous release. However, users are advised that the data contains anomalies and artifacts that will impede effectiveness for use in certain applications. The data are provided "as is," and neither NASA nor METI/Japan Space Systems (J-spacesystems) will be responsible for any damages resulting from use of the data.

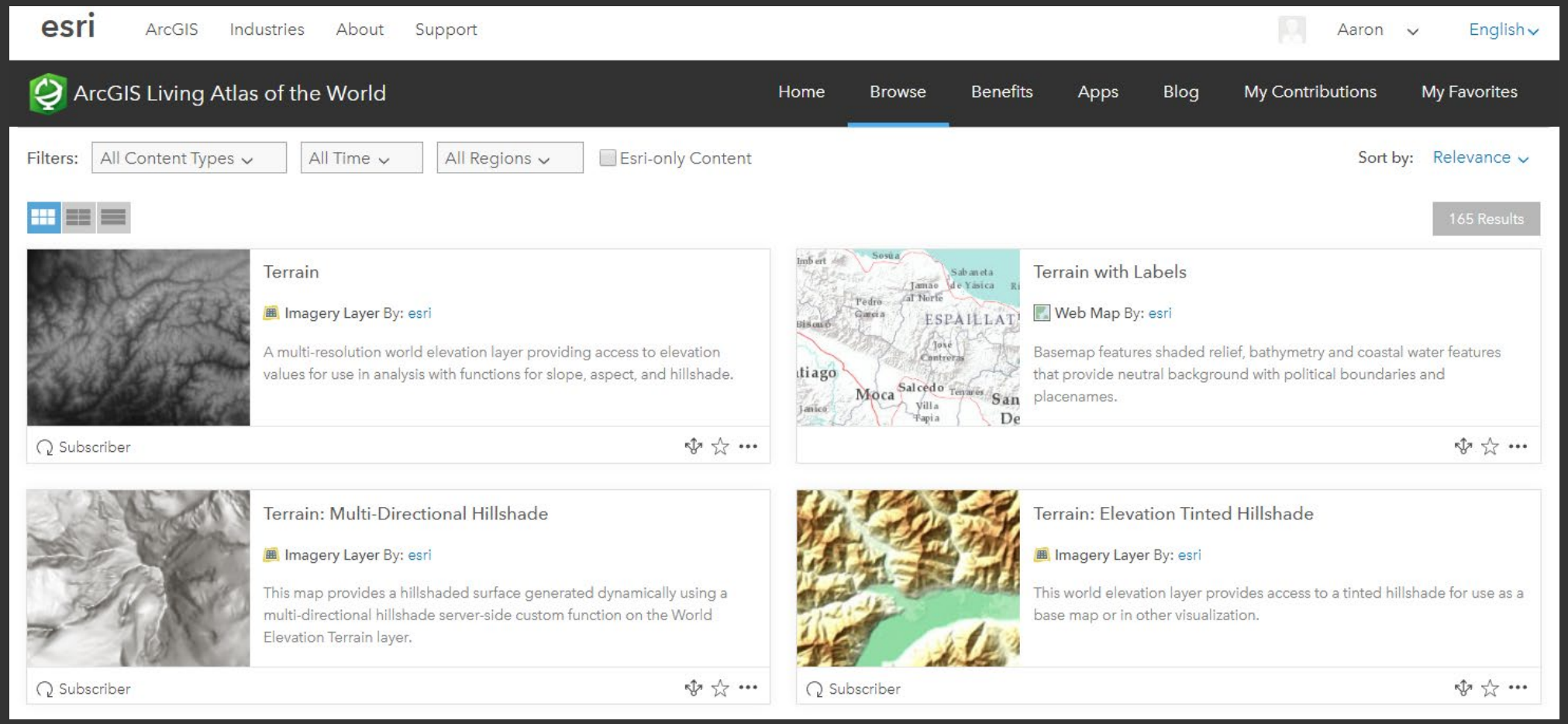
As a contribution from METI and NASA to the Global Earth Observation System of Systems (GEOSS), ASTER GDEM V2 data are available free of charge to users worldwide from the Land Processes Distributed Active Archive Center (LP DAAC) and J-spacesystems.

The GDEM is available for download from NASA Reverb, LP DAAC Global Data Explorer, and J-spacesystems ASTER GDEM Page.

This ASTER product is available at no charge for any user pursuant to an agreement between METI and NASA. For more information about the GDEM, see the Validation Report: ASTER GDEM V2 Validation Summary Report.

https://asterweb.jpl.nasa.gov/gdem.asp

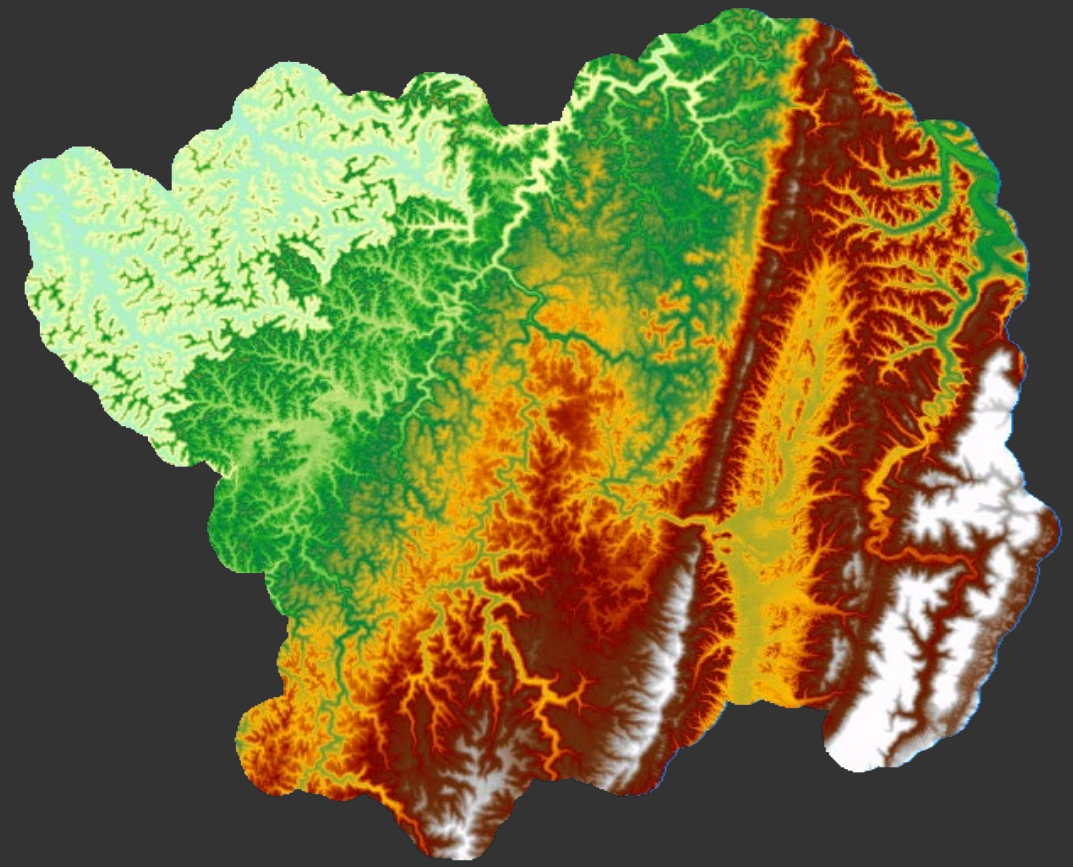
DEM data from Living Atlas



https://livingatlas.arcgis.com/en/home/

Things to know about your data

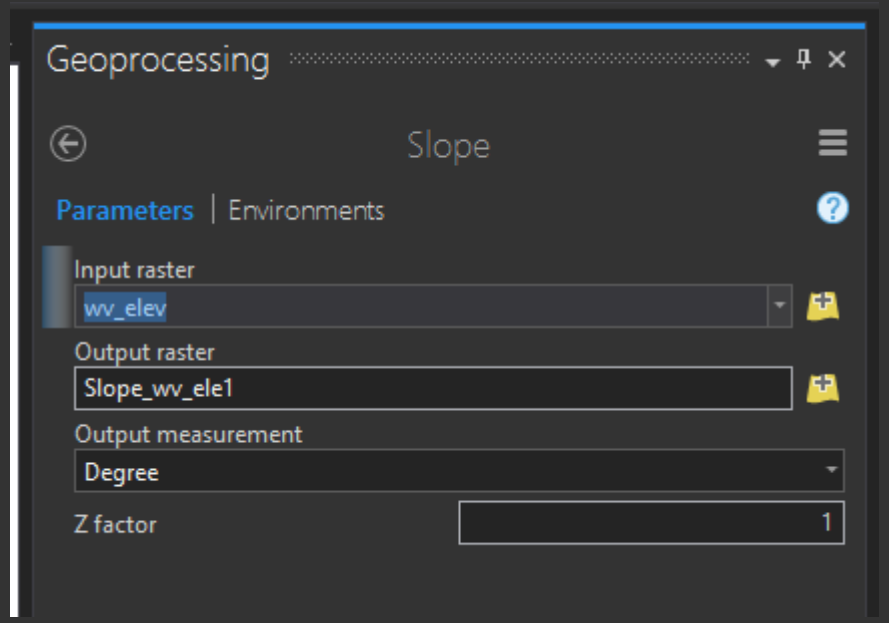
1. Source
2. Collection date(s)
3. Feet or meters?
4. Vertical datum
5. Horizontal datum
6. Accuracy/precision



Terrain Derivatives

Z-Factor

- If vertical and horizontal units are different, you can correct for this with a Z factor
- You can also use a Z factor to exaggerate the vertical relative to the horizontal

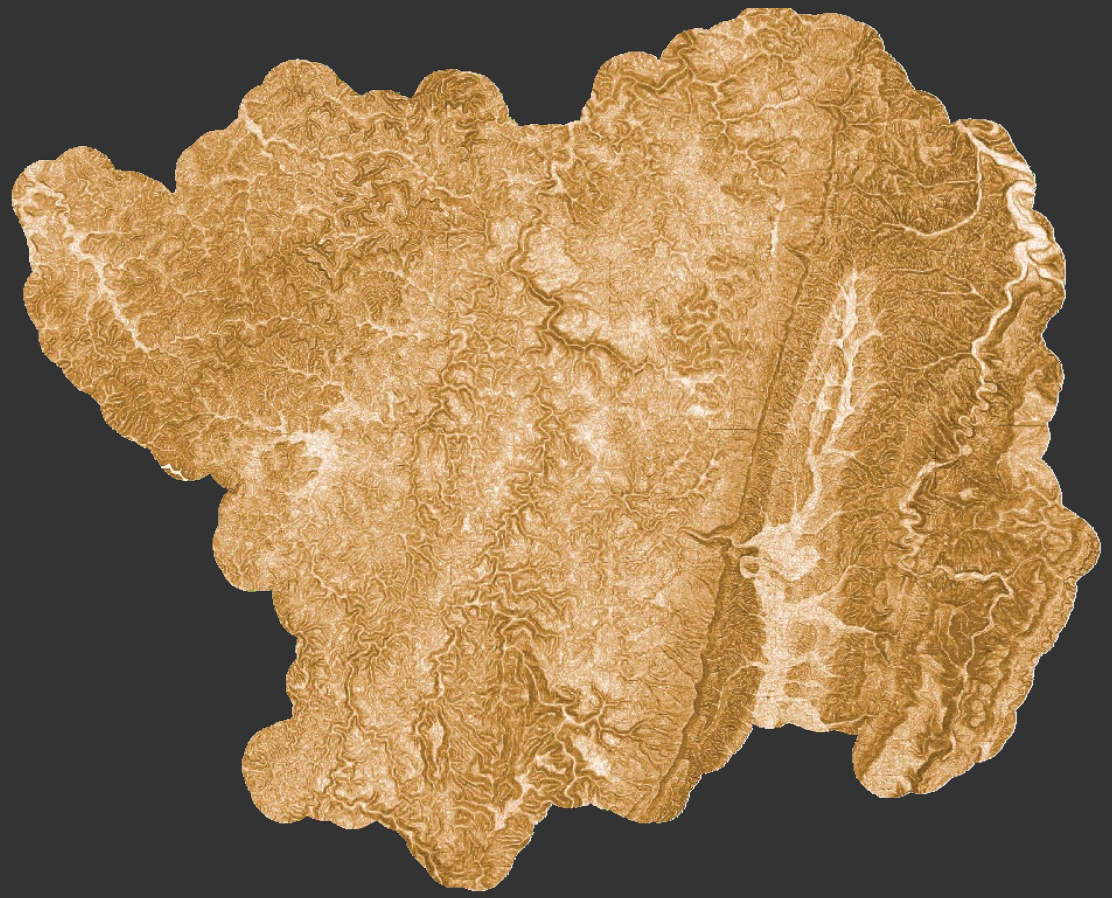


Topographic Slope

- Rate of elevation change
- Calculated using a 3 x 3 window

$$\text{Percent Slope} = \frac{Rise}{Run} \text{ X } 100$$

$$\text{Degrees Slope} = \frac{Rise}{Run} = \tan(\theta)$$



How is slope calculated in a GIS?

a	b	c
d	e	f
g	h	i

$$slope_radians = ATAN\ (\ \sqrt{\ ([dz/dx]^2 + [dz/dy]^2)}\ )$$

$$slope_degrees = ATAN\ (\ \sqrt{\ ([dz/dx]^2 + [dz/dy]^2)}\ ) * 57.29578$$

$$slope_degrees = ATAN\ (rise_run) * 57.29578$$

$$[dz/dy] = ((g + 2h + i)*4/wght3 - (a + 2b + c)*4/wght4) / (8 * y_cellsize)$$

$$[dz/dx] = ((c + 2f + i)*4/wght1 - (a + 2d + g)*4/wght2) / (8 * x_cellsize)$$

c, *f*, and *i* all have valid values, *wght1* = (1+2*1+1) = 4.
i is NoData, *wght1* = (1+2*1+0) = 3.
f is NoData, *wght1* = (1+2*0+1) = 2.

http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-slope-works.htm

How is slope calculated in a GIS?

