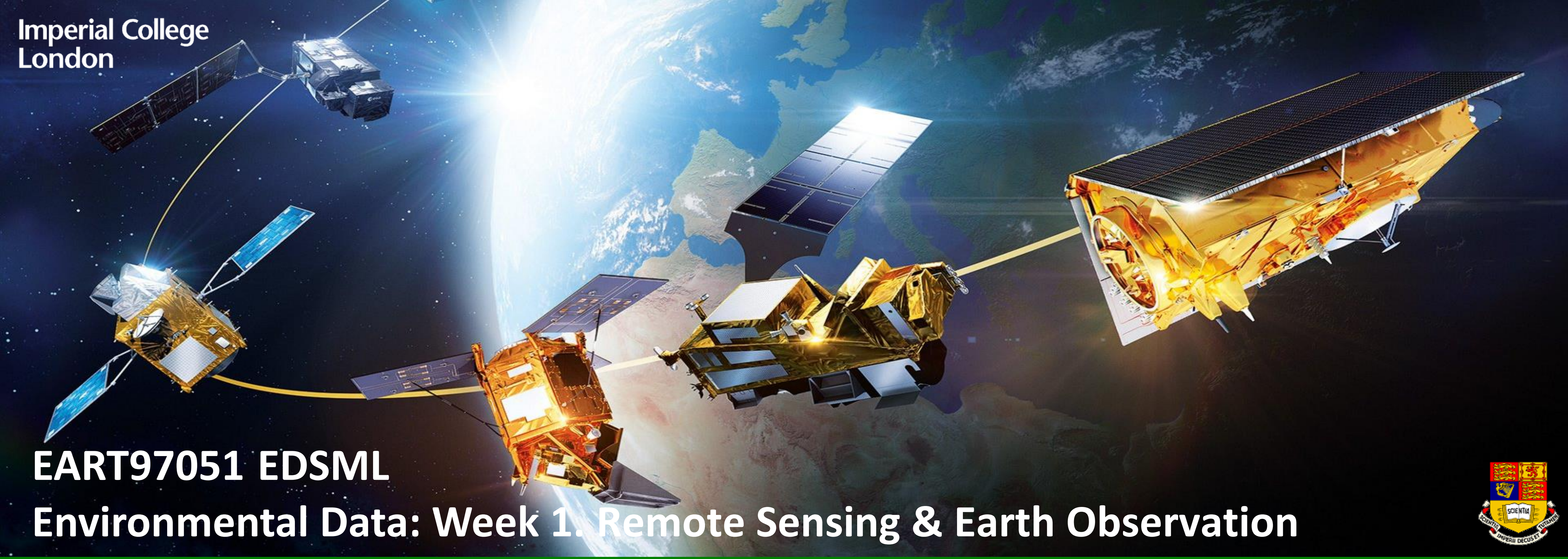

EART97051 EDSML
Environmental Data: Week 1. Remote Sensing & Earth Observation

5. Introduction to Digital Elevation Models and LiDAR

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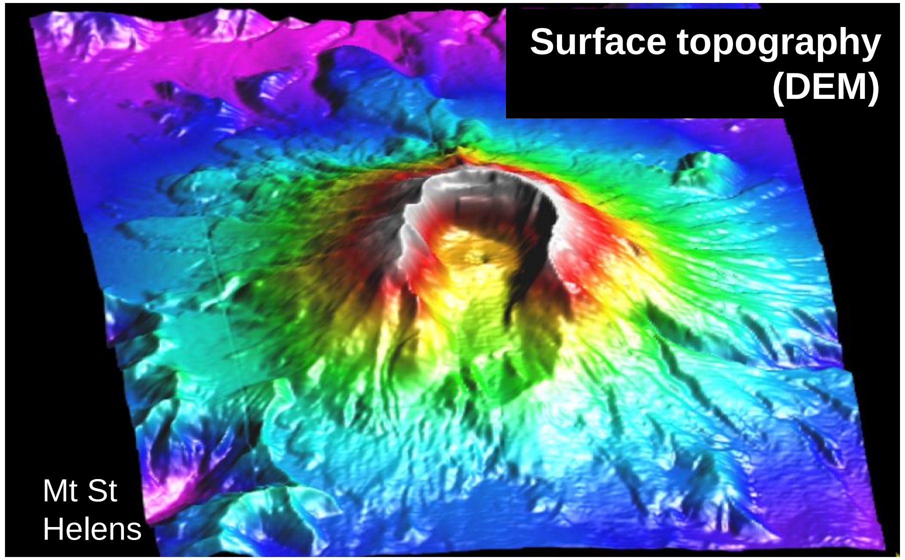
Intended Learning Outcomes

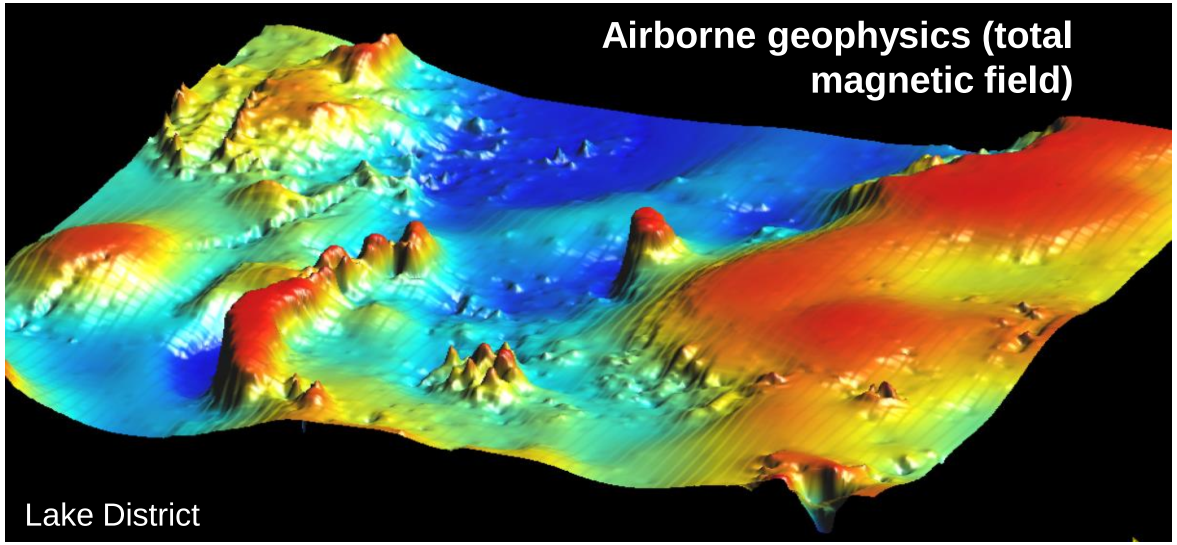
1. By the end of this session, you should understand what a **Digital Elevation Models is,** how it can be produced, how it can be used and the terrain variables that can be extracted from – slope, aspect, hillshade and curvature
2. **Principles of photogrammetric measurement** from **stereo imaging** to generate a DEM
3. A basic understanding of how we use LiDAR for generating DEMs and some of the uses

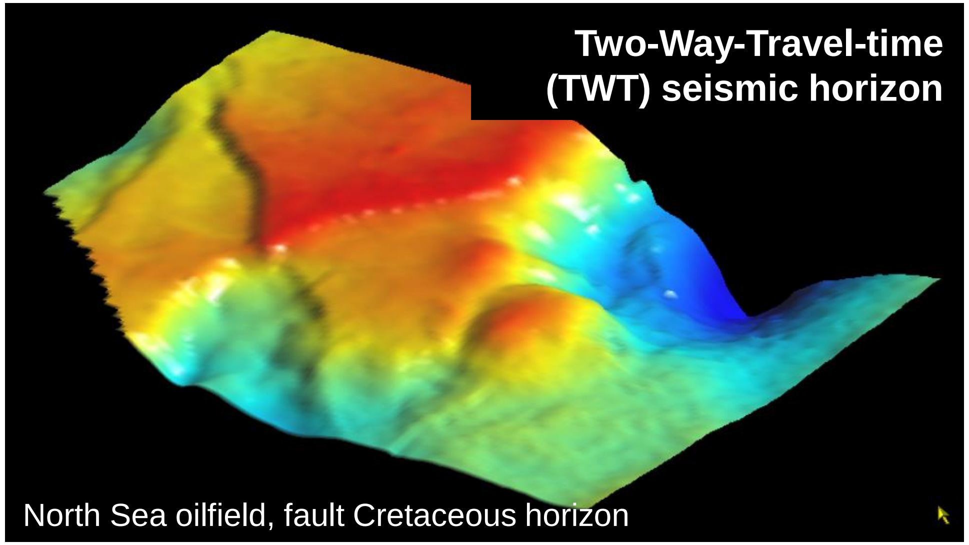
5.1 Digital Elevation Models (DEMs)

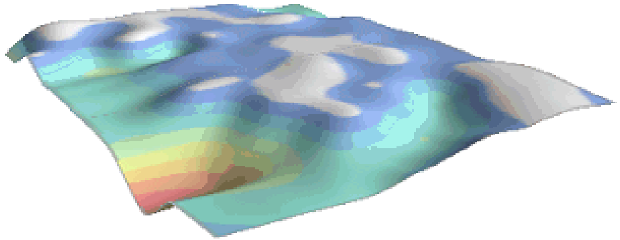
- A digital *surface (or DEM),* models a phenomenon that varies continuously across an area, such as **ground elevation, i.e. a DEM is usually a digital representation of topography.**
- Common terms: **Digital Elevation Model (DEM), and Digital Terrain Model (DTM) or Digital Surface Model (DSM)**
- Broadly two forms: ***Raster*** & *Vector* (*Triangulated Irregular Network (TIN) or Wireframe)*
- DEMs can be generated in a variety of ways (currently, in red):
  - Digital capture of contours and secondary conversion to a surface – the 'old days' !
  - Point surveys, e.g. surveying, to produce Triangulated Irregular Networks (TINs) or Wireframes from survey points, or via interpolation from point data - the 'old days' !
  - **Photogrammetry – from digital stereo images (aerial-photographic) surveys** - in operation ~1900 to present
  - **SAR Interferometry (InSAR) – since 2000 and increasingly in the 2020s+**
  - **LiDAR** – from airborne, UAV and satellite – in operation ~1990s – 2020s+
  - From narrow baseline stereo images using phase correlation & optical flow – currently mainly R&D
- DEMs are <u>models</u> of the surface morphology - there is always more detail than can ever be shown by a digital representation at any particular scale or spatial resolution. Hence a raster DEM is merely a regularly sampled representation of the real land surface shape and height

Raster Digital Elevation Models









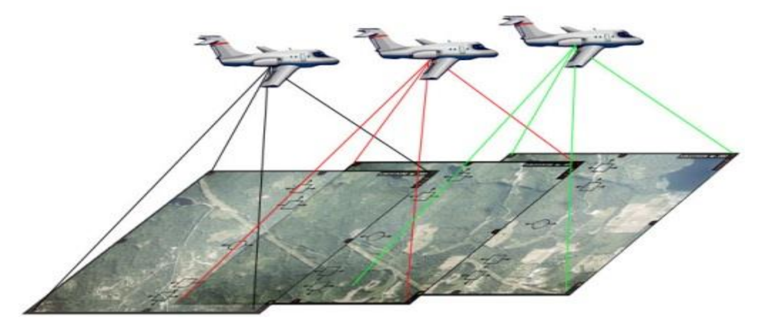
Snow depth (m)

Raster surfaces can represent any variable, e.g. elevation, rainfall intensity, magnetic susceptibility etc.