50	45	50
30	30	30
8	10	10

[dz/dx] = ((*c* + 2*f* + *i*)*4/*wght1* - (*a* + 2*d* + *g*)*4/*wght2*) / (8 * *x_cellsize*) = ((50 + 60 + 10)*4/(1+2+1) - (50 + 60 + 8)*4/(1+2+1)) / (8 * 5) = (120 - 118) / 40 = 0.05

[dz/dy] = ((*g* + 2*h* + *i*)*4/*wght3* - (*a* + 2*b* + *c*)*4/*wght4*) / (8 * *y_cellsize*) = ((8 + 20 + 10)*4/(1+2+1) - (50 + 90 + 50)*4/(1+2+1)) / (8 * 5) = (38 - 190) / 40 = -3.8

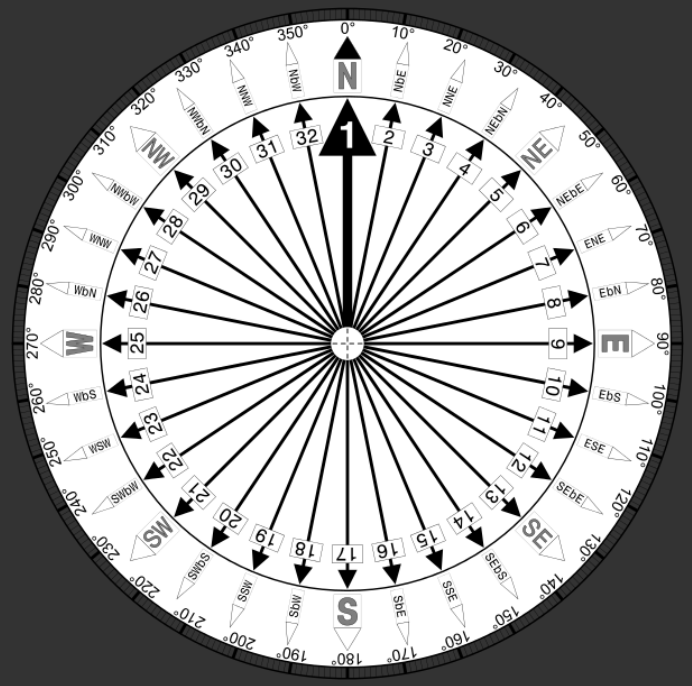
rise_run = $\sqrt{([dz/dx]^2 + [dz/dy]^2)} = \sqrt{((0.05)^2 + (-3.8)^2)}$ = $\sqrt{(0.0025 + 14.44)}$ = 3.80032

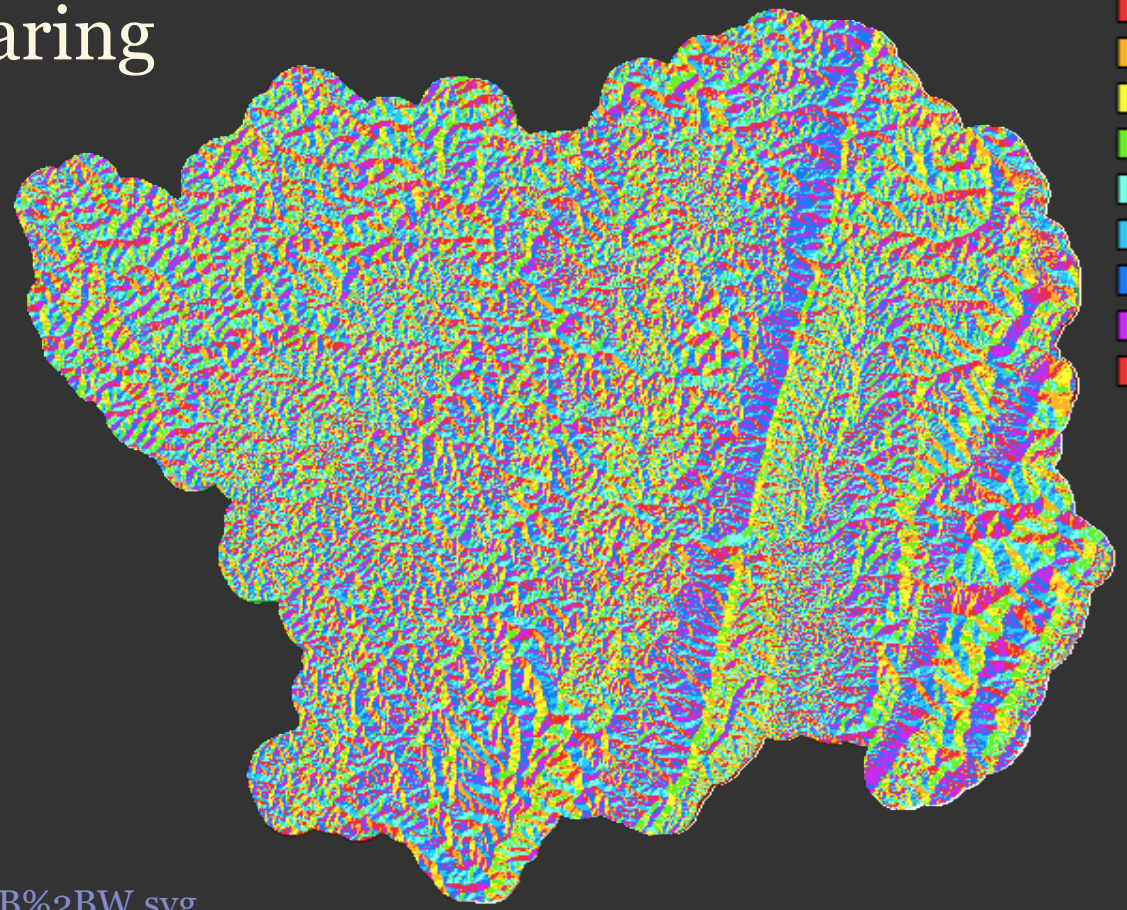
slope_degrees = ATAN (*rise_run*) * 57.29578 = ATAN (3.80032) * 57.29578 = 1.31349 * 57.29578 = 75.25762

http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-slope-works.htm

Topographic Aspect

- Direction of maximum slope
- Reported as a compass bearing





https://commons.wikimedia.org/wiki/File:Compass_Card_B%2BW.svg

How is topographic aspect calculated in a GIS?

a	b	c
d	e	f
g	h	i

$$[dz/dx] = ((c + 2f + i)*4/wght1 - (a + 2d + g)*4/wght2) / 8$$

$$[dz/dy] = ((g + 2h + i)*4/wght3 - (a + 2b + c)*4/wght4) / 8$$

$$aspect = 57.29578 * \text{atan2}([dz/dy], -[dz/dx])$$

http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-aspect-works.htm

How is topographic aspect calculated in a GIS?

101	92	85
101	92	85
101	91	84

[dz/dx] = ((*c* + 2*f* + *i*)*4/*wght1* - (*a* + 2*d* + *g*)*4/*wght2*) / 8 = ((85 + 170 + 84)*4/(1+2+1) - (101 + 202 + 101)*4/(1+2+1)) / 8 = -8.125

[dz/dy] = ((*g* + 2*h* + *i*)*4/*wght3* - (*a* + 2*b* + *c*)*4/*wght4*) / 8 = ((101 + 182 + 84)*4/(1+2+1) - (101 + 184 + 85)*4/(1+2+1)) / 8 = -0.375

aspect = 57.29578 * atan2 ([dz/dy], -[dz/dx]) = 57.29578 * atan2 (-0.375, 8.125) = -2.64

cell = 90.0 - *aspect* = 90 - (-2.64) = 90 + 2.64 = 92.64

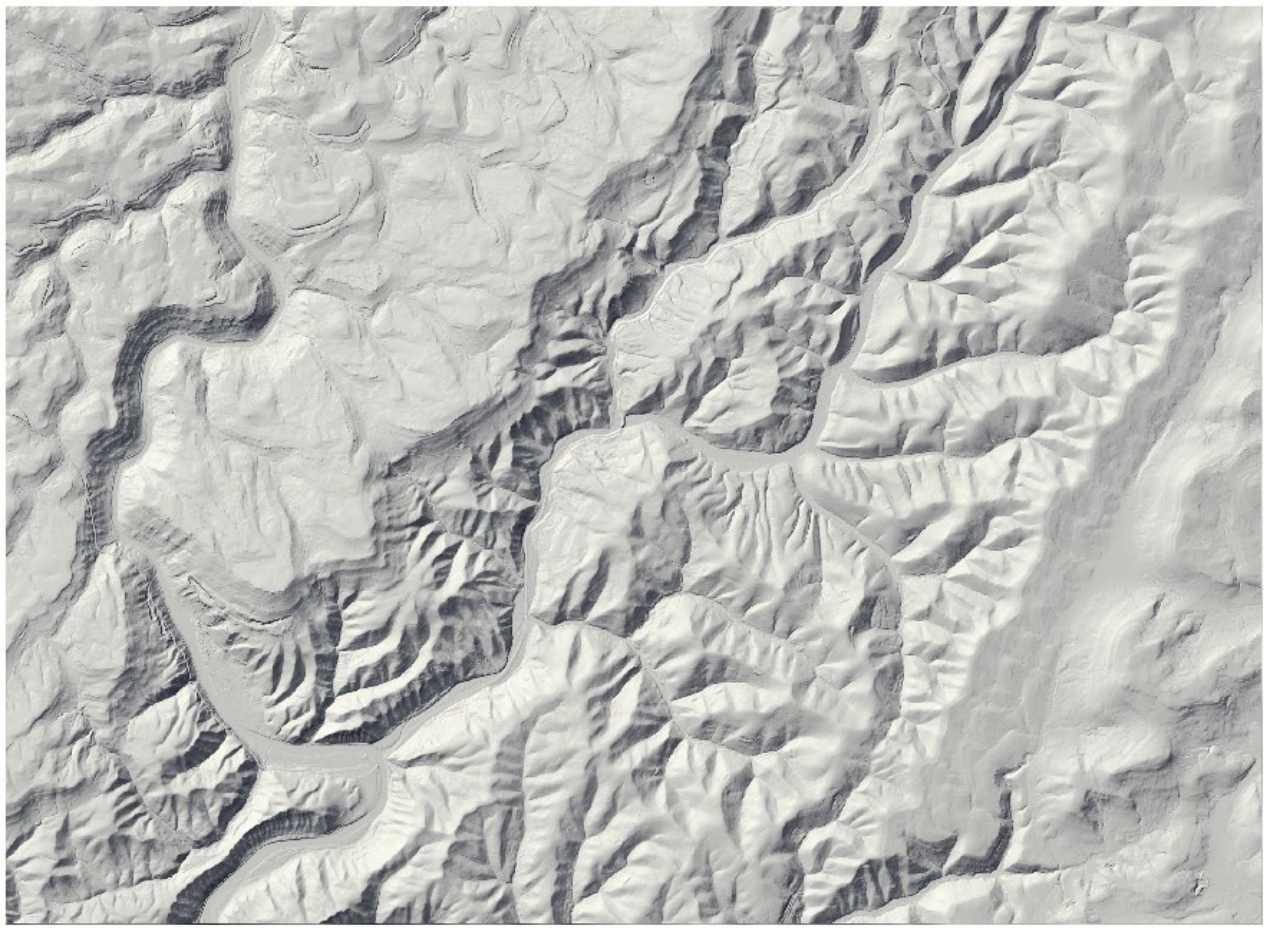
http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-aspect-works.htm

Hillshade

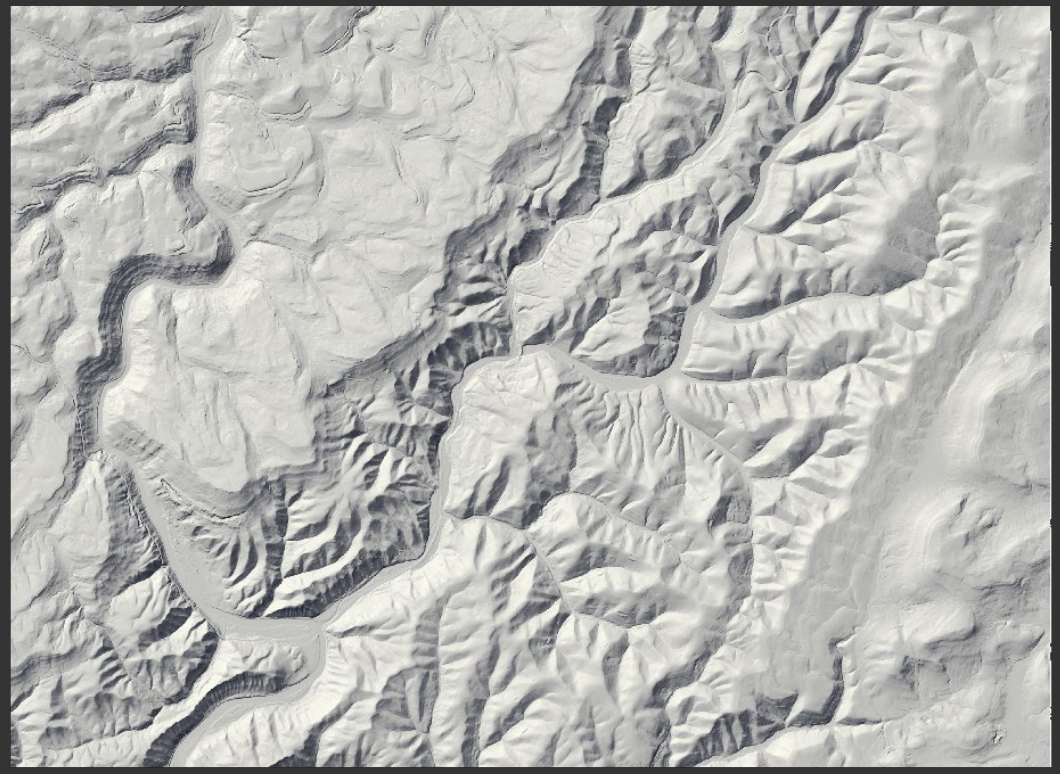
- A visual representation of a terrain using shadows
- Shadows are cast over the landscape to create a shaded relief surface

Sun Position

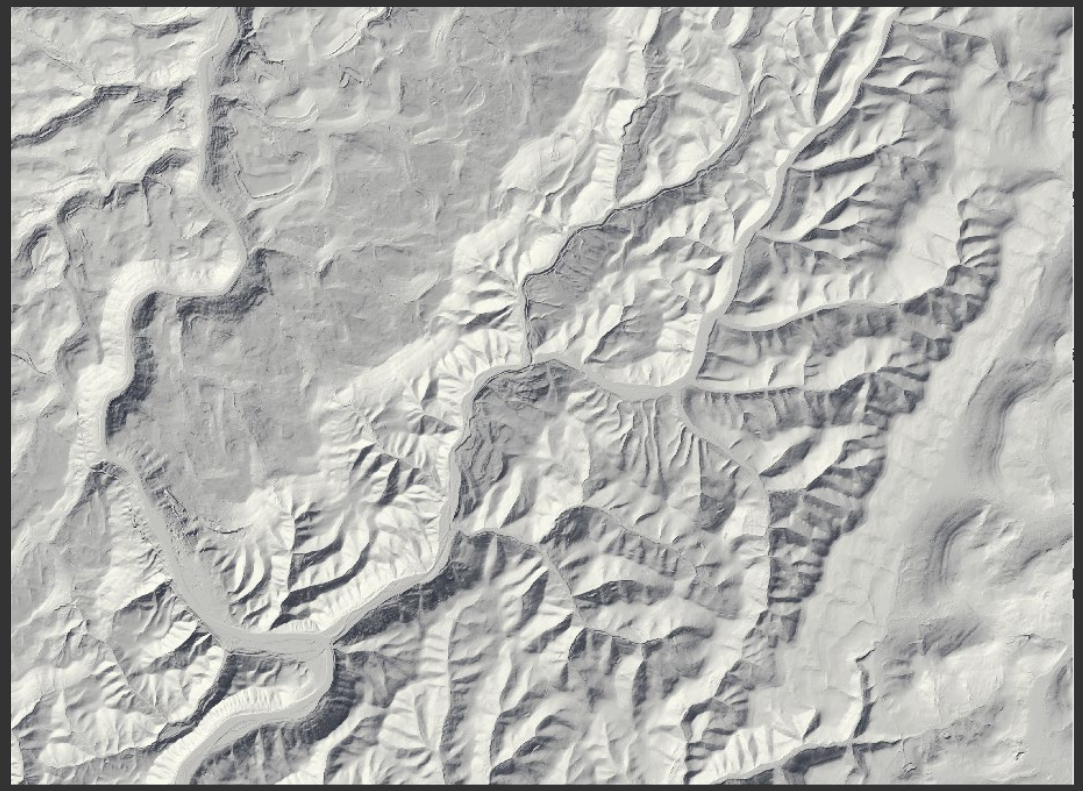
- Azimuth = compass bearing of Sun
- Altitude = height of Sun above horizon (as an angle)



Sun Position Matters

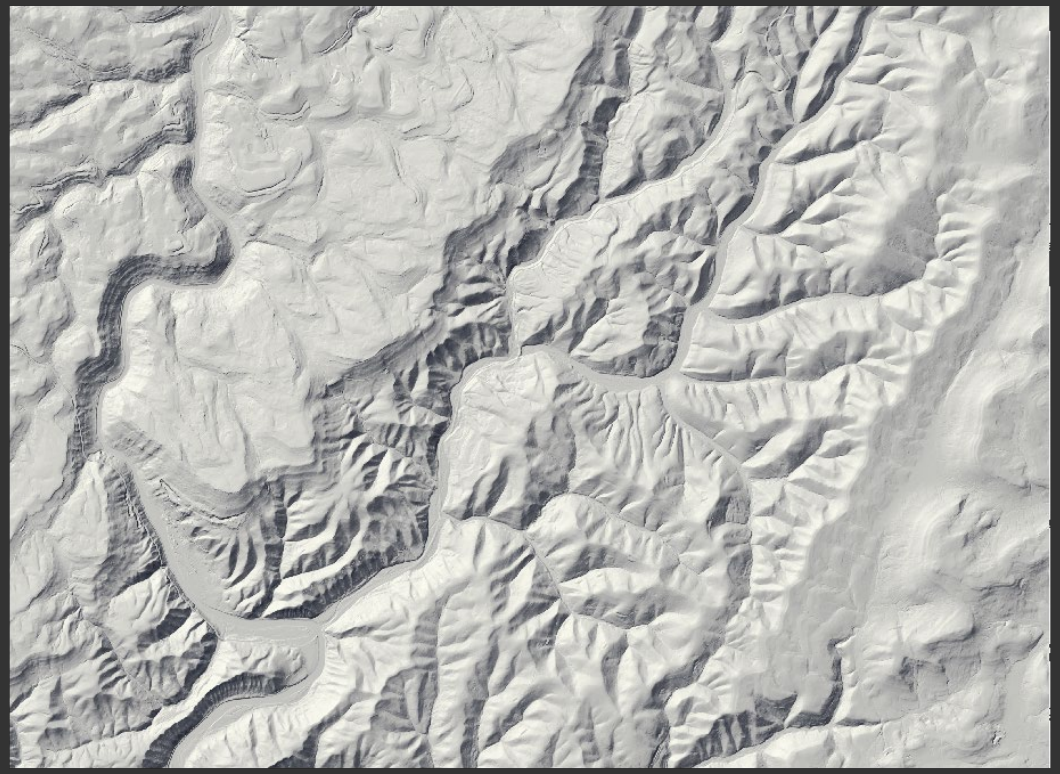


Azimuth = 315, Altitude = 45

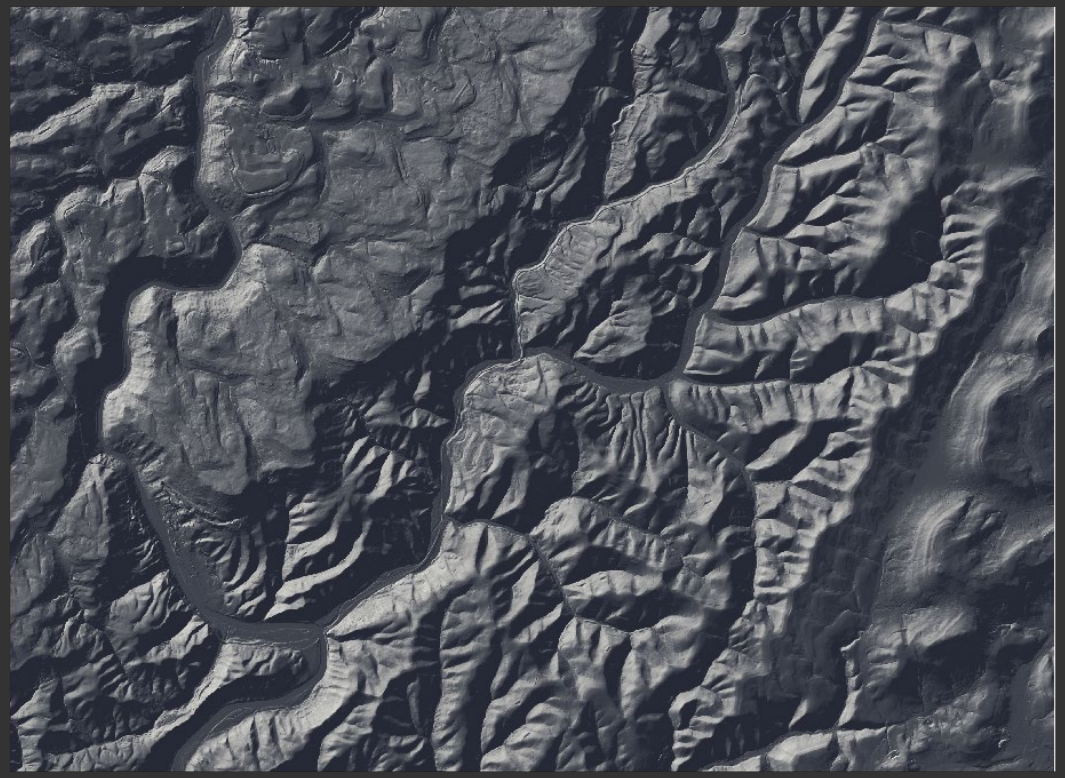


Azimuth = 135, Altitude = 45

Sun position matters



Azimuth = 315, Altitude = 45



Azimuth = 315, Altitude = 10

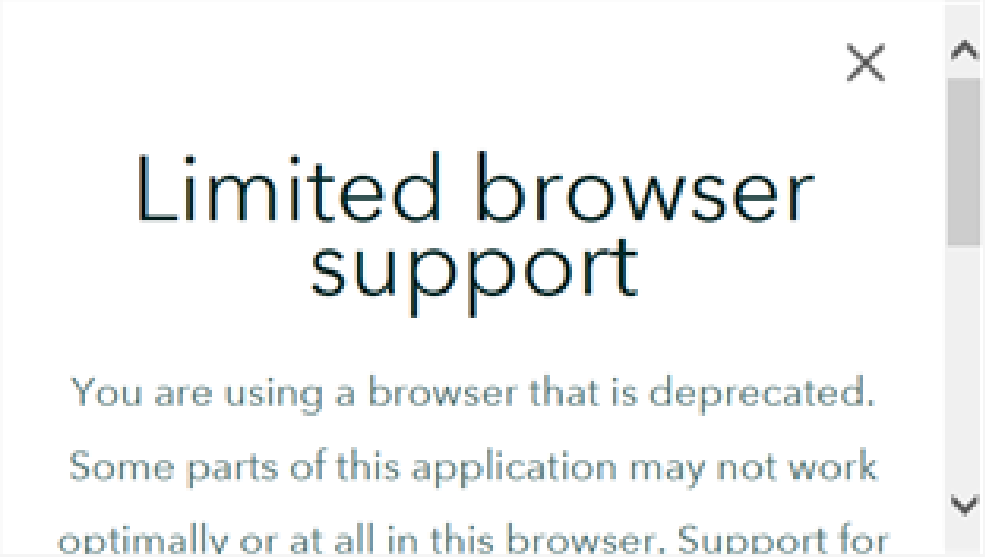
Multidirectional Hillshades

- Combine multiple sun positions
- North + Northwest + West + Southeast
- Extra weight for northwest
- Subtle detail on slopes that face all directions
- Useful in subtle terrain