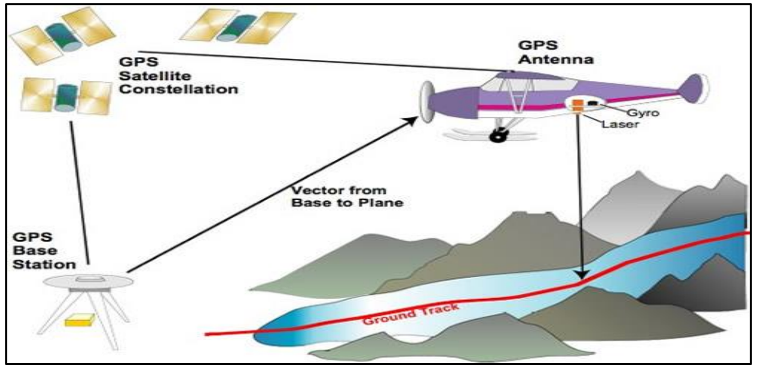
From these digital models we extract surface variables to quantify the character of the terrain – slope, aspect, hillshade and curvature

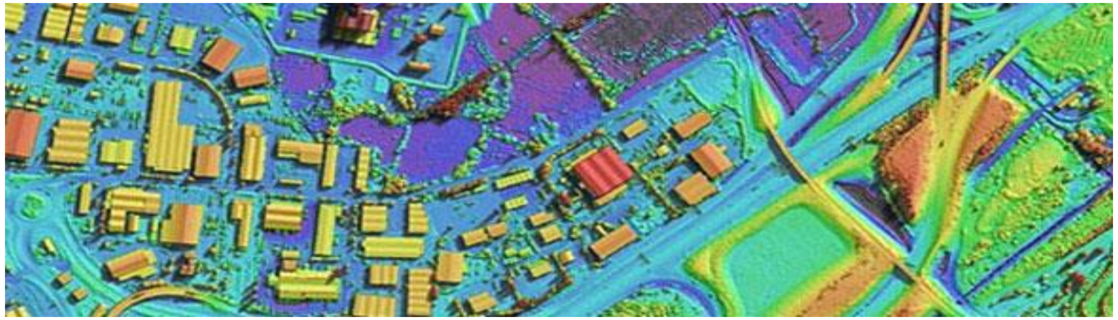
Methods of DEM generation

1. Photogrammetry from stereo imagery

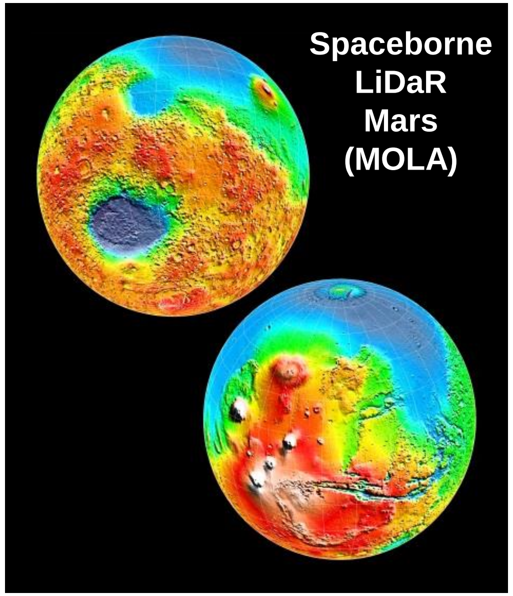


2. Airborne LiDaR (Light Detection & Ranging) scanner survey

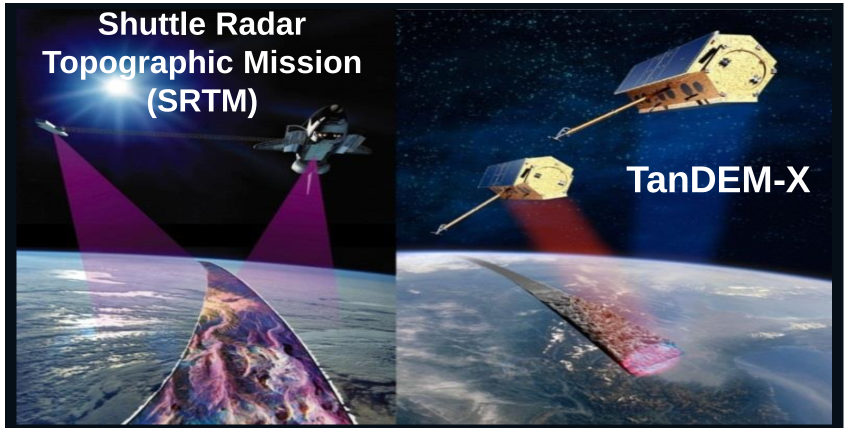


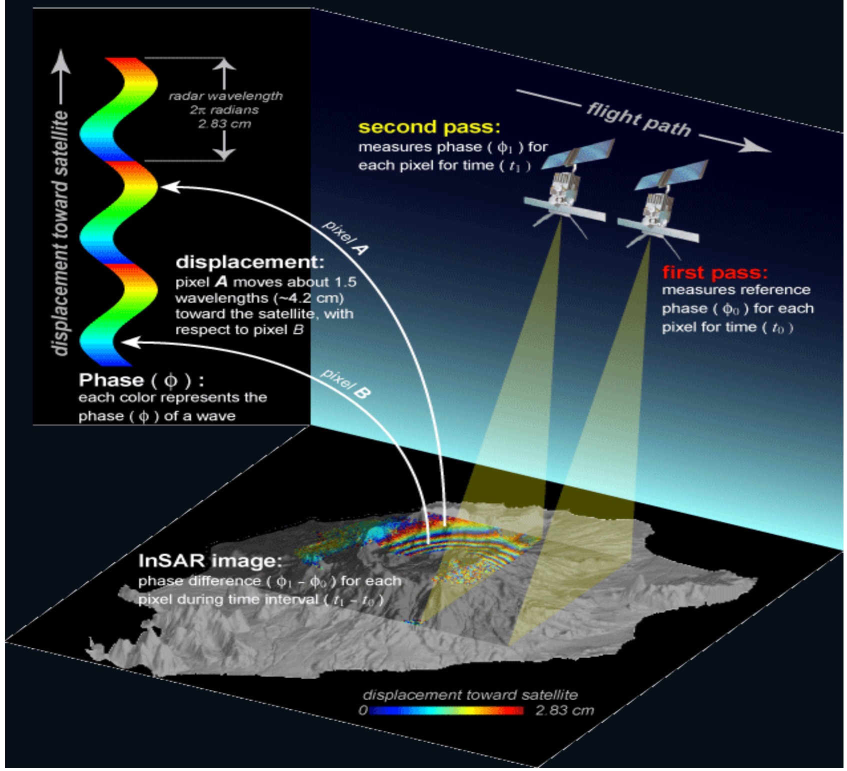


3. Close-range photogrammetry (outcrop scale stereo photographs from ground or drone)



5. Spaceborne SAR Interferometry (InSAR) from imaging radar e.g. SRTM, Sentinel-1, TanDEM-X





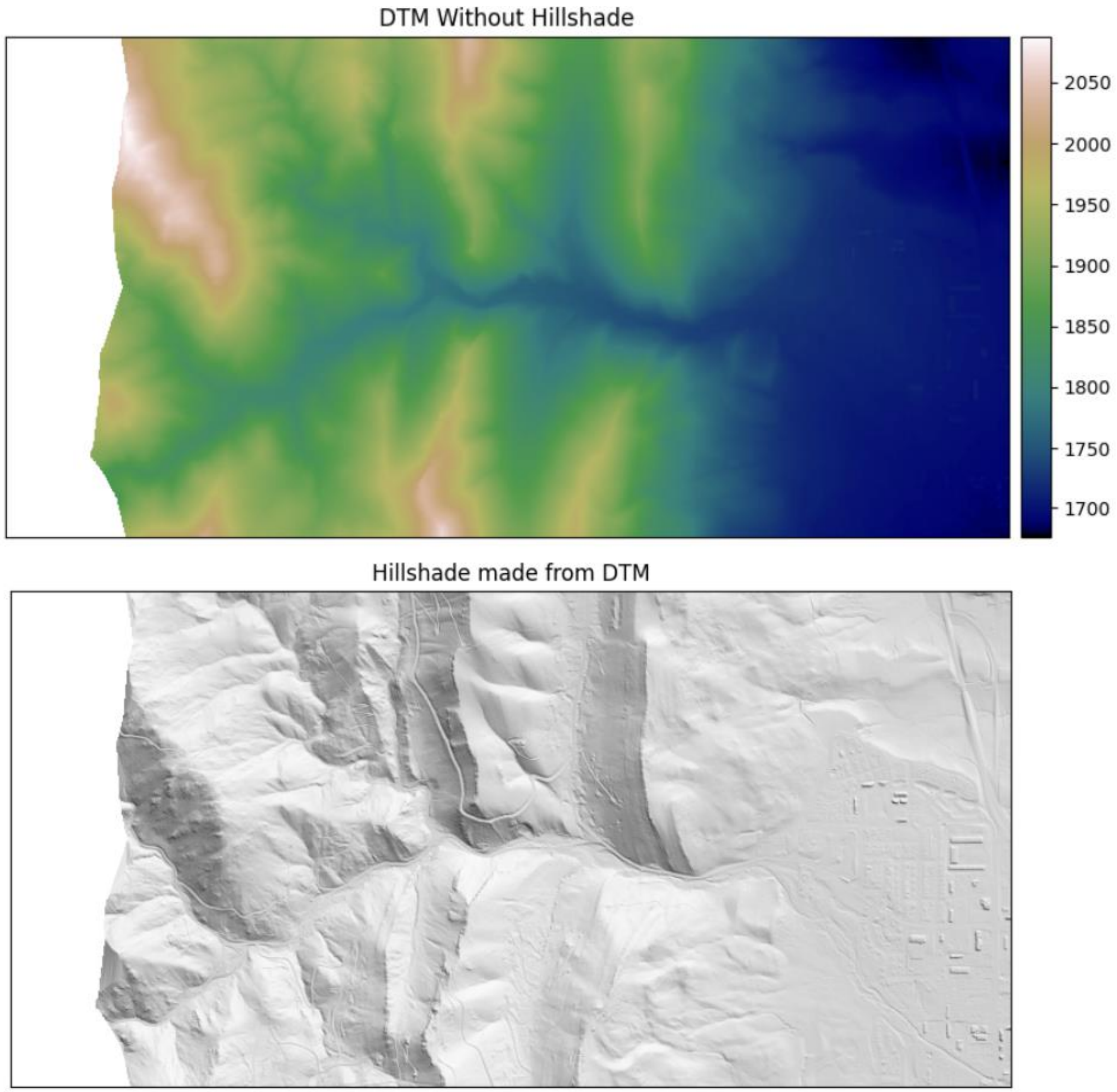
Where can I get DEM data?

USGS website

- [where-can-i-get-**global**-elevation-data?] Best detail is from:
  - Aster Global DEM (GDEM), 30 m resolution (2000-2013), and
  - Shuttle Radar Topographic Mission (SRTM), 30 m (2000)
- what-types-elevation-datasets-are-available-and-in-what-formats-do-they-come?