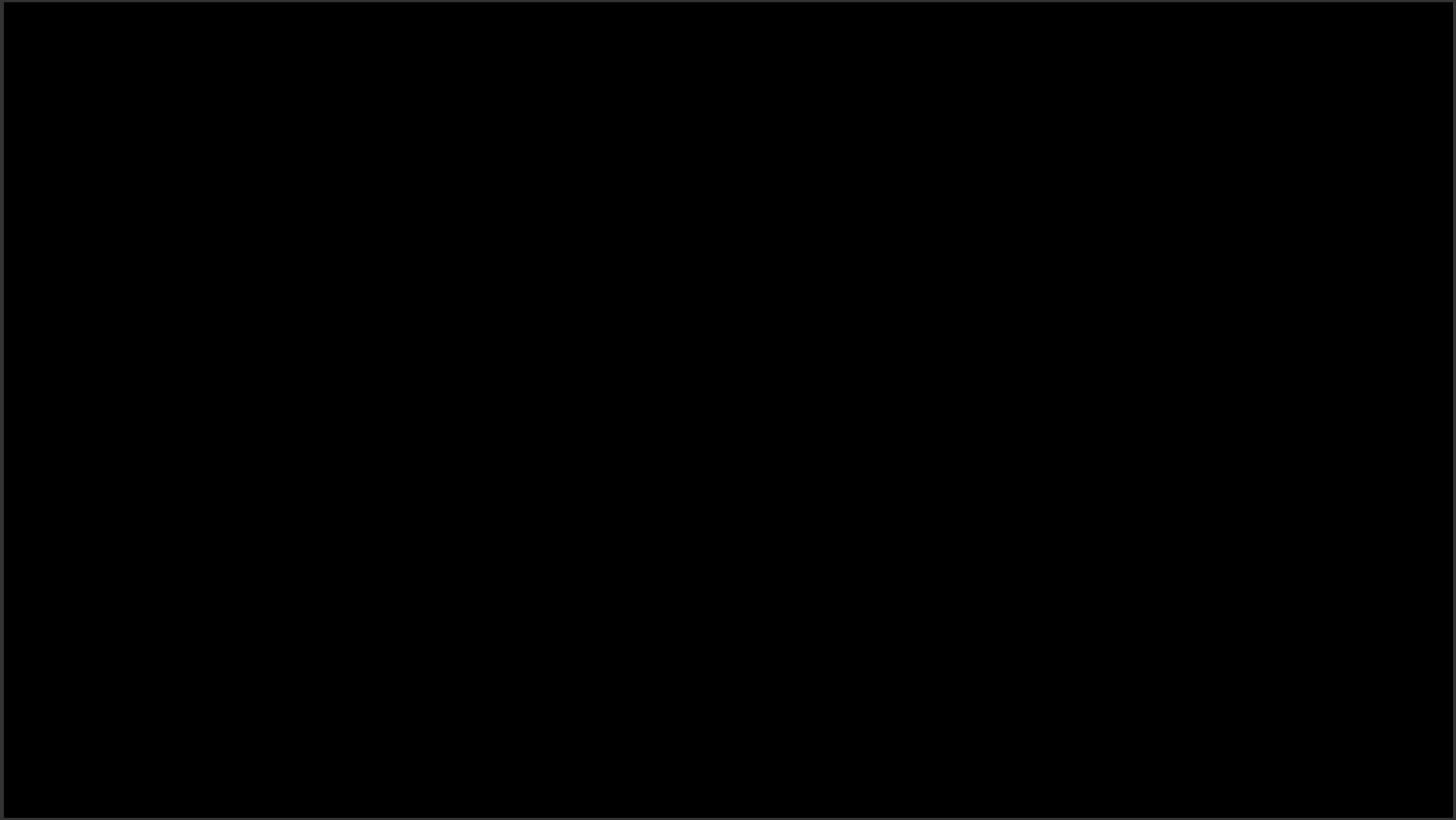
WV LiDAR-Derived Hillshade

Web Object

Select this object and click the **Web Object** button to edit



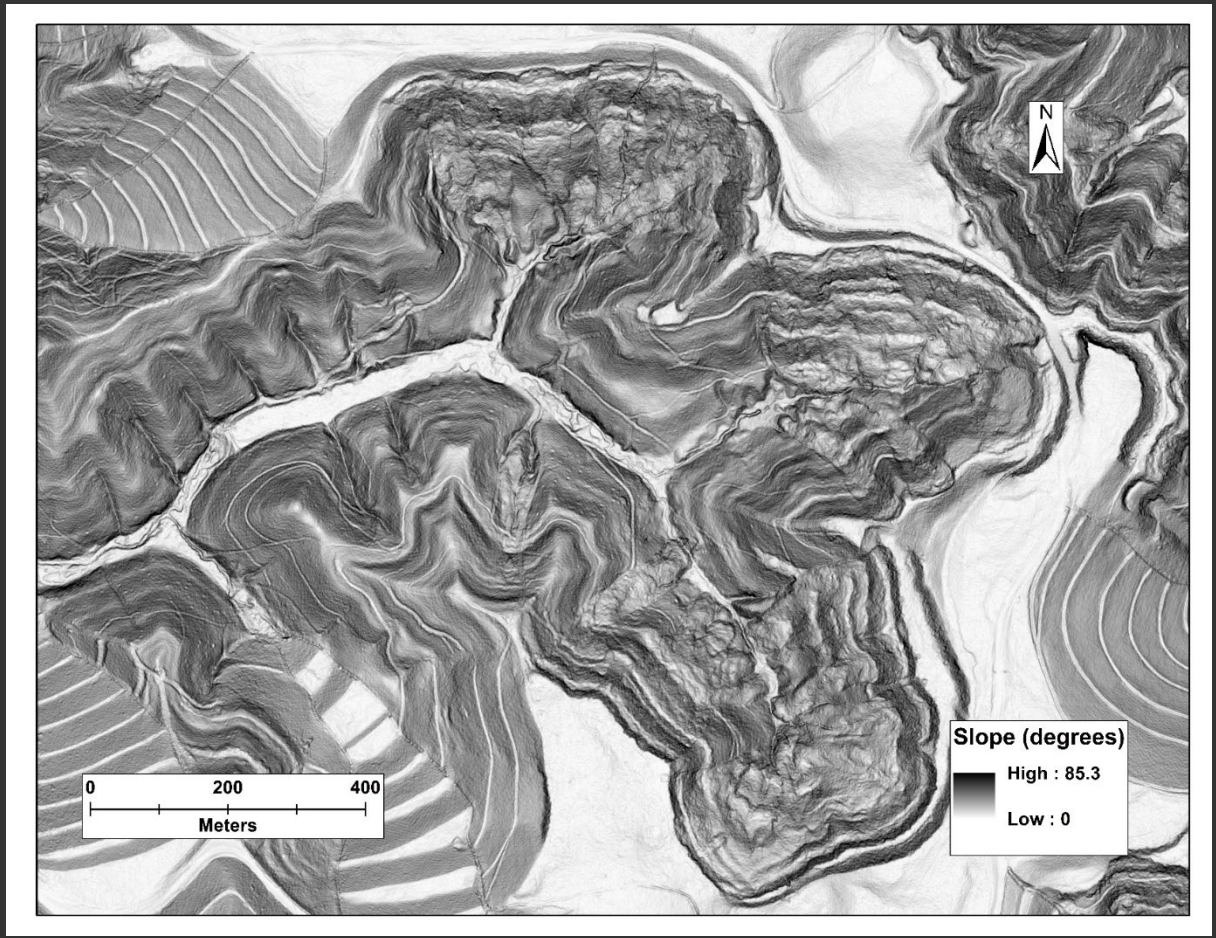
Video: Hillshades



Slopeshade

- Display slope using a white-black stretch
- White = shallow slopes
- Black = steep slopes

$$= \left(1 - \frac{Slope\ in\ Degrees}{90}\right) X\ 255$$



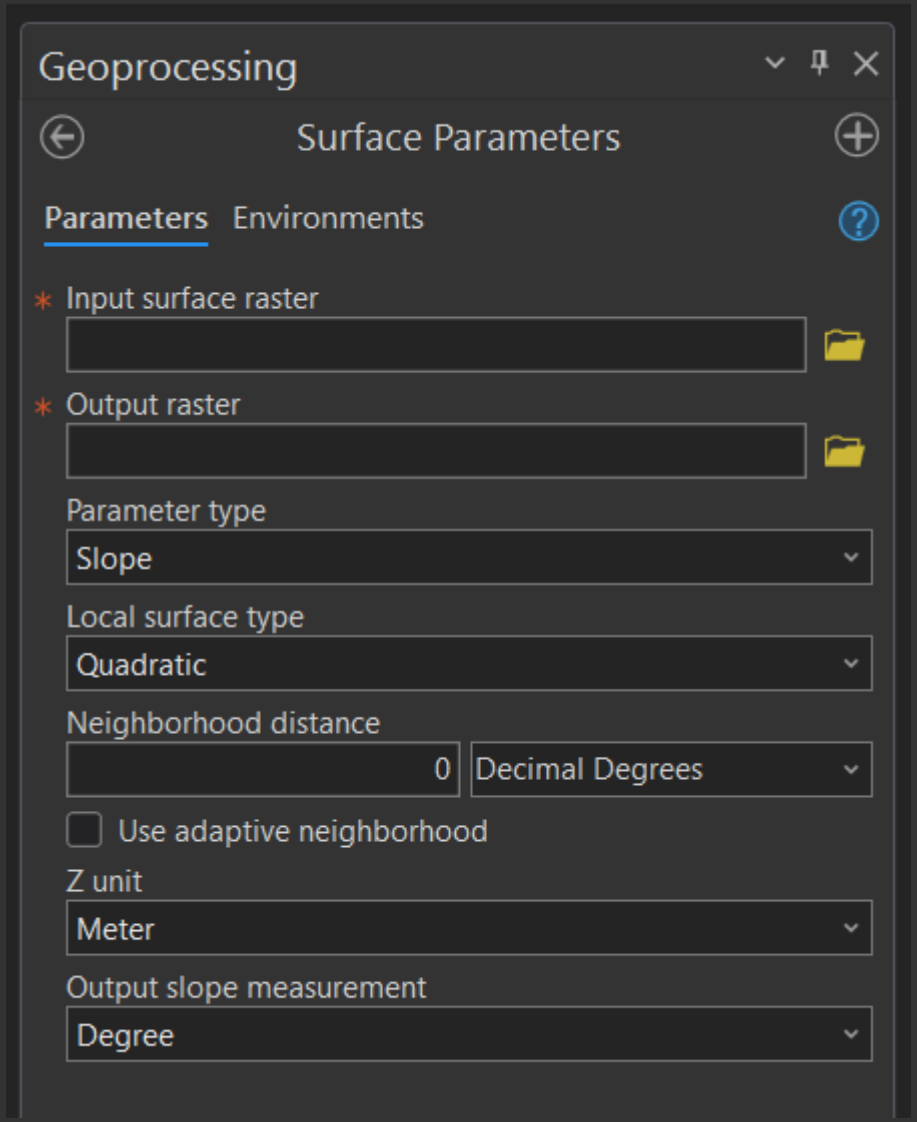
Map by Miles Reed

Surface Curvature

Negative = Concave
Positive = Convex
Near Zero = Flat

- Concavity/convexity of a surface
- Profile Curvature = curvature in direction of slope
- Planar Curvature = curvature perpendicular to direction of slope

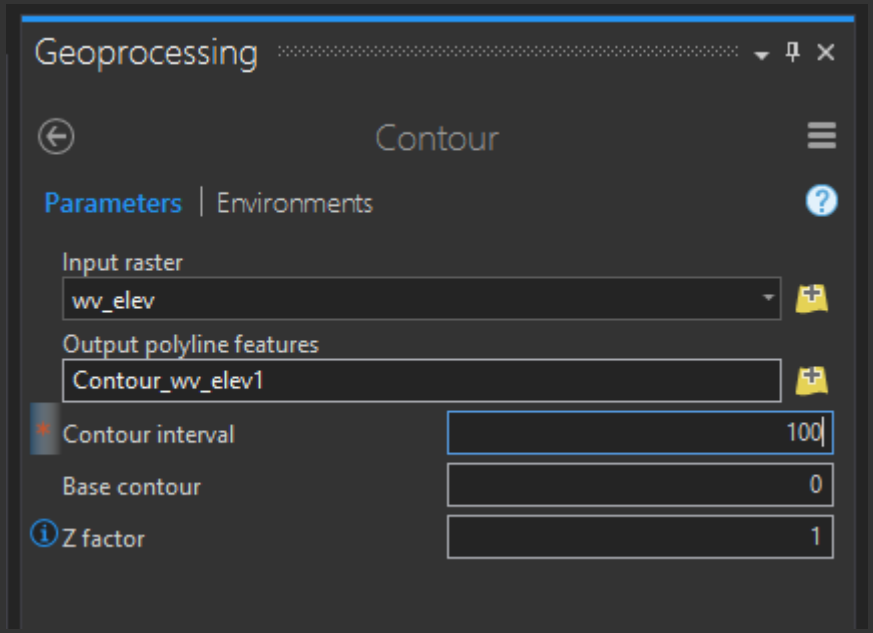
Surface Parameters

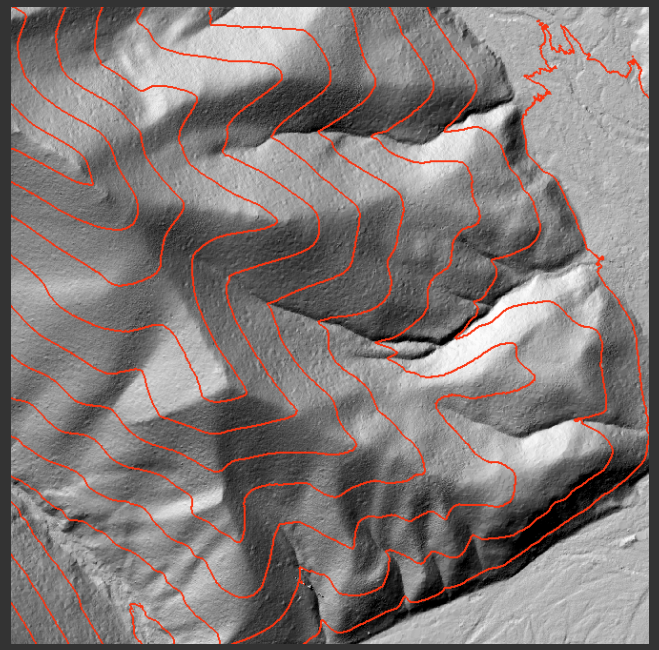


- Slope, Aspect, multiple measures of Curvature
- Can change the size of the moving window

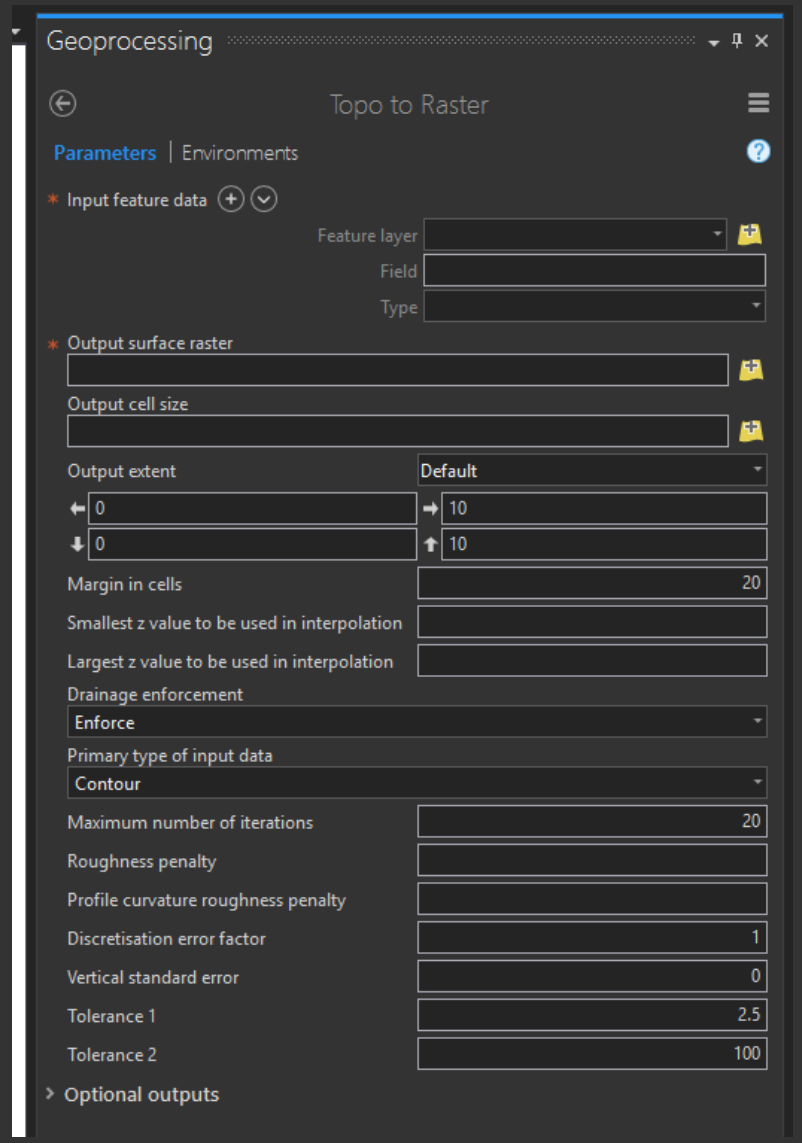
Contours

- Raster → Vector
- Must define an interval
- May require some smoothing





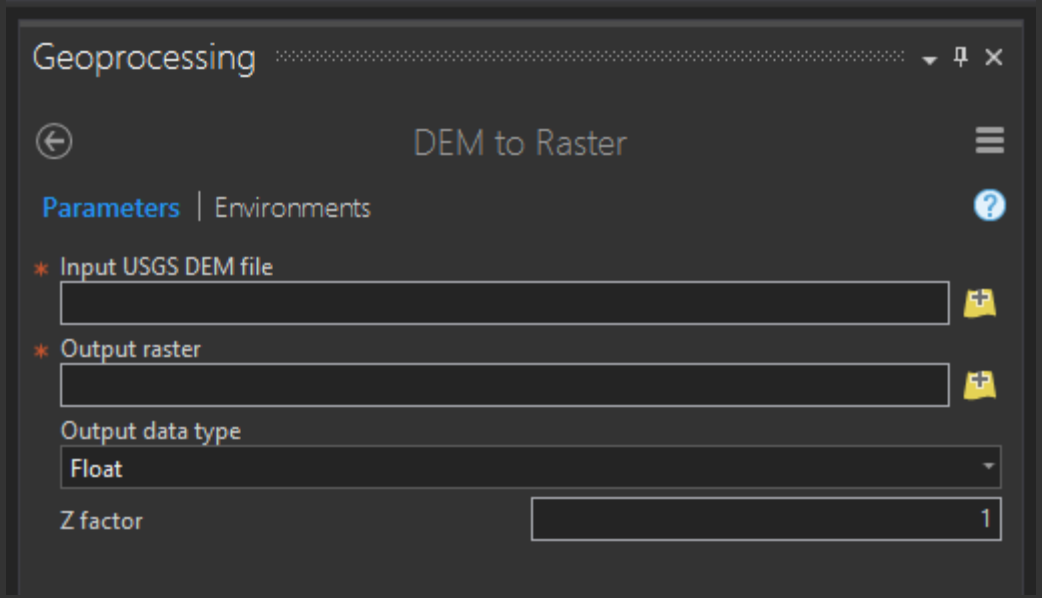
Contours to DEM



- Vector → Raster

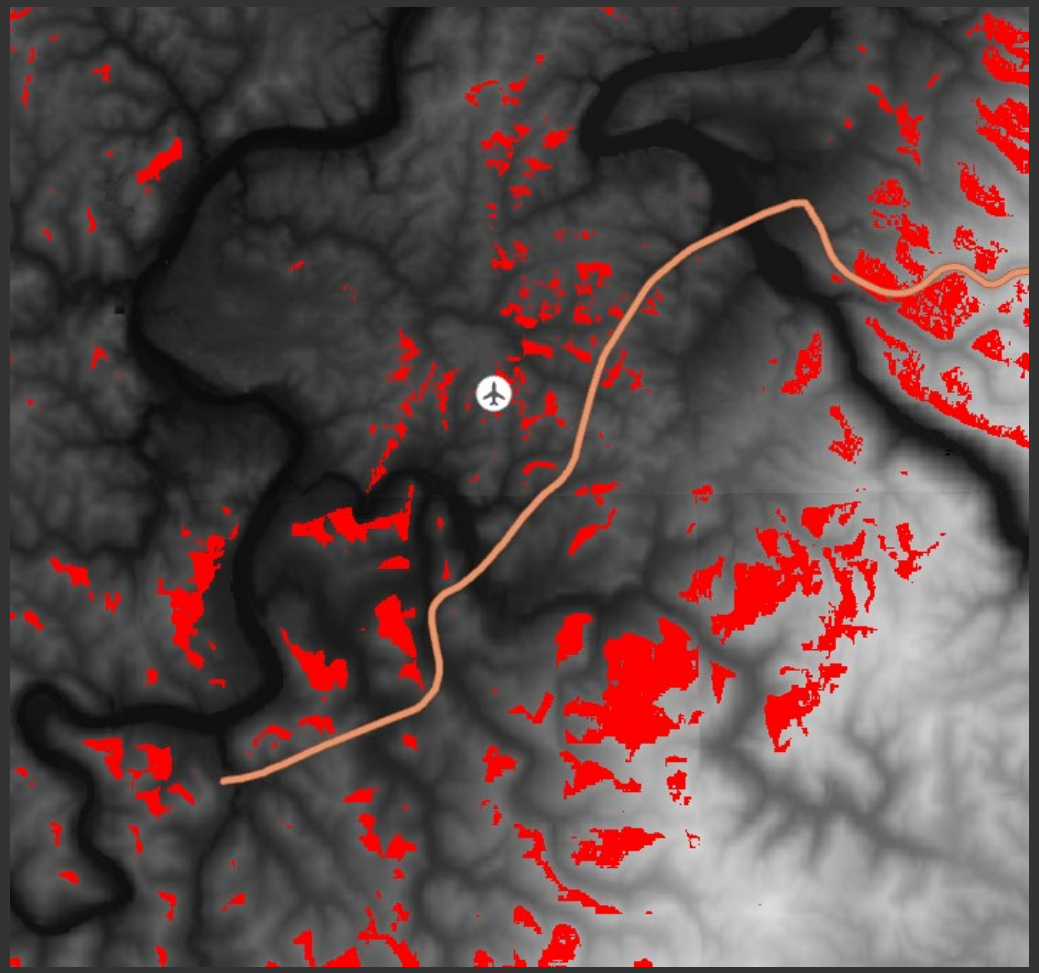
DEM to Raster

- Converts a DEM in United States Geologic Survey (USGS) format to a raster dataset

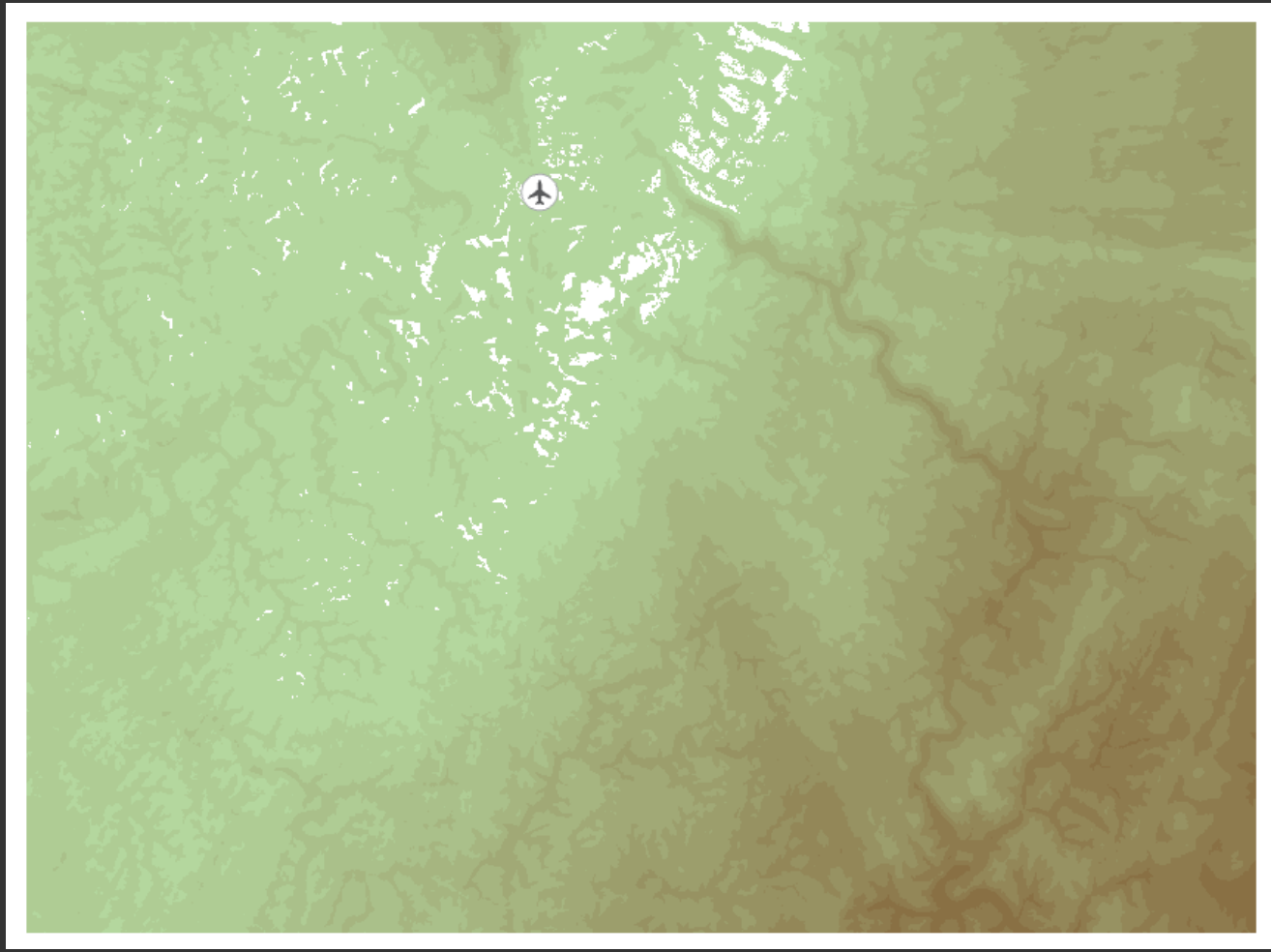


Viewshed Analysis

- Given terrain conditions, what can you see from a vantage point?
- Requires: DEM and location of vantage point
- Just takes into account topography
- Above Ground Level Output = raster output of height that must be added to the cell in order for it to be visible from the vantage point