Exploring a DEM

- Exploring digital elevation models—ArcGIS Pro | Documentation



5.2 Extracting surface variables from DEMs

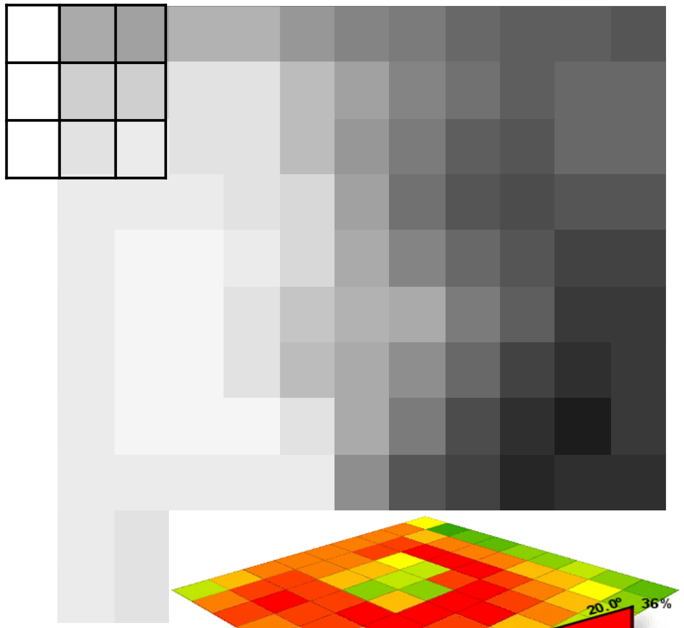
- A hillslope has 2 components: gradient (angle) & aspect (direction)
  - **Gradient (g)** = maximum rate of change in magnitude and is *first derivative of elevation at a position*
  - **Aspect (a)** = the azimuth direction (compass bearing) of maximum g
  - Both are vector products

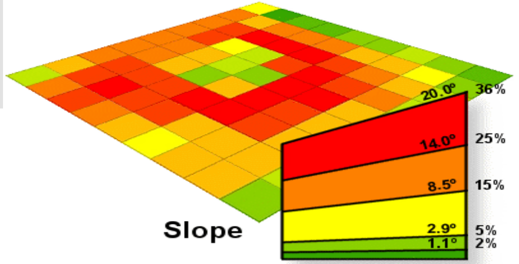
a) Slope

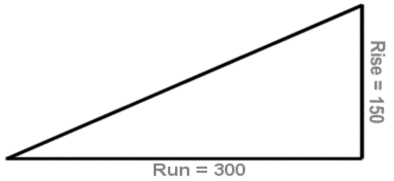
- **Gradient / Slope** – theoretically defined by a plane tangent to a surface at a point = angle of inclination (steepness or gradient) of a surface
- Slope in **degrees or percent**
  - Max slope in degrees = 90 but in percent can approach infinity.
- ‘Neighbourhood’ calculation from any surface variable using 3x3 moving window* from a raster DEM as follows:

$$\tan g \quad = \quad \sqrt{[(\delta z/\delta x)^2 + (\delta z/\delta y)^2]}$$

* *Image convolution*



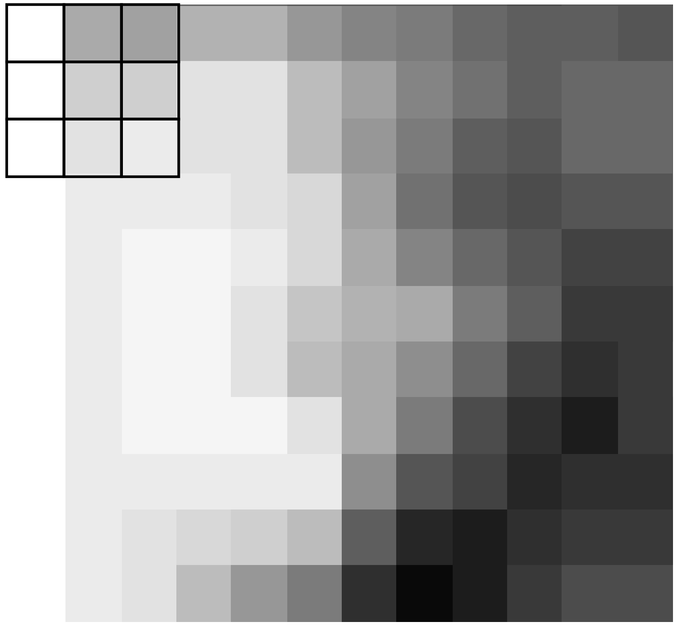




Calculation of the degree of slope or the percent of slope.

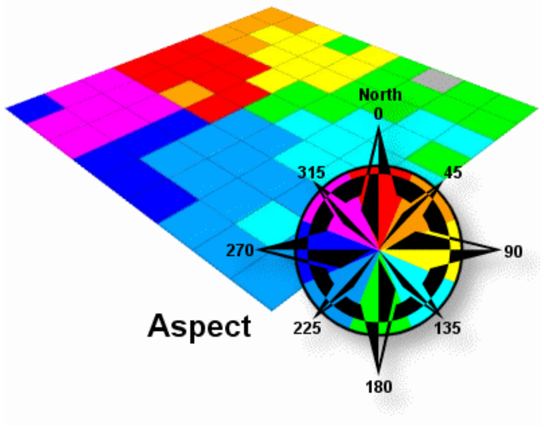
Degree	Percent
= Arctan(rise/run)	= (Rise/run)100
= Arctan(150/300)	= (150/300)100
= 26.56°	= 50

b) Aspect or azimuth



- Represents the **facing direction (*a*)** of a surface or section of a surface
- Given numerically as orientation or direction of gradient relative to North – as a bearing or azimuth
- ‘Neighbourhood’ calculation from any surface variable using 3x3 moving window* from a raster DEM as follows:

$$\tan a = \frac{(\delta z / \delta x)}{(\delta z / \delta y)}$$



- Aspect grid cell DN values in are compass directions
  - Range from **0 to 360** (North is 0 and in a clockwise direction, 90 is east, 180 is south, and 270 is west)
  - Grid cells that have 0 slope (flat areas) are assigned a value of -1

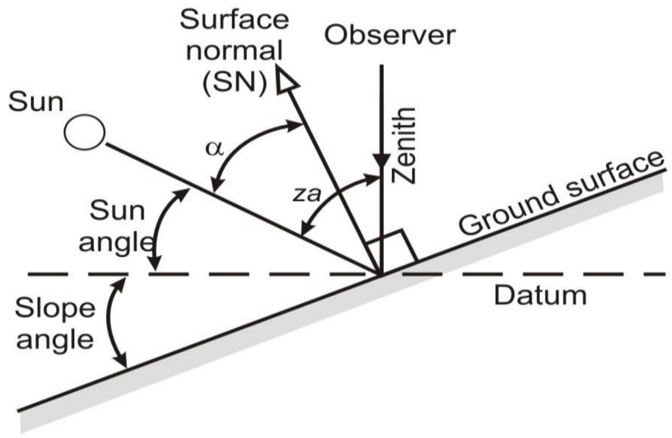
$$\text{if}\left(\delta z_x = 0 \ AND \ \delta z_y = 0\right), \quad a = -1$$

* *Image convolution*

c) Oblique Light **Hillshading**

- Simulates realistic terrain view in 2D by estimating light intensity of a position based on its relative orientation to the light source (illumination vector). Illumination vector is determined by 2 angles:
  - **Azimuth** in positive degrees from 0-360, measured clockwise from north,
  - **Altitude** in positive degrees, with 0 deg at the horizon and 90 deg directly overhead.
- The hillshade DN (*h*) value assigned to the output pixel is **proportional to the cosine of the three-dimensional angle between the illumination vector and the surface normal**
- The surface normal (SN) vector is perpendicular to a surface – is defined for any pixel by its DN value and the values of its closest 8 neighbouring pixels (in a 3x3 moving window*).
- 'Neighbourhood' calculation from a raster DEM, using 3x3 moving window, and requires also calculation of slope and aspect:

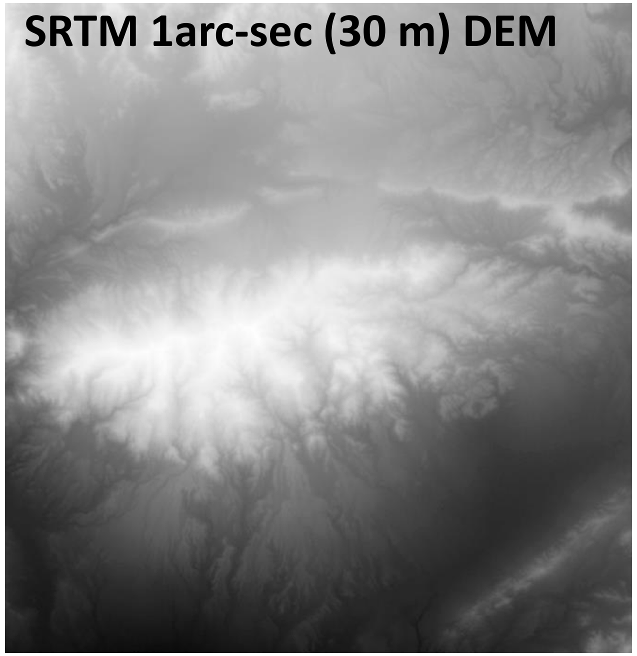
$$h = 255((\cos(za)(\cos(slope)) + (\sin(za)\sin(slope)\cos(azimuth - aspect)))$$