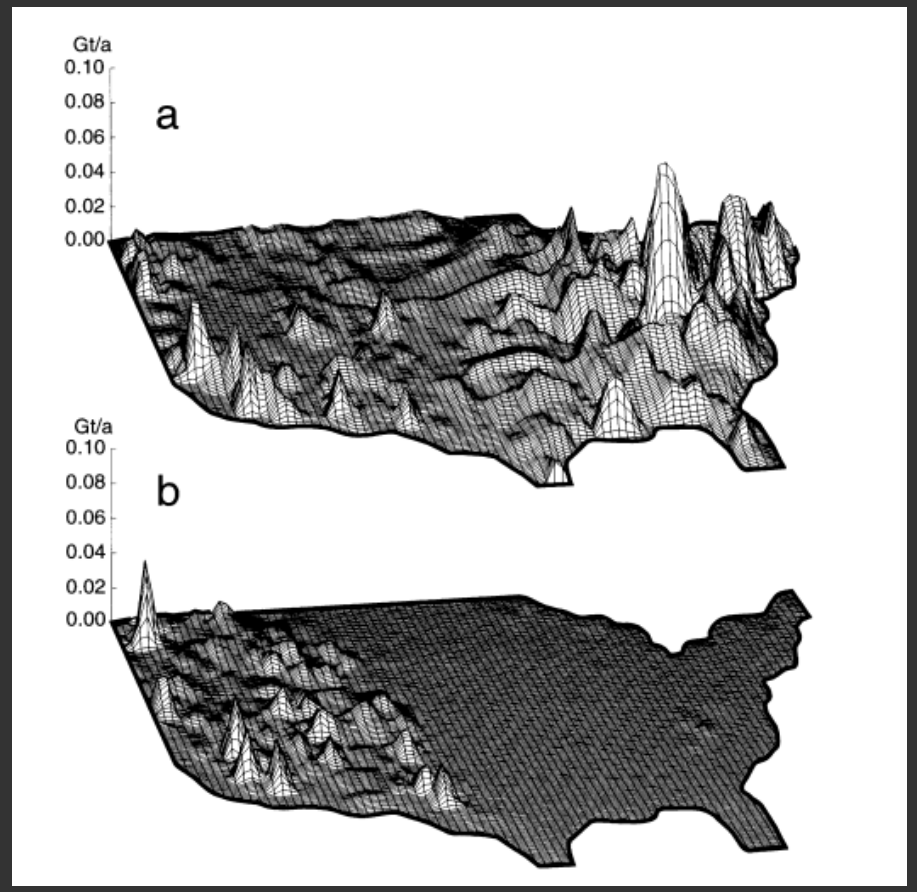


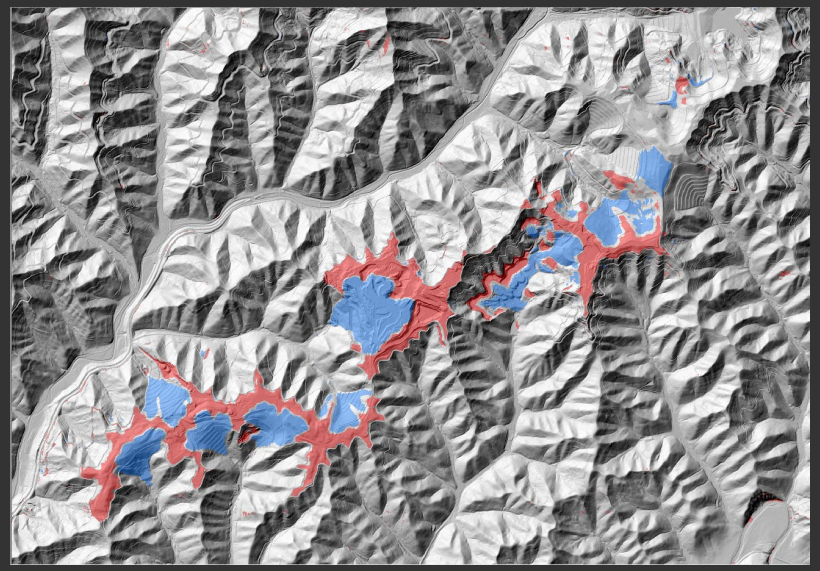
Above Ground Level Raster

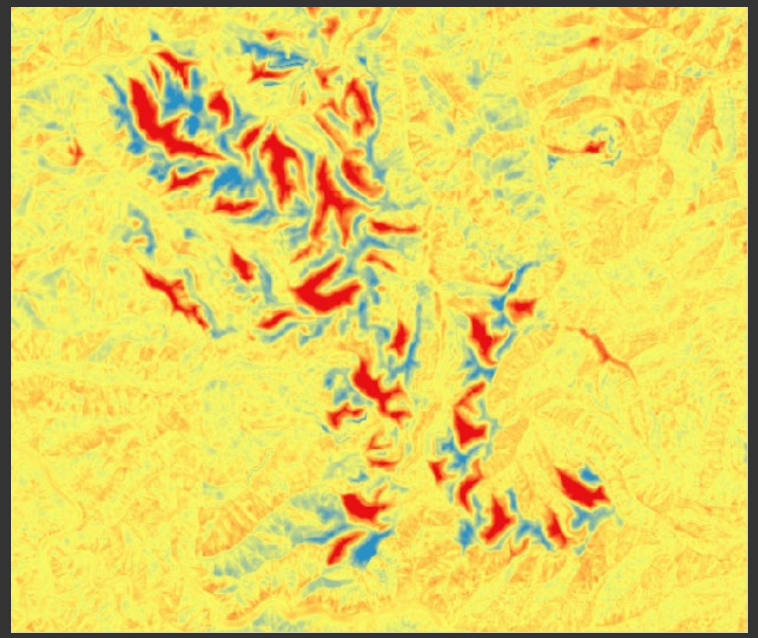


Cut and Fill Analysis

- Subtract DEM surfaces pre- and post- terrain change



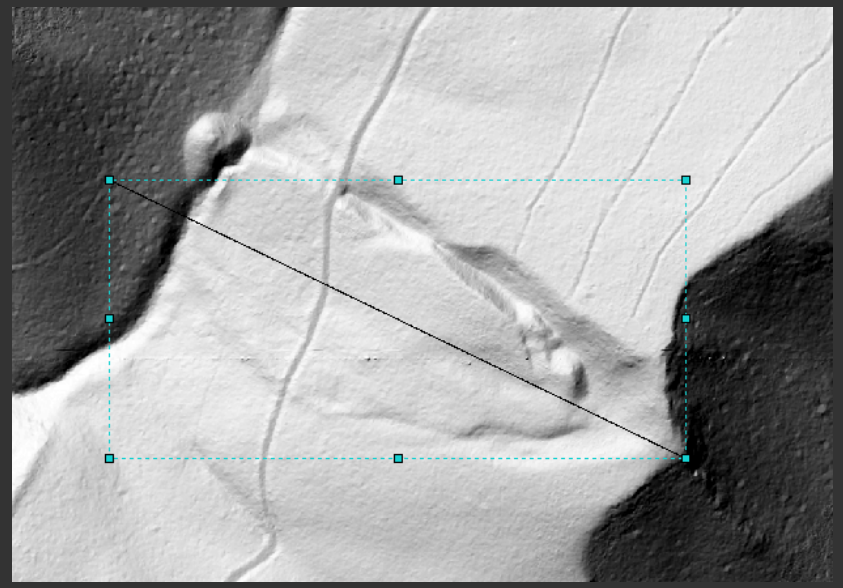


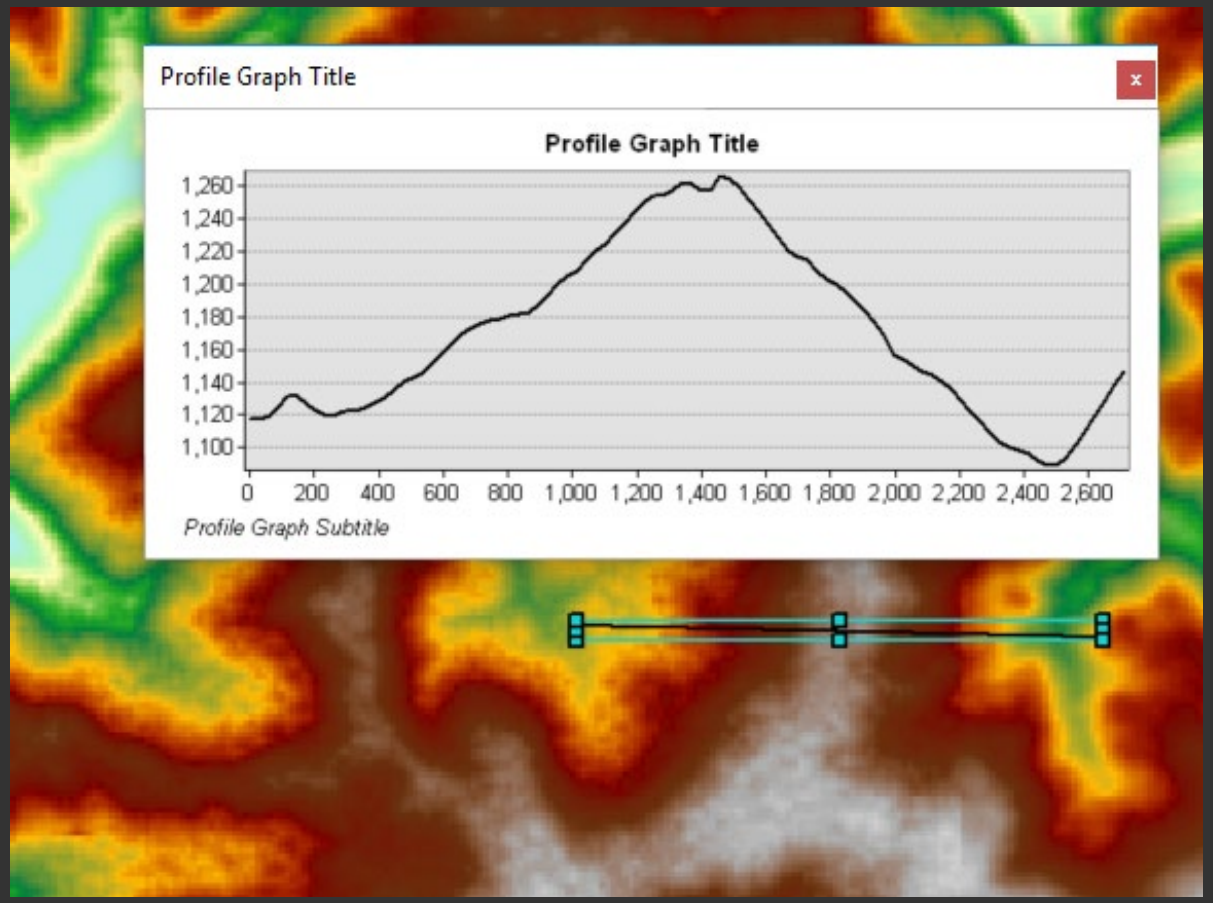


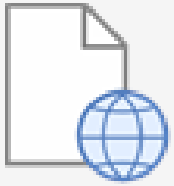
Hooke, R.L. (1999). "Spatial distribution of human geomorphic activity in the United States: comparison to rivers," *Earth Surface Processes*, 24: 687-692.

Profiles

- Available with 3D Analyst
- Can export to a table







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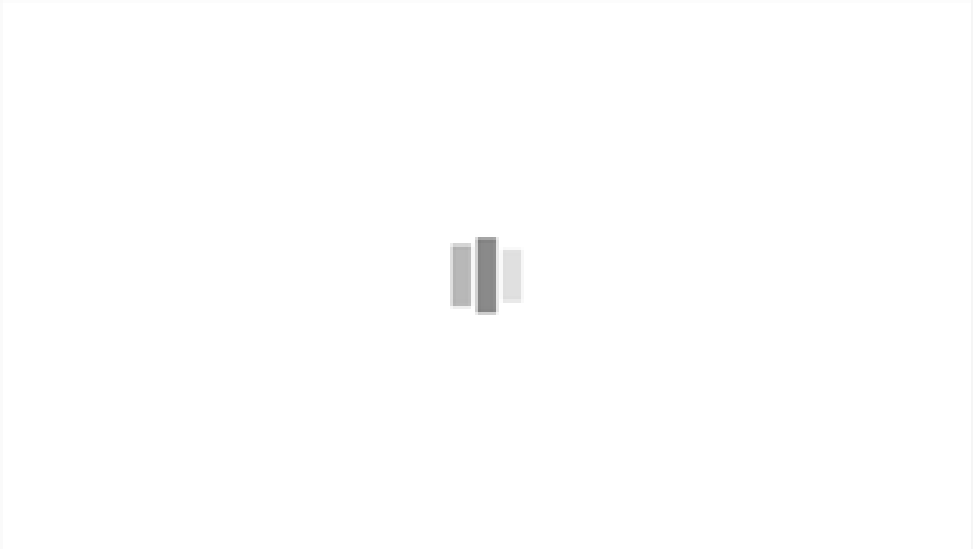
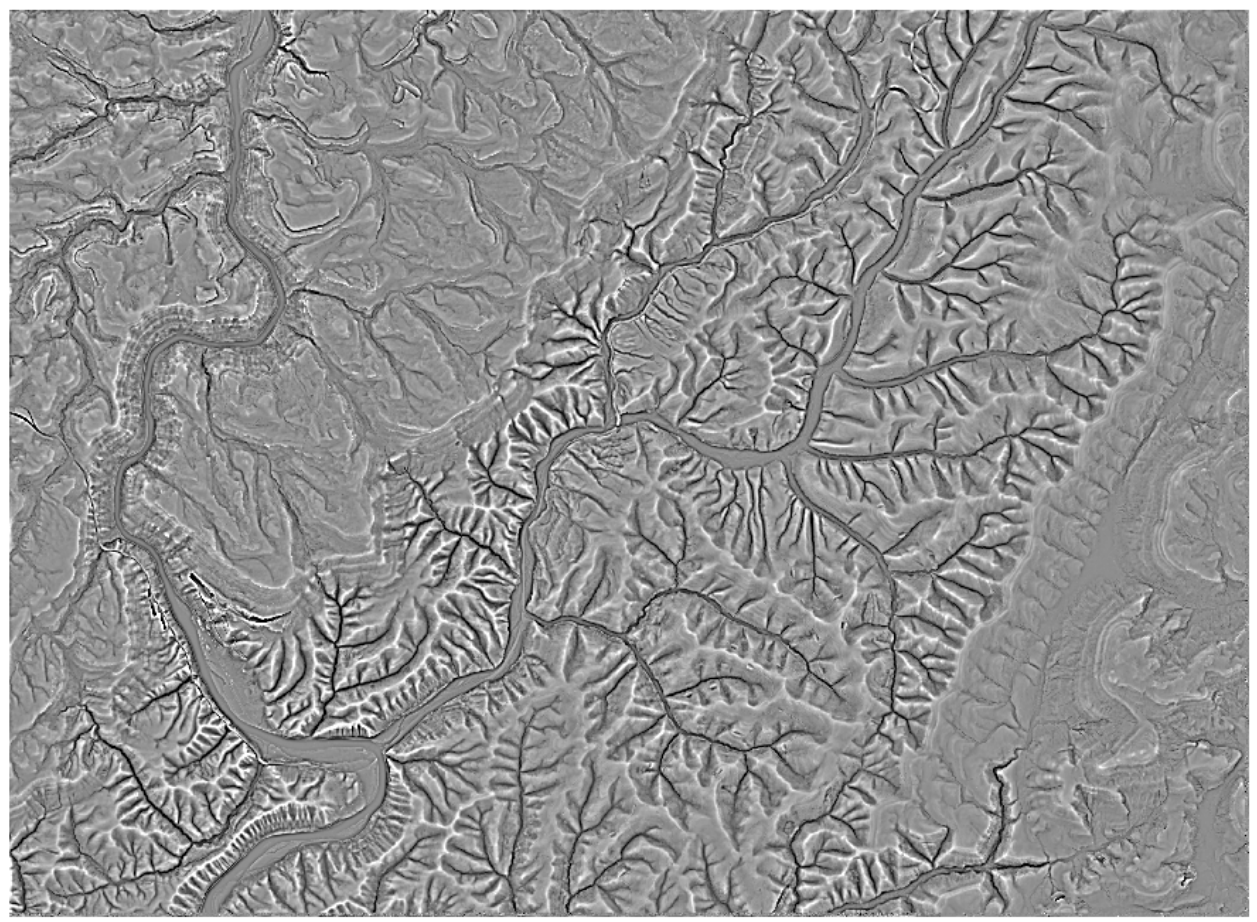