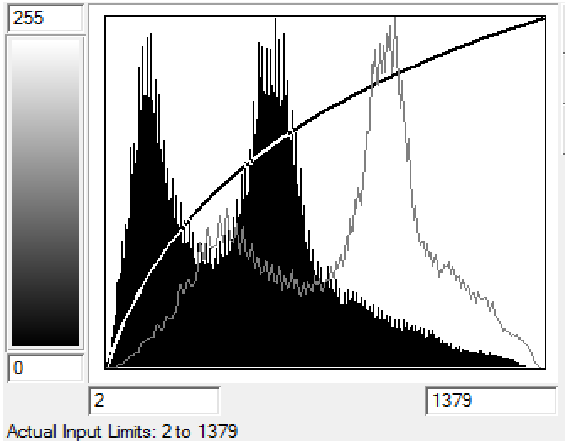


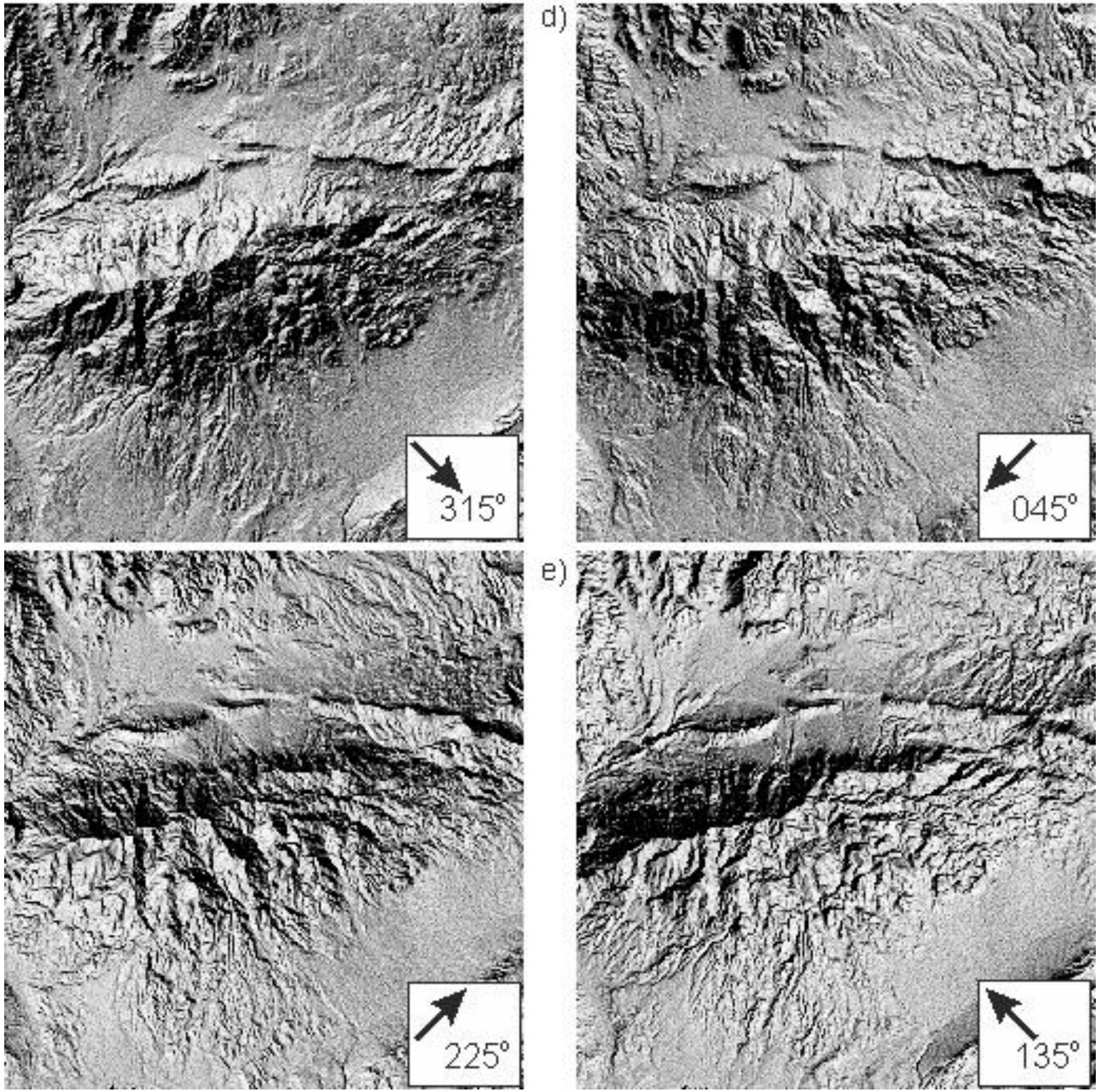
* *Image convolution*

Hillshading effects with illuminations from differing azimuths

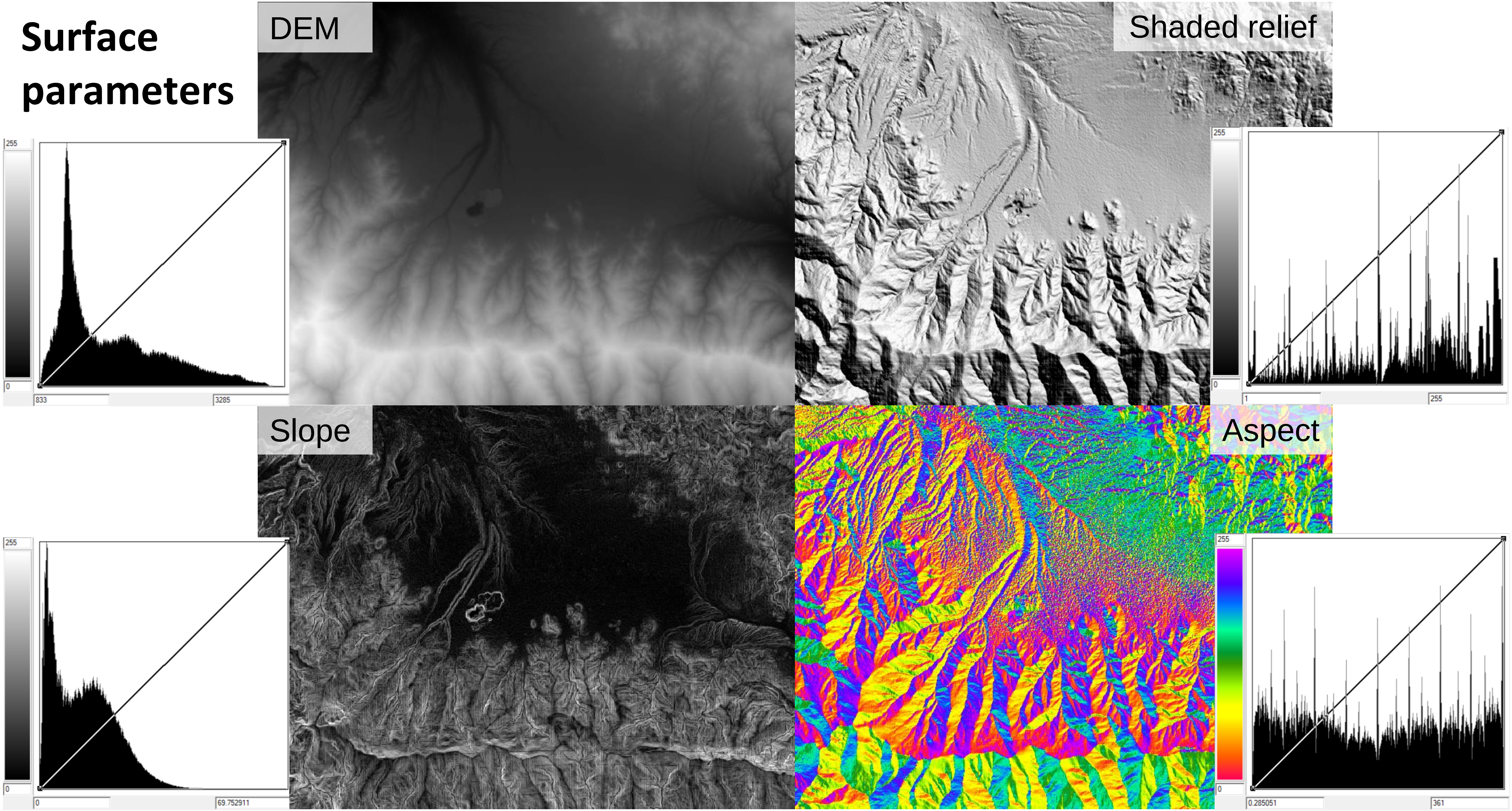
(and at constant elevation angle of 45^{o})







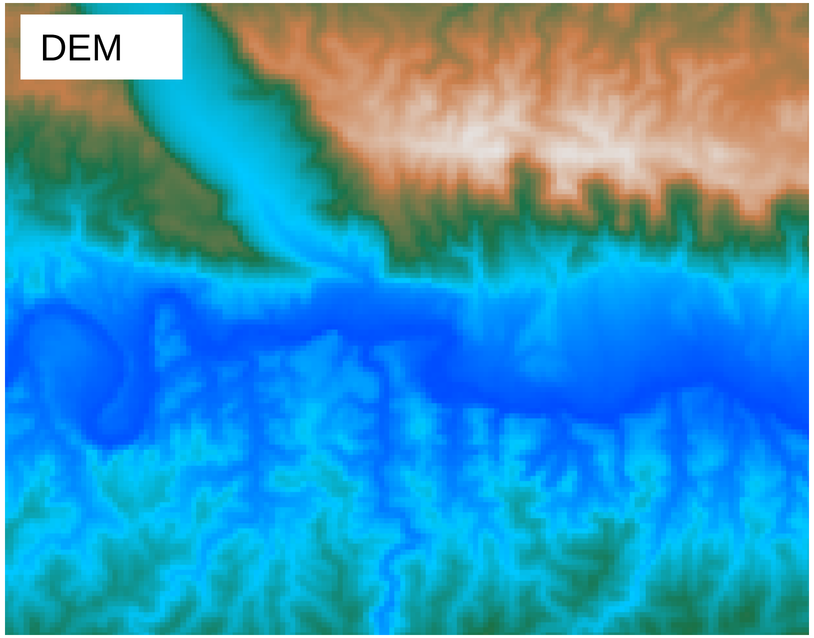
Surface parameters

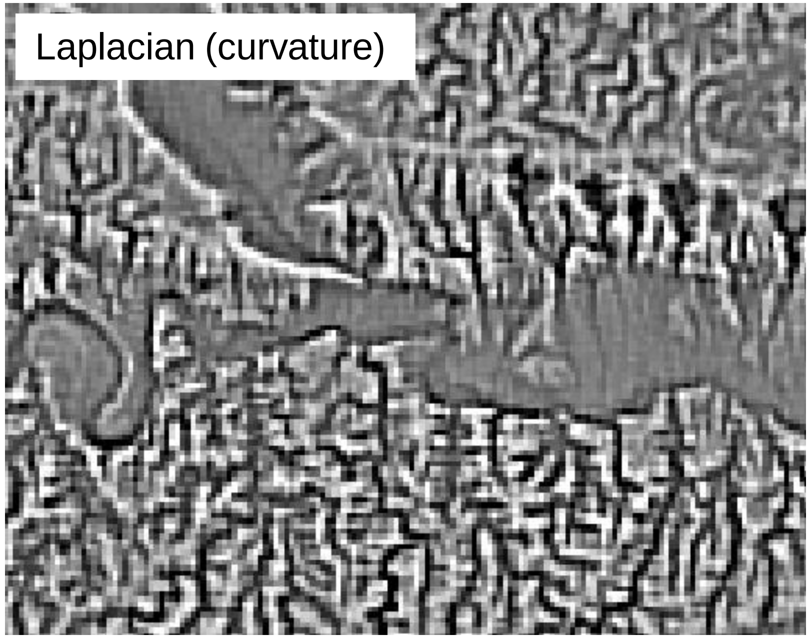


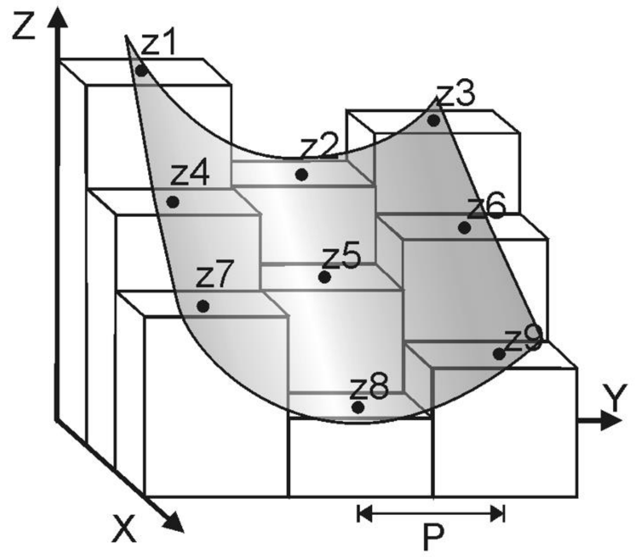
d) Curvature

- *Curvature is the **rate of change** in* surface orientation of a variable across an area Calculated on a pixel-by-pixel basis in a 3x3 moving window
- Curvature is the *first derivative of the surface normal vector* (SN), and the *second derivative (Laplacian) of a position* on a surface (with respect to the changing rate of gradient *g)*
- The Laplacian, as a scalar, is composed of components in both *x* and *y* directions and so can be decomposed to the aspect direction and the direction perpendicular to aspect, by a second partial differentiation of elevation (*z*) in these two directions.

$$c_{true} = \frac{(\partial^2 z/\partial \alpha^2)}{(1 + (\partial z/\partial \alpha)^2)^{3/2}}$$



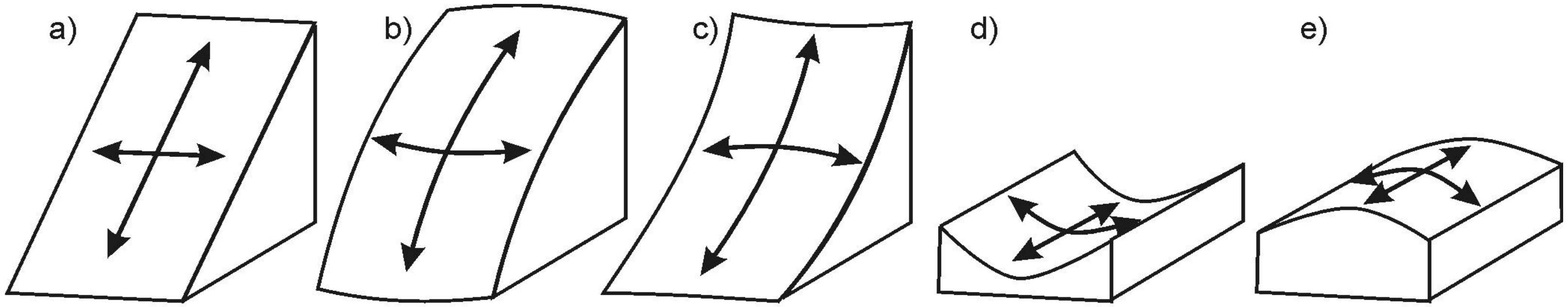




Curvature signals of land features

Geomorphological Feature	Surface characteristics	Second derivatives: profile & plan curvature
Peak	Point that lies on a local convexity in all directions (all neighbours lower).	$c_{profile} > 0, \quad c_{cross} < 0$
Pit	Point that lies in a local concavity in all directions (all neighbours higher).	$c_{profile} < 0, \quad c_{cross} > 0$
Ridge	Point that lies on a local convexity that is orthogonal to a line with no convexity/concavity.	$c_{profile} \approx 0, \quad c_{cross} < 0$
Channel	Point that lies in a local concavity that is orthogonal to a line with no concavity/convexity.	$c_{profile} \approx 0, \quad c_{cross} > 0$
Pass	Point that lies on a local convexity that is orthogonal to a local concavity (saddle).	$c_{profile} < 0, \quad c_{cross} < 0$
Plane	Points that do not lie on any surface concavity or convexity (flat or planar inclined).	$c_{profile} = 0, \quad c_{cross} = 0$