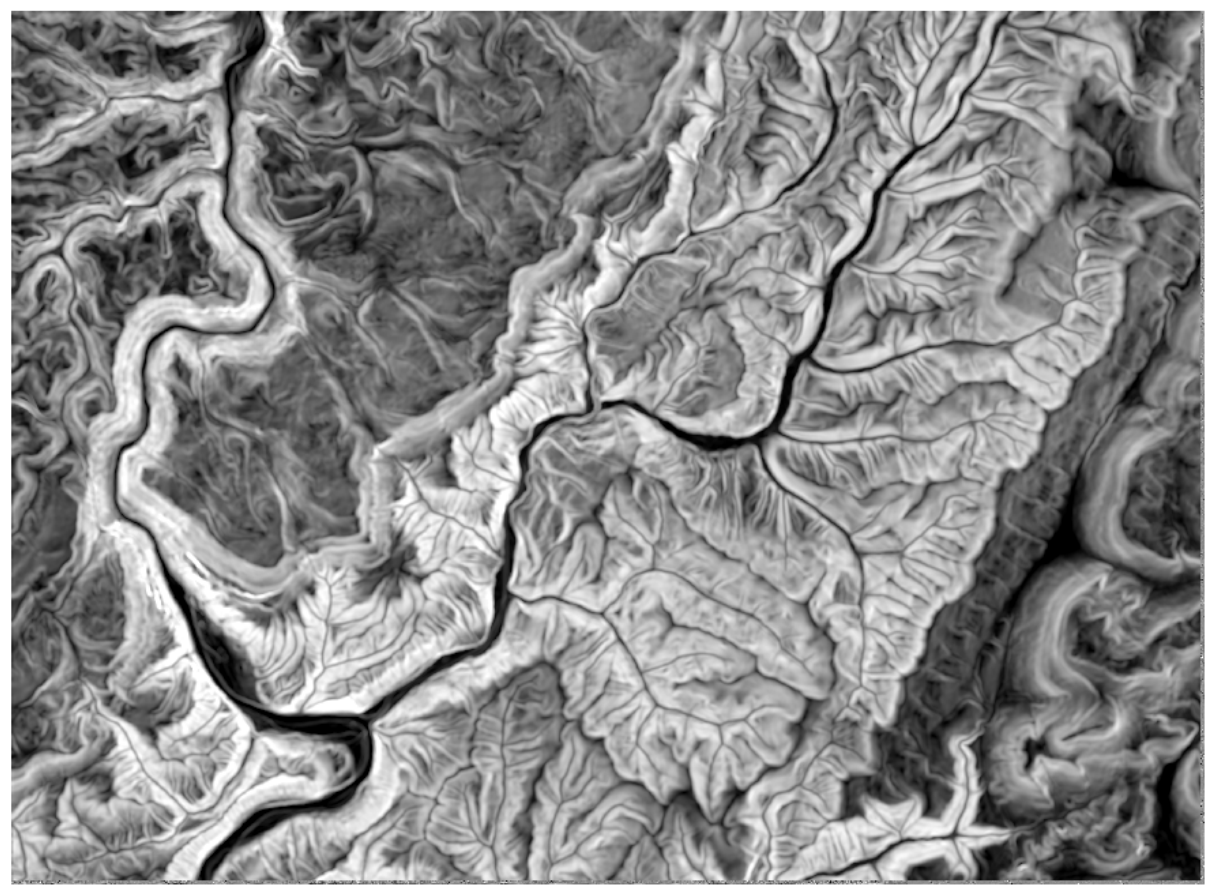
Slope Position

- Elevation at cell compared to elevation of surrounding cells
- Must calculate mean using neighborhood analysis
- "DEM" – "Mean"
- Ridge vs. Valley



Topographic Roughness

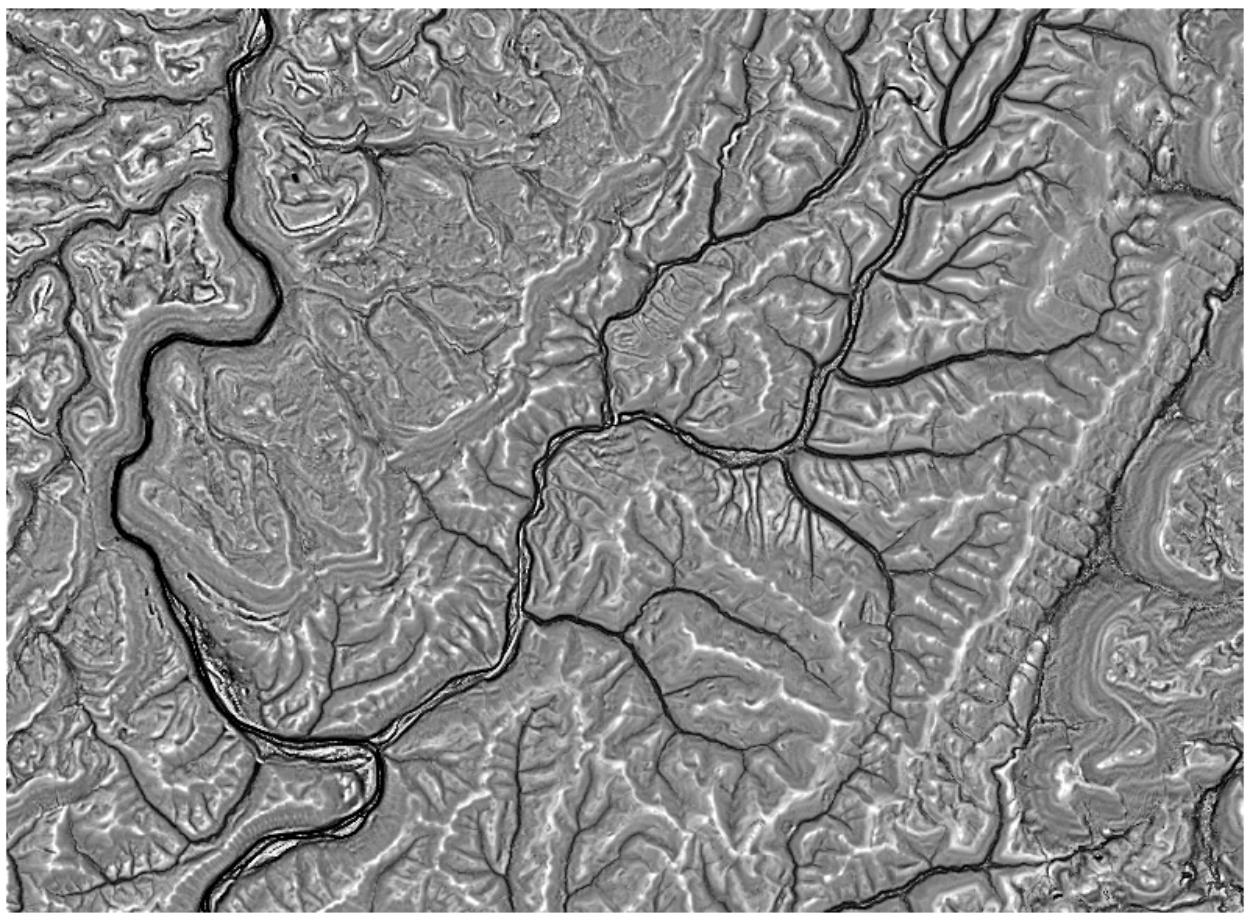
- Measure of topographic variability
- Square root of standard deviation of elevation measurements within a neighborhood



Topographic Dissection

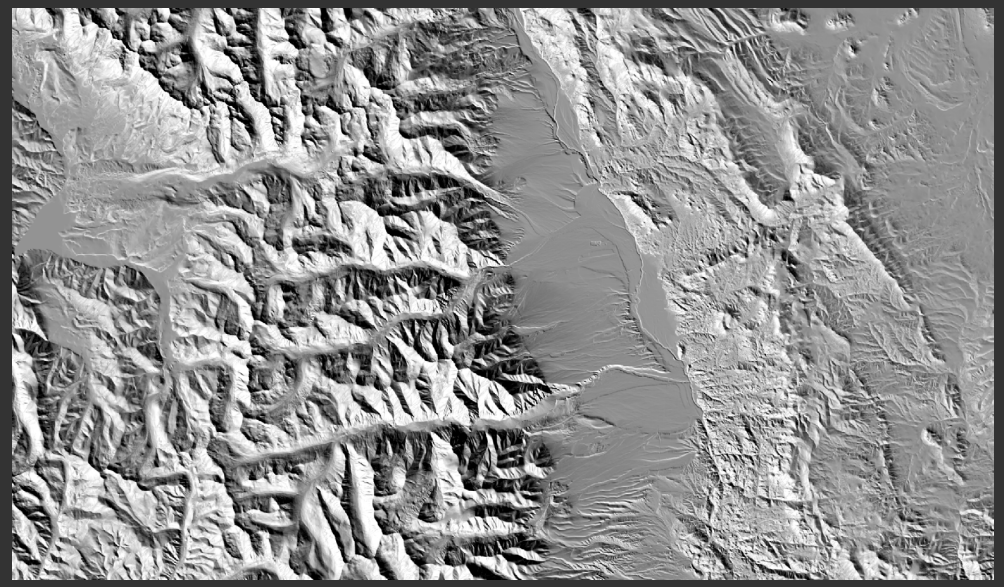
- Measure of incision

$$\frac{Elevation\ - Minimum\ Elevation}{Maximum\ Elevation\ - Minimum\ Elevation}$$