Curvature can be used for geomorphological analysis



Planar slope
$c_{profile}$ & $c_{cross} = 0$
$g_{profile}$ & g_{cross} = constant

Convex slope
$c_{profile} < 0, \quad c_{cross} > 0$
$g_{profile}$ & g_{cross} = variable

Concave slope
$c_{profile} > 0, \quad c_{cross} < 0$
$g_{profile}$ & g_{cross} = variable

Valley
$c_{profile} = 0, \quad c_{cross} < 0$
$g_{profile}$ = constant
g_{cross} = variable

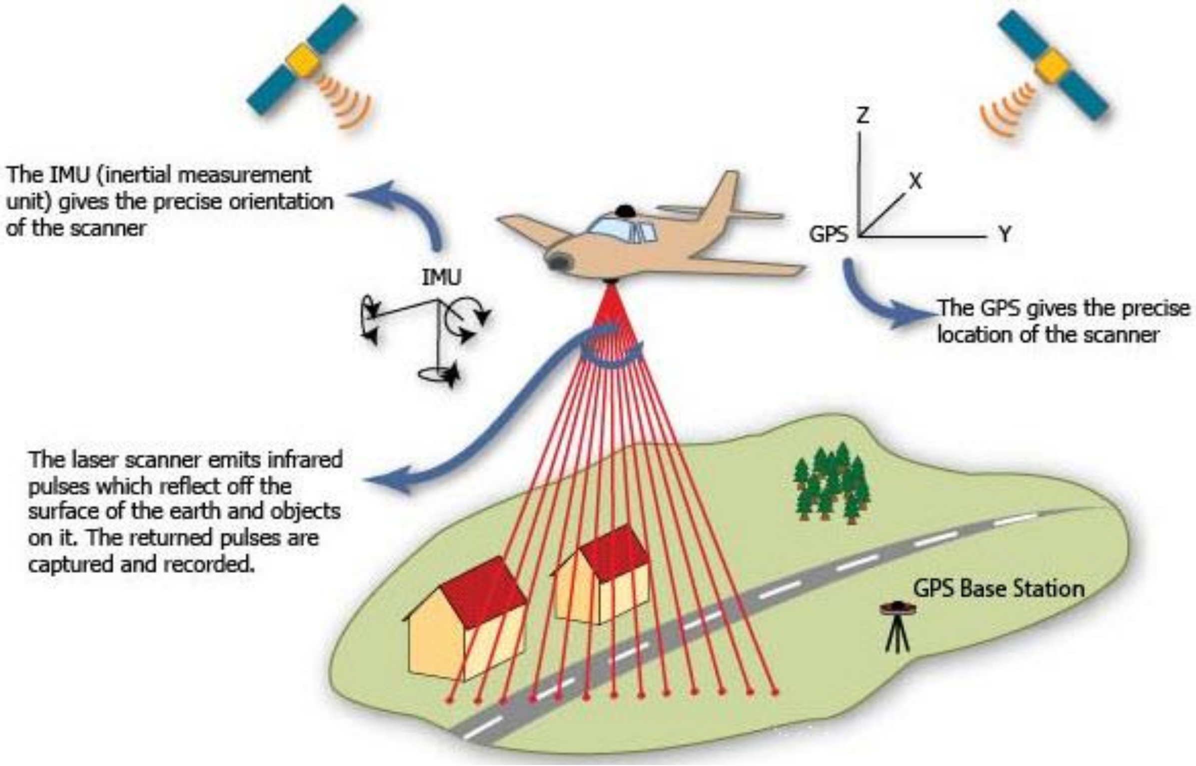
Ridge
$c_{profile} = 0, \quad c_{cross} > 0$
$g_{profile}$ = constant
g_{cross} = variable

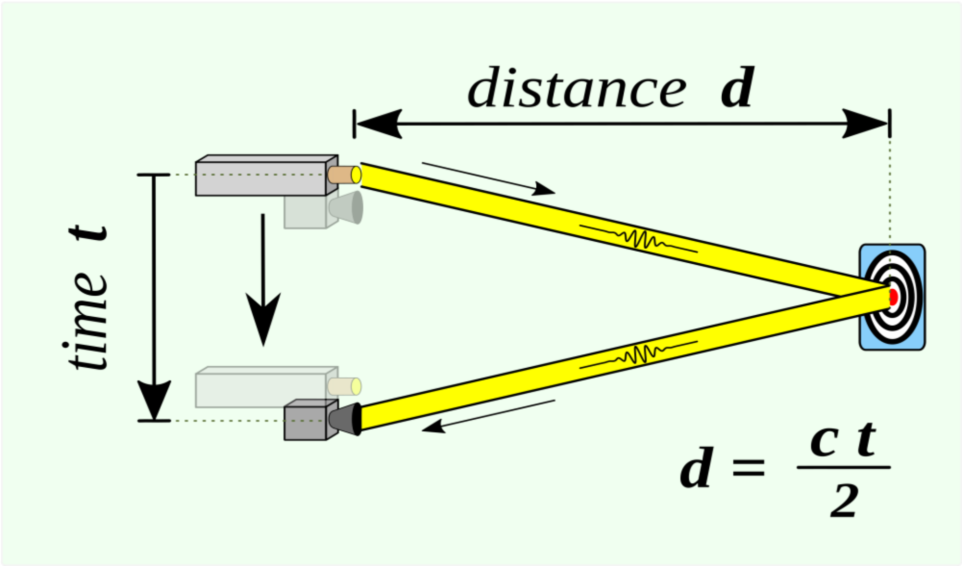
5.4 What is LiDAR?

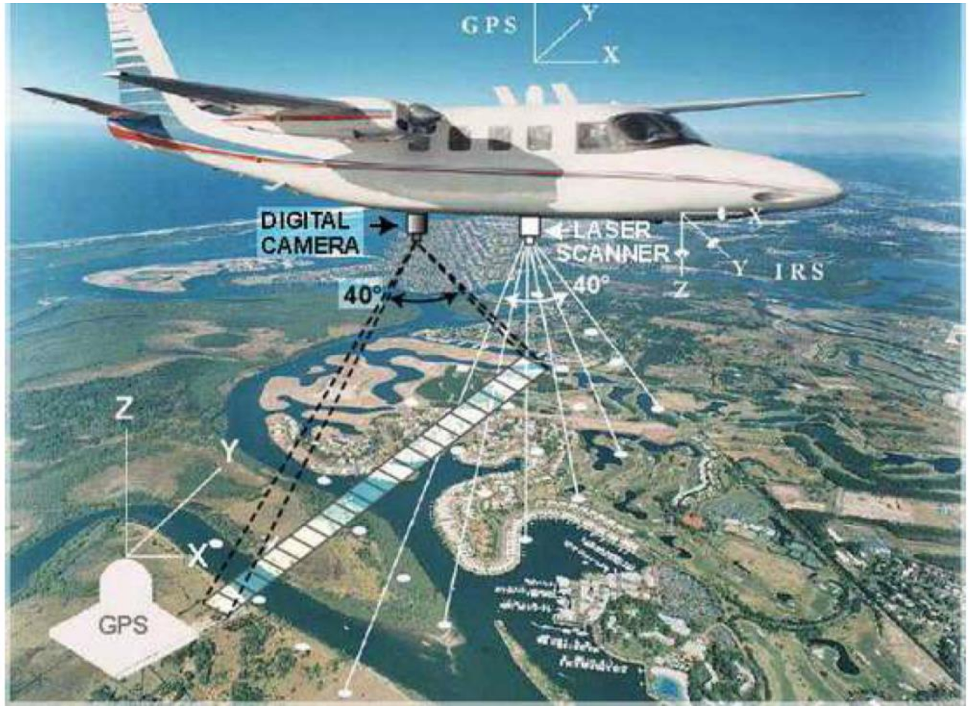
- Light Detection And Ranging or Laser scanning
- Active sensing – emits energy and detects the returned energy
- LiDAR is a method for determining ranges (variable distances) by targeting an object with a laser and measuring the time for the reflected light to return to the receiver, i.e. individual reflections of the energy from target objects are collected, based on time and direction, and used to generate a point cloud of measurements
- Each point represents a reflection from a particular target object, and the distance to that object is recorded as a point in space
- The distance of the object from the sensor = (speed of light x time of flight between energy pulses) /2, i.e.

$$\boldsymbol{d} = \frac{\boldsymbol{ct}}{\boldsymbol{2}}$$

- LiDAR = an important source of elevation data (and more)






GPS
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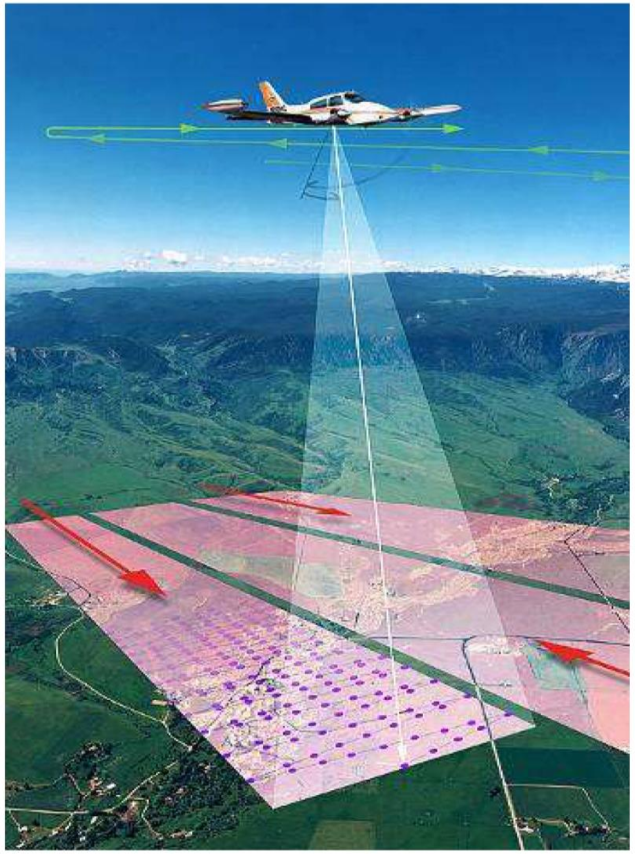
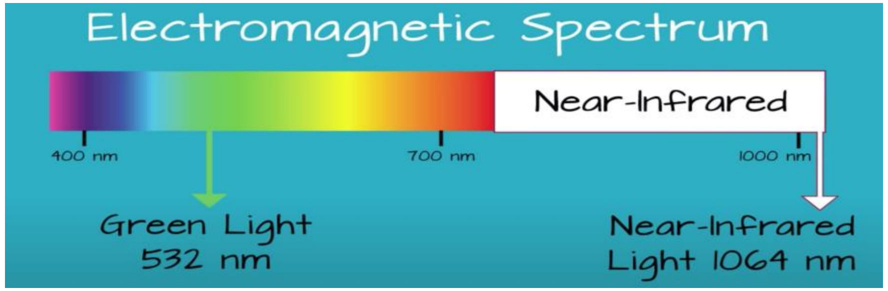
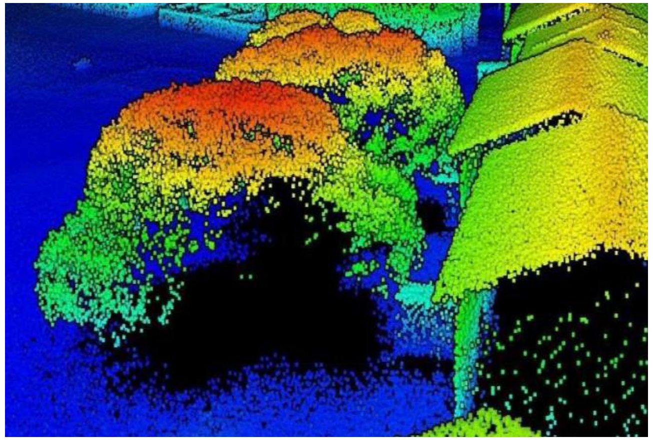


LiDAR survey data processing workflow

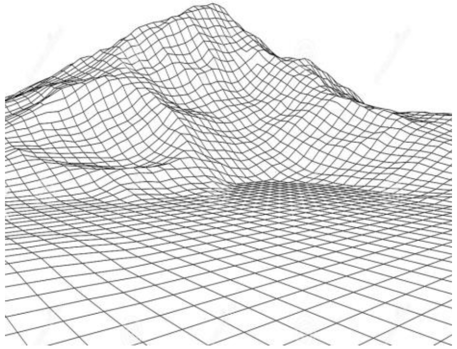
- Light source & photodetector generates a laser beam of low divergence
  - Can resolve relatively small objects < a few hundred metres away from the laser
- Power ~ 10 watts, and commonly at IR wavelengths
- Produces a point cloud, consisting of x, y & z positions of the reflections from each object in the field of view



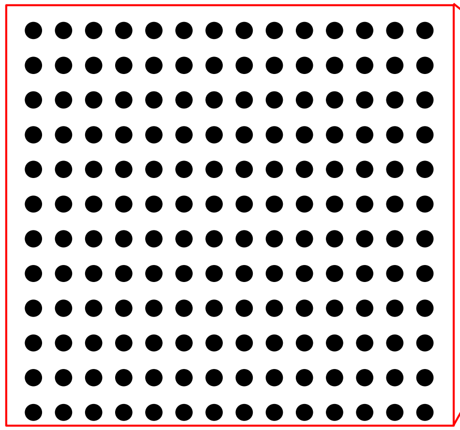
Raw point cloud



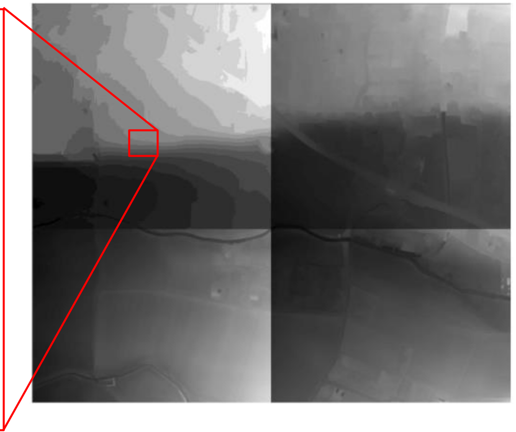
Wireframe (or TIN)



ASCII gridded points



Raster DSM tiles



Terrain products

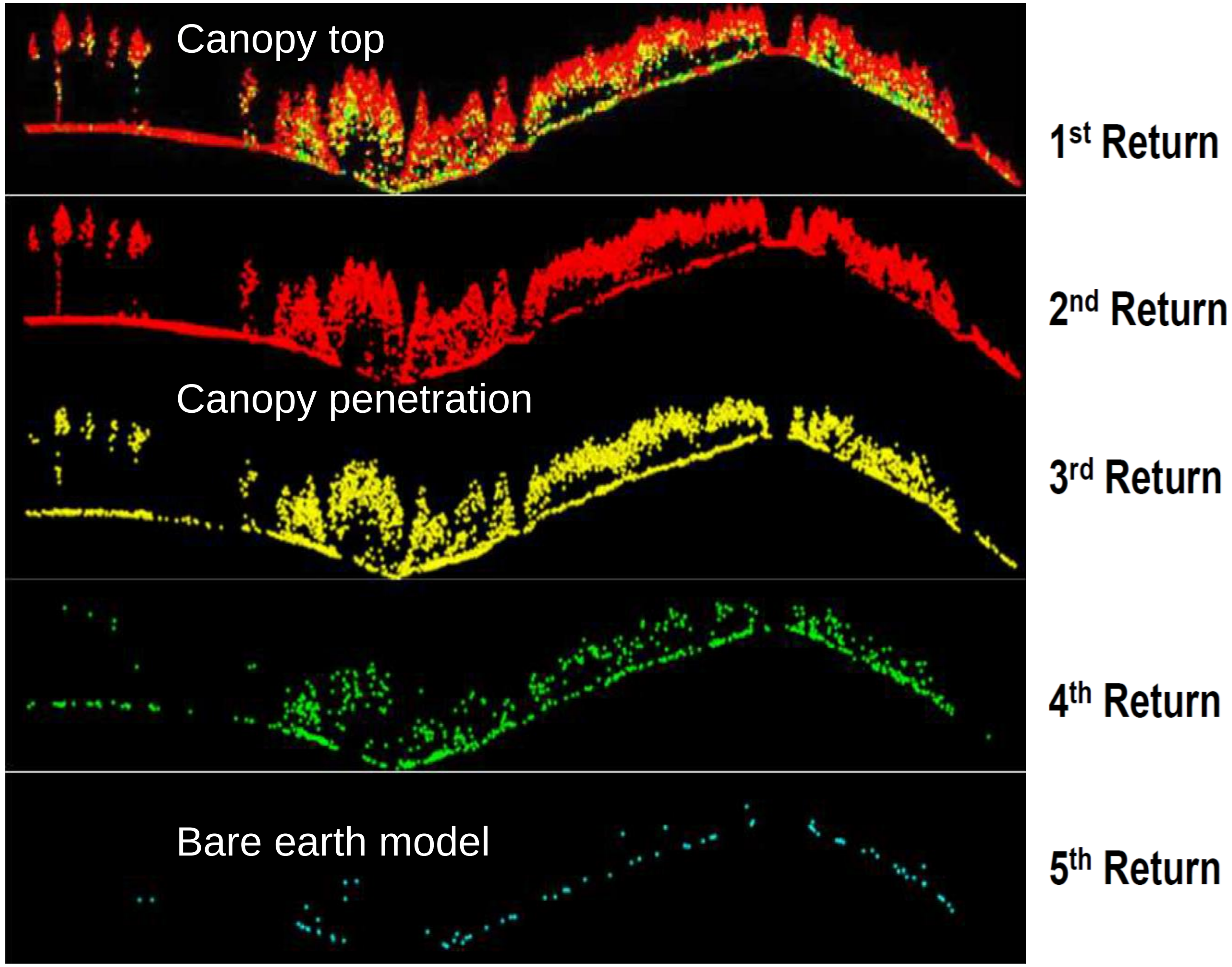
- DSM & DTM
- Hillshade
- Slope & aspect
- Drainage etc

Canopy penetration

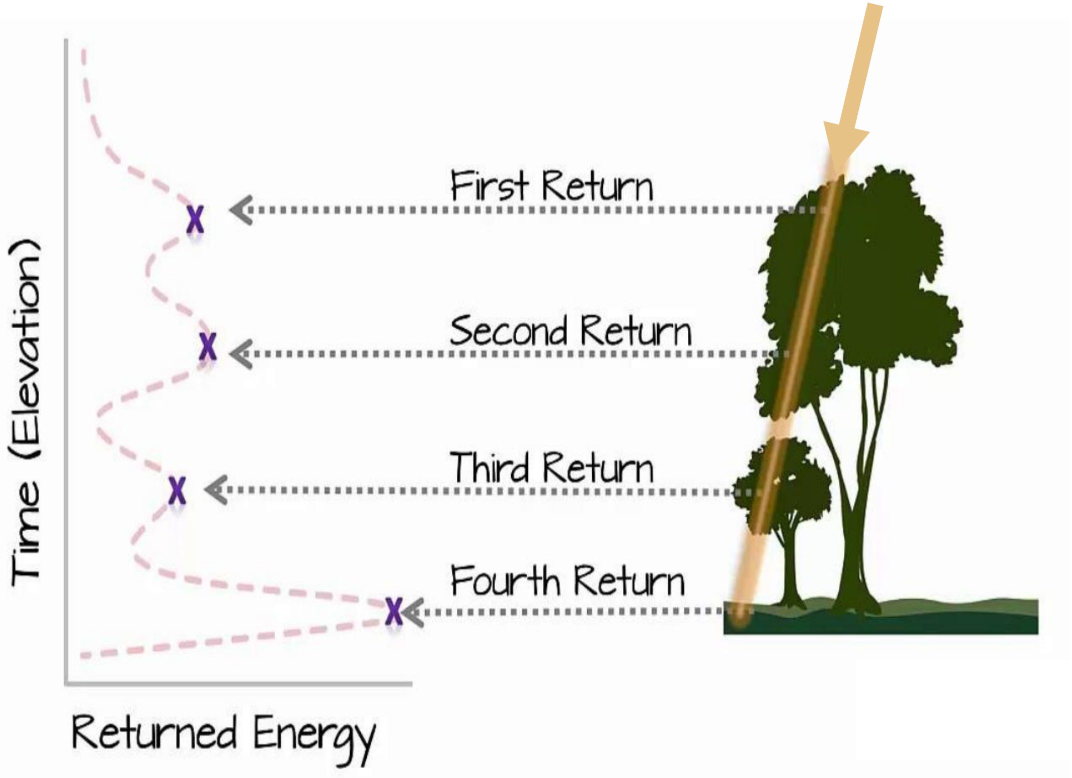
The laser beams can penetrate through a canopy to reach the ground, thus forming a ‘Bare earth’ model (or **Digital Terrain Model**)

[Digital Elevation Model contains the raw heights of ground or buildings, trees etc where these are present]