Heat Load Index

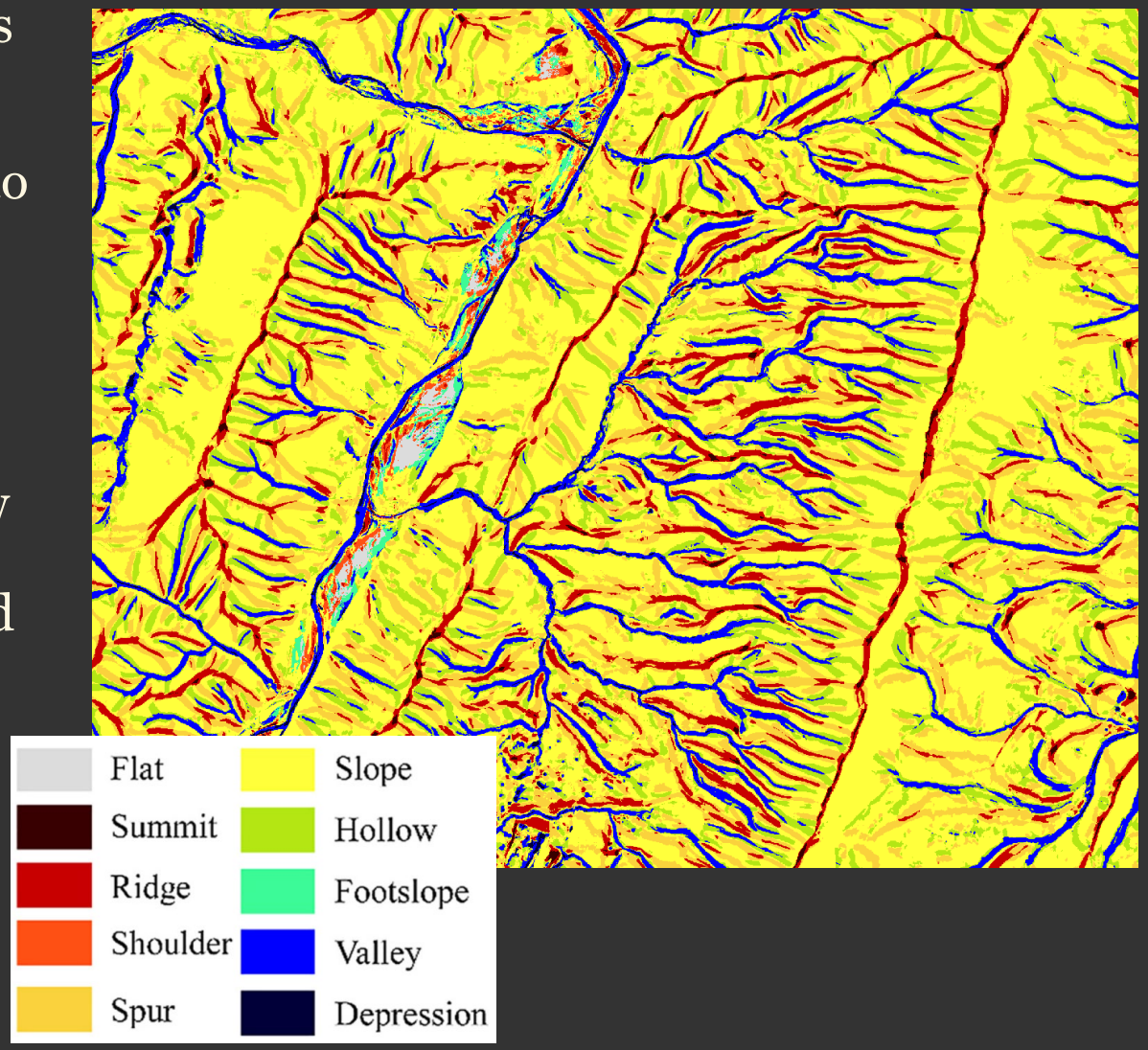
- A southwest facing slope should have warmer temperatures than a southeast facing slope, even though the amount of solar radiation they receive is equivalent
- The McCune and Keon (2002) method accounts for this by "folding" the aspect so that the highest values are southwest and the lowest values are northeast
- Additionally, this method accounts for steepness of slope, which is not addressed in most other aspect rescaling equations



McCune, B. and Keon, D., 2002. Equations for potential annual direct incident radiation and heat load. *Journal of vegetation science*, *13*(4), pp.603-606.

Geomorphons

- A categorization of terrain features or landform types that are size-, orientation-, and local relief-invariant
- Cell is compared to its neighbors in eight directions to characterize the patterns on the landscape and determine in which directions elevation is higher, lower, or at the same altitude as the reference cell location
- So as not to limit the analysis to a 3-by-3 cell window and to allow for mapping similar landforms with variable sizes or scales, a line-of-sight method is used as opposed to the direct cell neighbors.

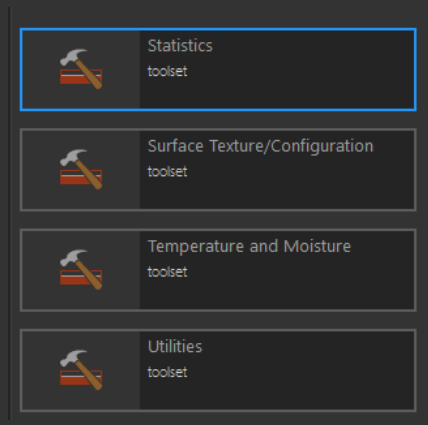


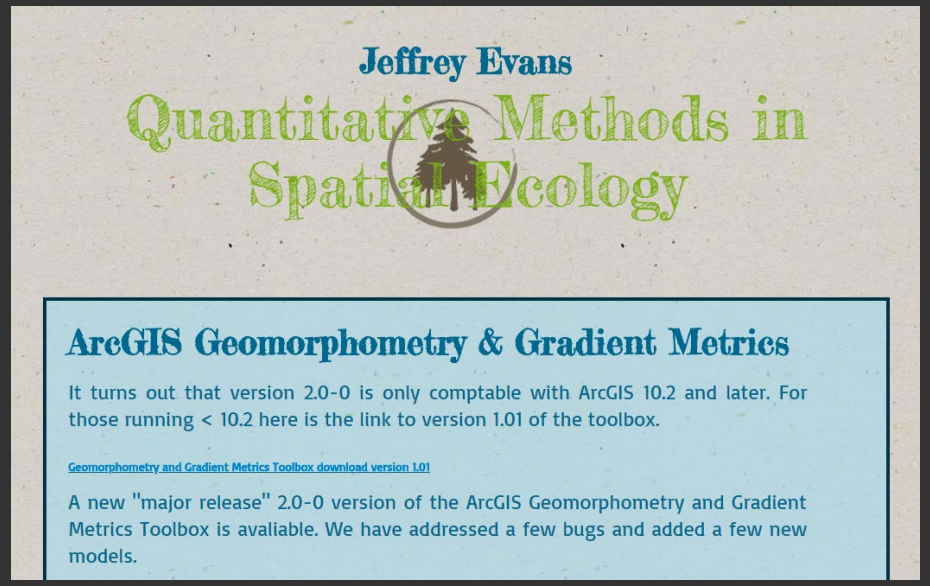
Stepinski, T.F. and Jasiewicz, J., 2011. Geomorphons-a new approach to classification of landforms. *Proceedings of geomorphometry, 2011*, pp.109-112.

Jasiewicz, J. and Stepinski, T.F., 2013. Geomorphons—a pattern recognition approach to classification and mapping of landforms. *Geomorphology, 182*, pp.147-156.

Geomorphometry & Gradients Metrics Toolbox

- Slope position
- Dissection
- Topographic roughness
- Compound topographic moisture index (CTMI)
- Heat load index
- Ecological land units (ELUs)
- Etc.

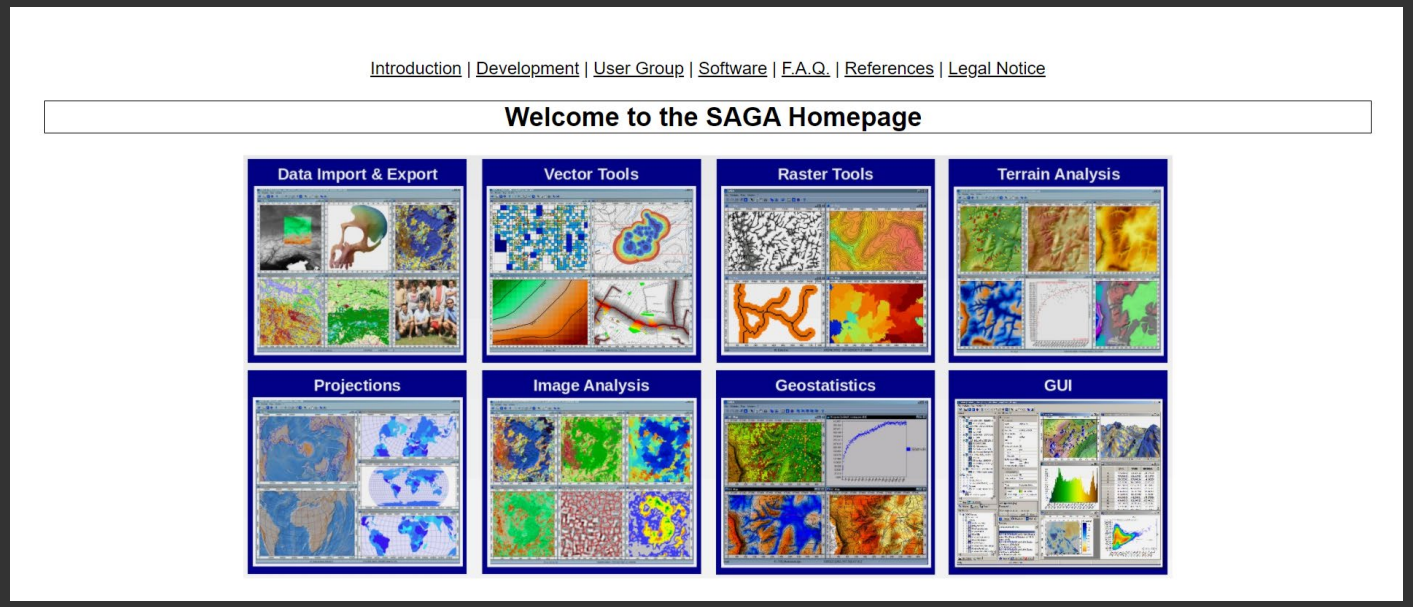




http://evansmurphy.wixsite.com/evansspatial/arcgis-gradient-metrics-toolbox

SAGA

- System for Automated Geoscientific Analysis
- Wide variety of terrain analysis tools included
- Integrated with QGIS
- Available in R and Python



http://www.saga-gis.org/en/index.html

Franklin (2020)

INTERNATIONAL JOURNAL OF REMOTE SENSING
2020, VOL. 41, NO. 19, 7700–7733
https://doi.org/10.1080/01431161.2020.1792577

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REVIEW ARTICLE

Check for updates

Interpretation and use of geomorphometry in remote sensing: a guide and review of integrated applications

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ABSTRACT
An understanding of topographic surfaces and a system of geomorphometric variables underlies the effective use of Digital Elevation Models (DEMs) in remote sensing. This paper is focussed on the basic concepts and structure of geomorphometric variable types relevant to geophysical and biophysical remote sensing applications. In general, remote sensing analysts must be satisfied that there is a reasonable expectation that geomorphometric processing will benefit the remote sensing project at hand based on physical or mathematical relationships. Careful selection of local, textural, and contextual geomorphometric variables is required. The characteristics of these data can help optimize the analysis approach, which increasingly involves machine learning algorithms and Object-based DEM Analysis (OBDA) methods. Examples from the literature and a DEM of the Peterborough Drumlin Field are used to illustrate the discussion.

ARTICLE HISTORY
Received 21 April 2020
Accepted 27 May 2020

1. Introduction

Geomorphometry is the science of quantitative terrain analysis using Digital Elevation Models (DEMs) (Evans 1972). Increased use of geomorphometry has been reported in certain, well-defined remote sensing applications, notably wetlands (Merchant et al. 2019), forest biomass (Shen et al. 2018), mass wasting (Maxwell et al. 2020), soils (Guevara, Vargas, and Poulter 2019), drainage mapping (Azizian and Brocca 2020) and structural analyses (Yeomans et al. 2019). These and other remote sensing applications expect *a priori* to benefit from the use of geomorphometric variables developed to quantify topographic surfaces. Successful use of geomorphometry requires that remote sensing analysts understand the concept and interpretation of topographic surfaces and be versant with a system of geomorphometric variables. The essential logic is as follows:

Franklin, S.E., 2020. Interpretation and use of geomorphometry in remote sensing: a guide and review of integrated applications. *International Journal of Remote Sensing*, *41*(19), pp.7700-7733.

Maxwell and Shobe (2022)

Earth-Science Reviews 226 (2022) 103944

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Land-surface parameters for spatial predictive mapping and modeling

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ARTICLE INFO

Keywords:
Geomorphometry
Land-surface parameters
Digital land surface model
Digital elevation model
Landforms
Spatial predictive modeling
machine learning

ABSTRACT

Land-surface parameters derived from digital land surface models (DLSMs) (for example, slope, surface curvature, topographic position, topographic roughness, aspect, heat load index, and topographic moisture index) can serve as key predictor variables in a wide variety of mapping and modeling tasks relating to geomorphic processes, landform delineation, ecological and habitat characterization, and geohazard, soil, wetland, and general thematic mapping and modeling. However, selecting features from the large number of potential derivatives that may be predictive for a specific feature or process can be complicated, and existing literature may offer contradictory or incomplete guidance. The availability of multiple data sources and the need to define moving window shapes, sizes, and cell weightings further complicate selecting and optimizing the feature space. This review focuses on the calculation and use of DLSM parameters for empirical spatial predictive modeling applications, which rely on training data and explanatory variables to make predictions of landscape features and processes over a defined geographic extent. The target audience for this review is researchers and analysts undertaking predictive modeling tasks that make use of the most widely used terrain variables.

To outline best practices and highlight future research needs, we review a range of land-surface parameters relating to steepness, local relief, rugosity, slope orientation, solar insolation, and moisture and characterize their relationship to geomorphic processes. We then discuss important considerations when selecting such parameters for predictive mapping and modeling tasks to assist analysts in answering two critical questions: What landscape conditions or processes does a given measure characterize? How might a particular metric relate to the phenomenon or features being mapped, modeled, or studied? We recommend the use of landscape- and problem-specific pilot studies to answer, to the extent possible, these questions for potential features of interest in a mapping or modeling task. We describe existing techniques to reduce the size of the feature space using feature selection and feature reduction methods, assess the importance or contribution of specific metrics, and parameterize moving windows or characterize the landscape at varying scales using alternative methods while highlighting strengths, drawbacks, and knowledge gaps for specific techniques. Recent developments, such as explainable machine learning and convolutional neural network (CNN)-based deep learning, may guide and/or minimize the need for feature space engineering and ease the use of DLSMs in predictive modeling tasks.

Maxwell, A.E. and Shobe, C.M., 2022. Land-surface parameters for spatial predictive mapping and modeling. *Earth-Science Reviews*, p.103944.

This is the end of this lecture module.

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