Photon counting LiDAR



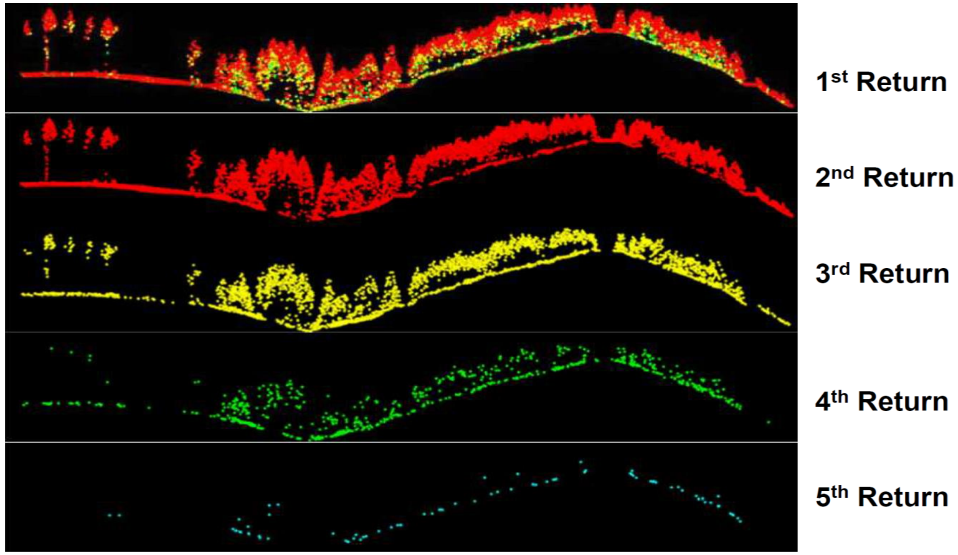
Full waveform & discrete

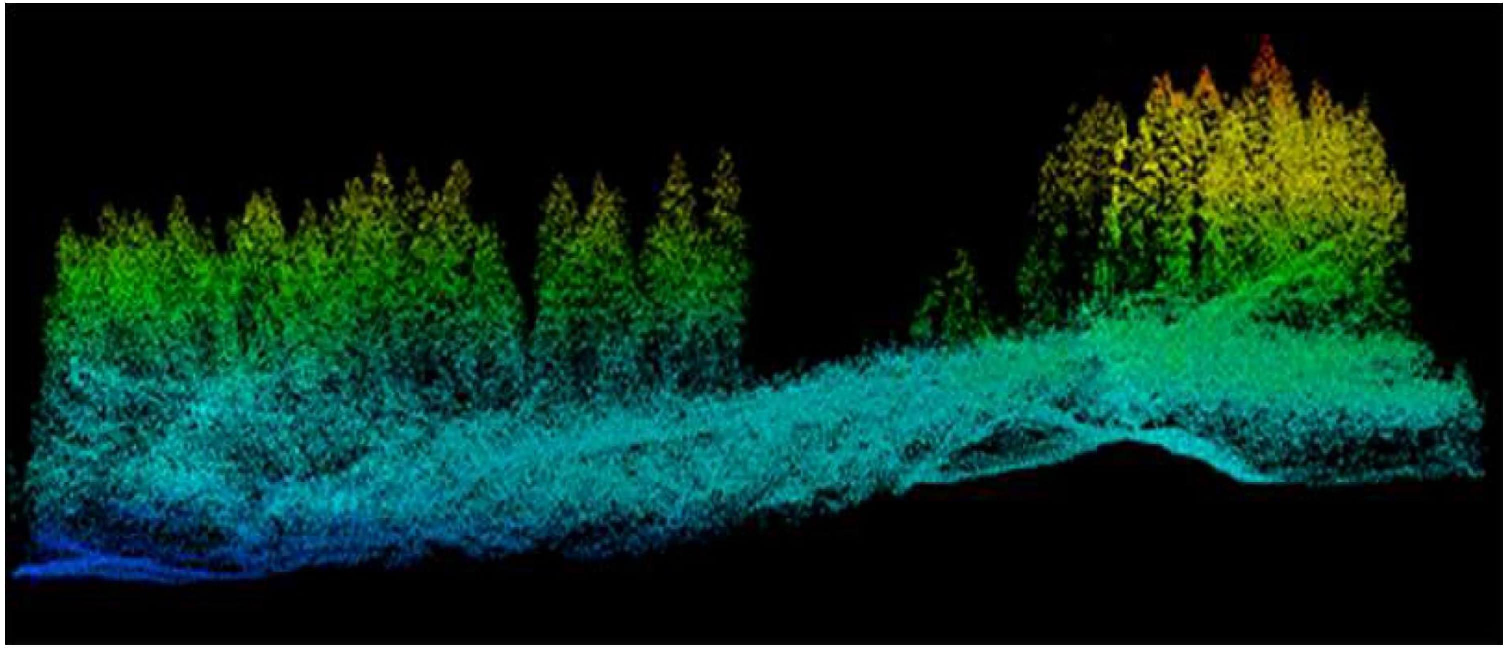


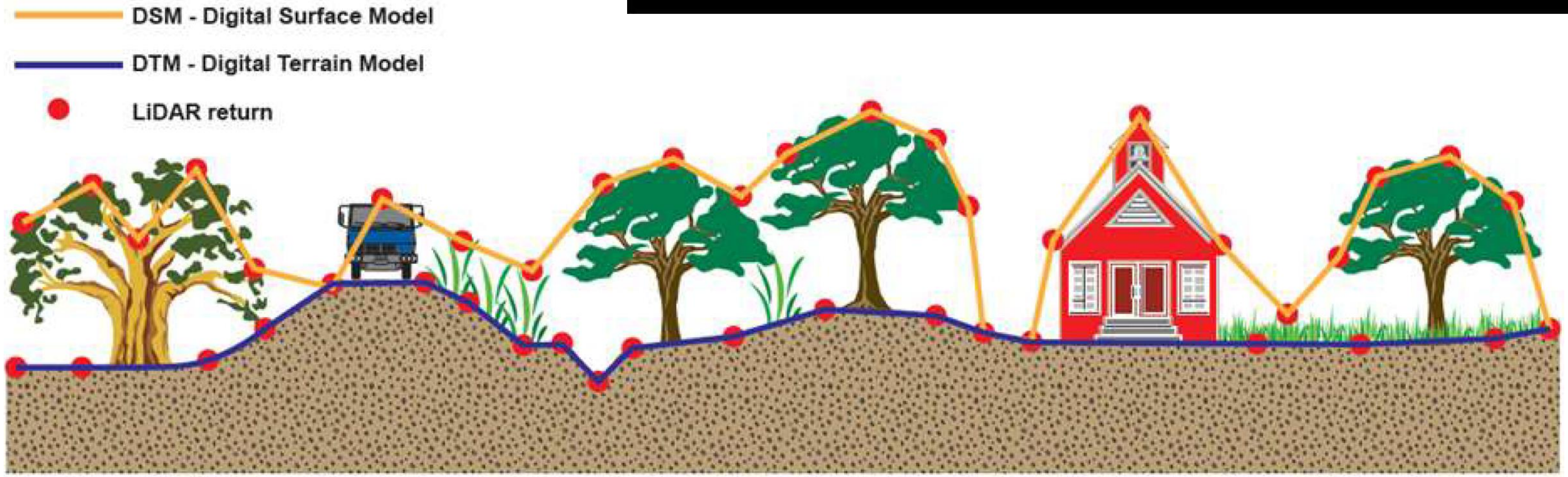
The returned pulse is classified into one or more discrete returns:

- X, Y, Z & intensity
- Returns are recorded when intensity exceeds a predefined system threshold.
- Multiple returns are recorded (usually 1-5). Last returns are important for detecting the ground

What the difference between LiDAR DSM and DTM?

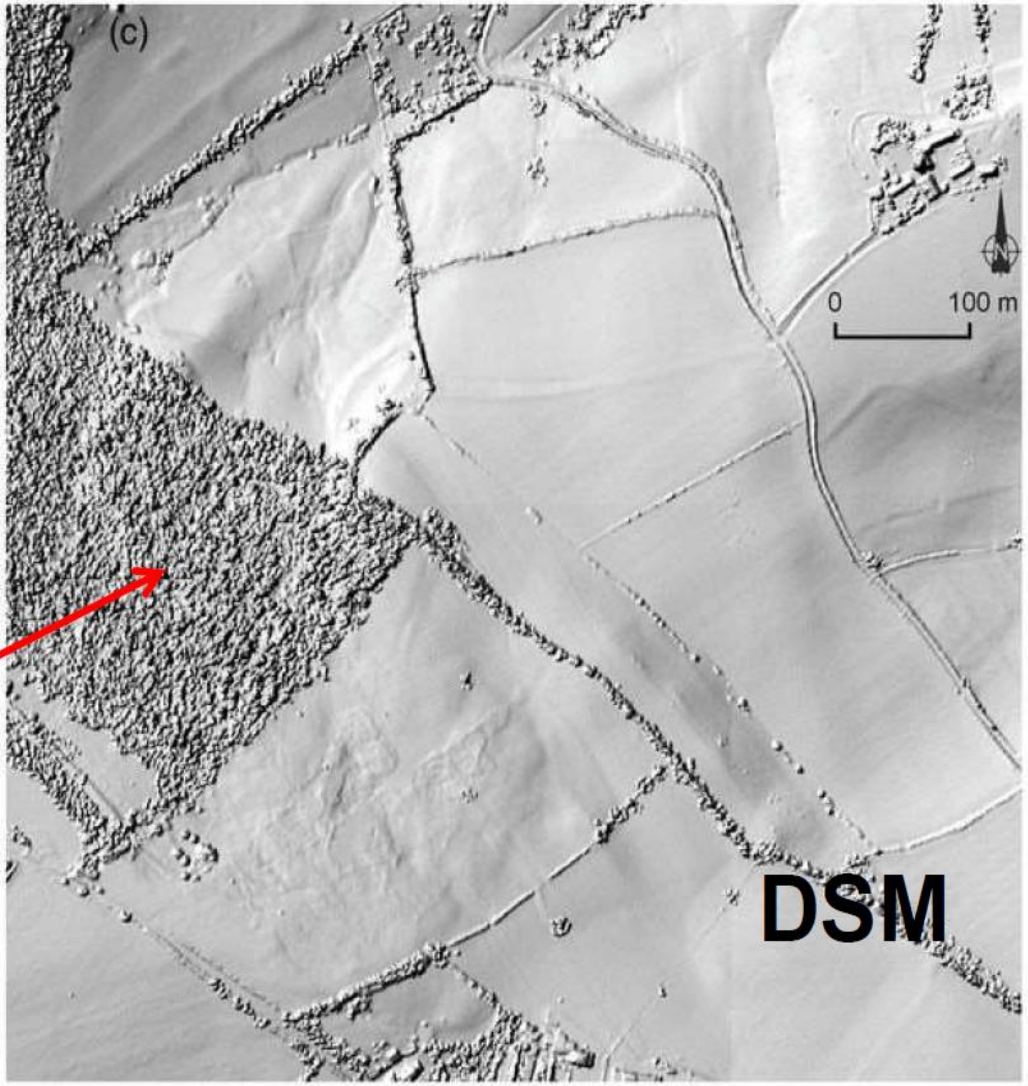




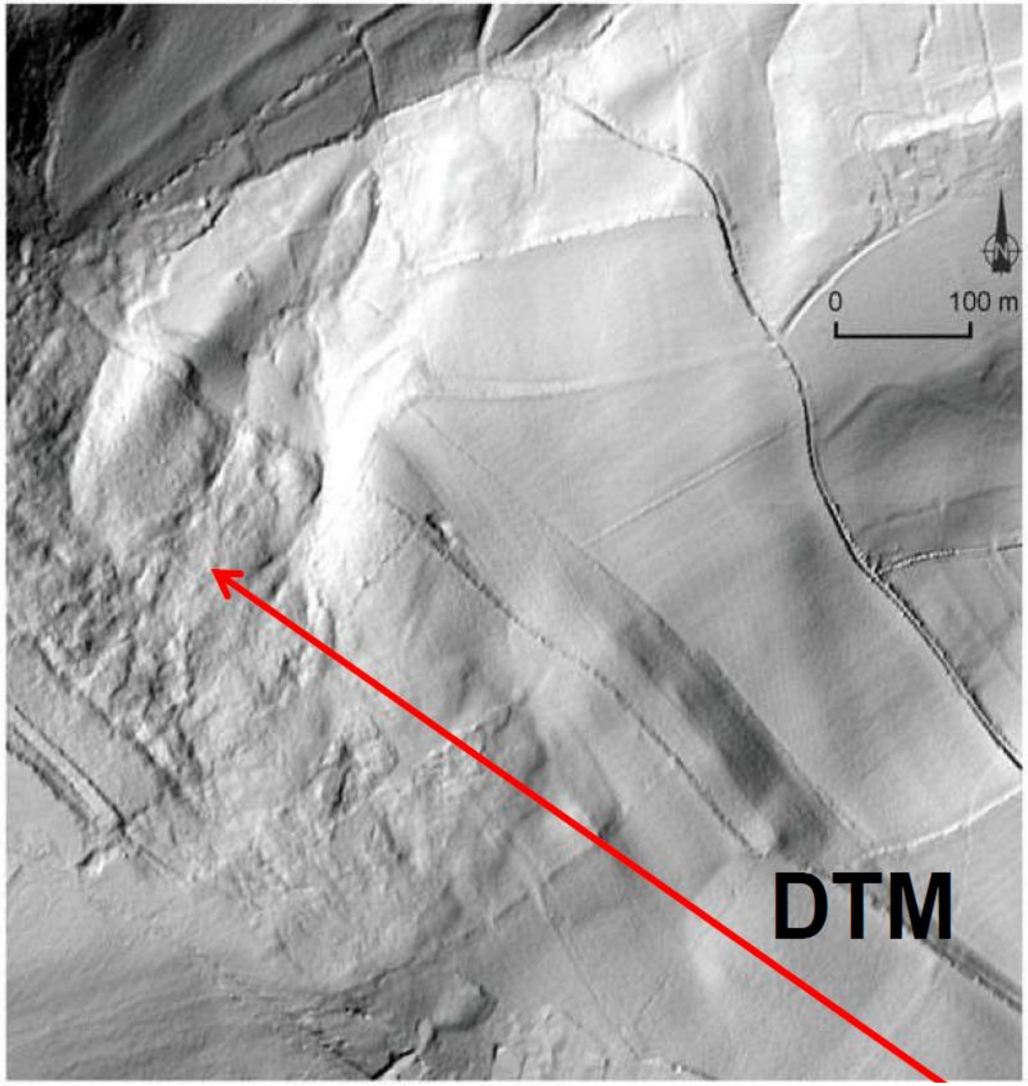


What the difference between LiDAR DSM and DTM?

‘Bare Earth’ model



Tree cover

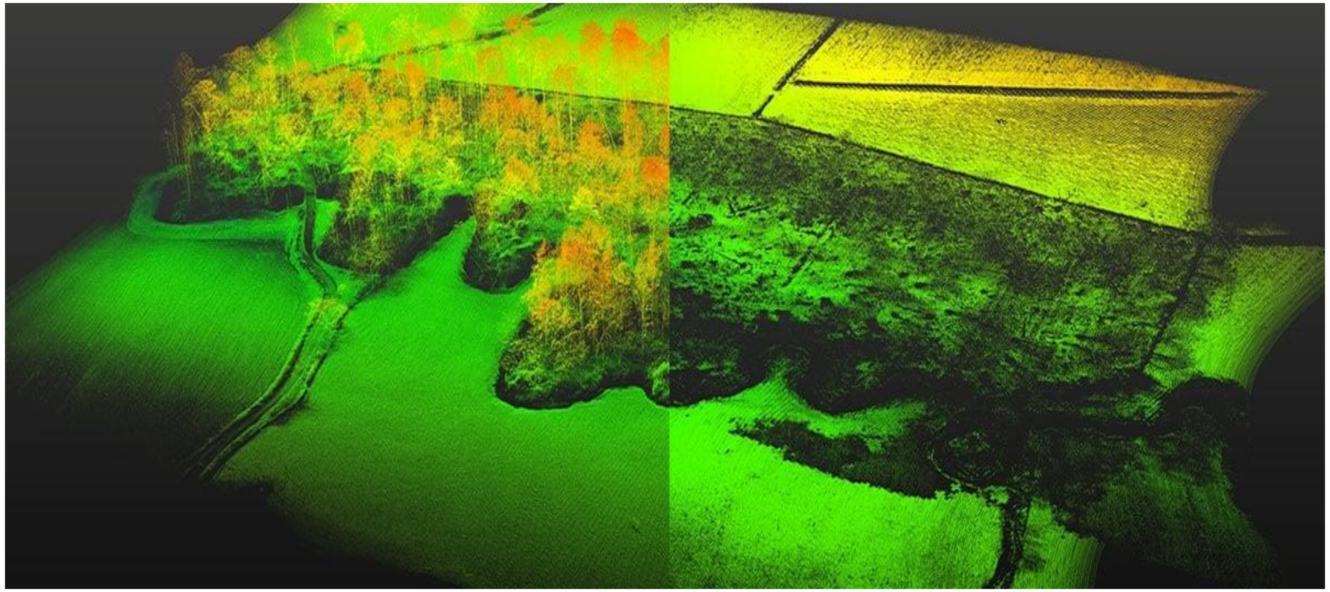


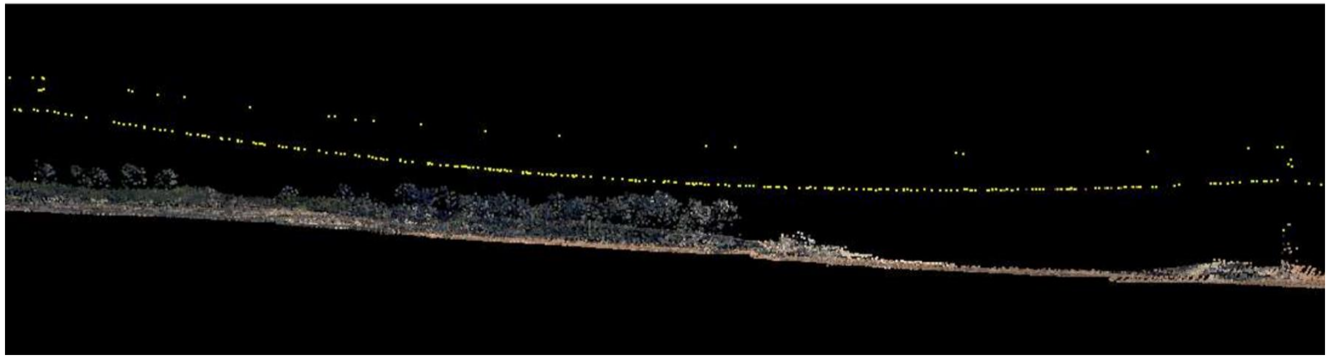
Ground beneath trees

8.4 What can you do with these Bare Earth data?

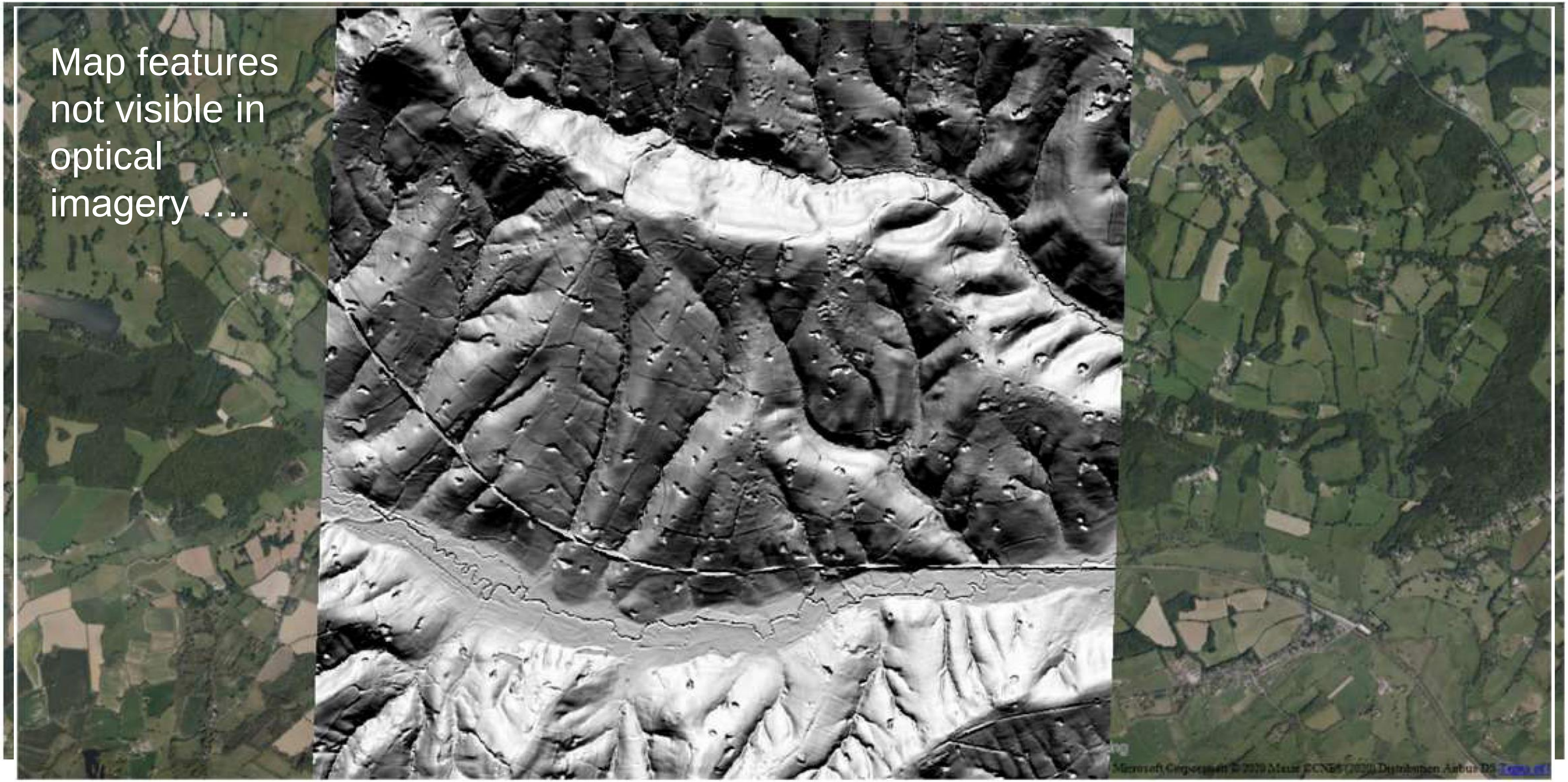
- Runway approach zone encroachment: in aviation – allowing determination of runway obstructions in the approach zone
- Vegetation management: along a transmission line - to see where and how much vegetation is encroaching
- View obstruction: in urban planning - to check how a proposed building would affect the viewshed of residents and businesses
- Detecting power lines above canopy and ground
- Biomass estimation

- Bare earth ground model also reveals expression of outcropping surface geological features (lithological & structural)



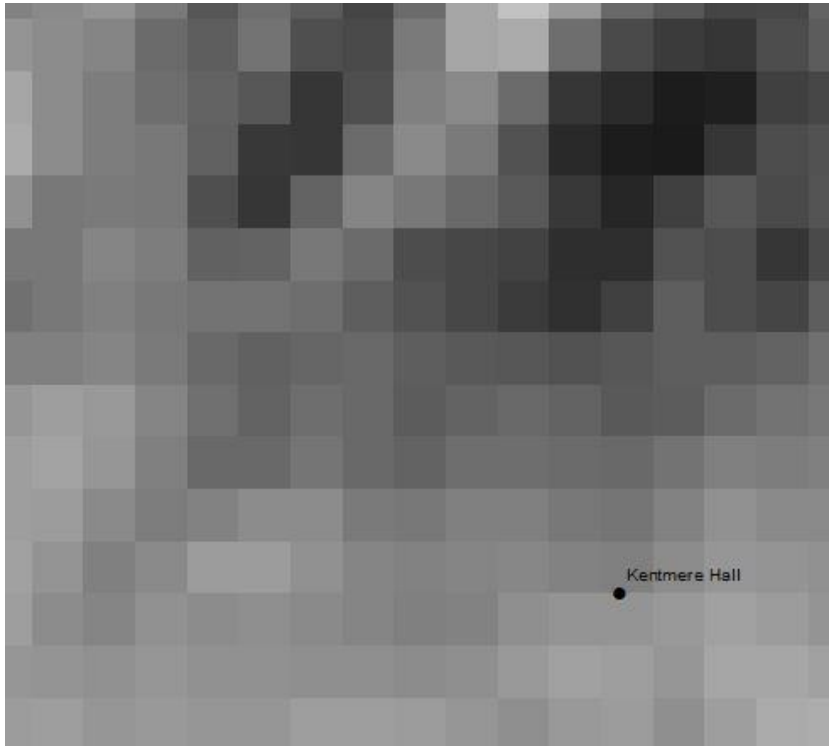


What can you do with these bare earth data?

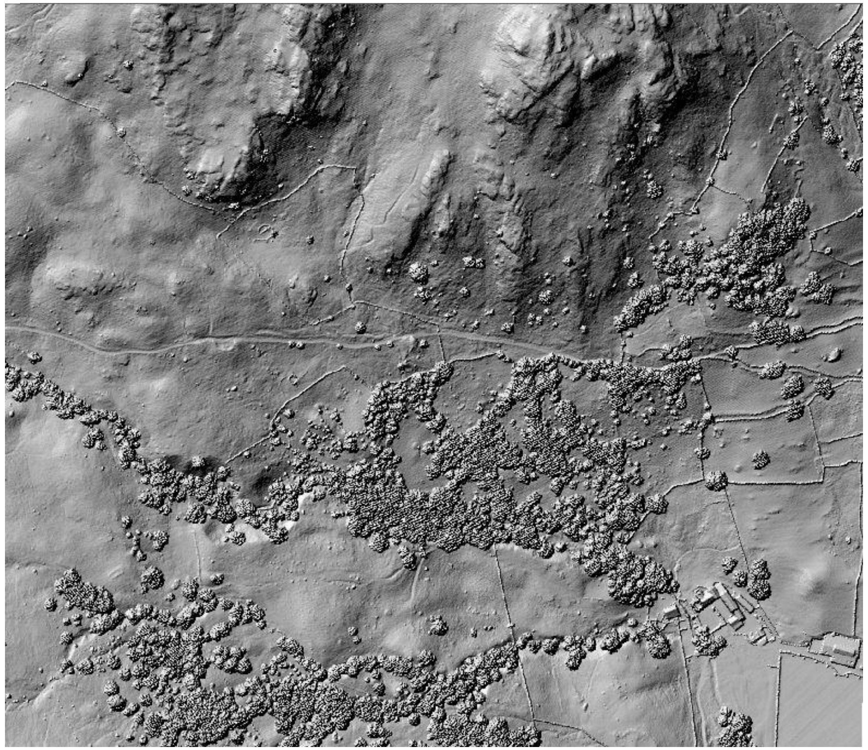


LiDAR offers a great leap forward in terrain modelling

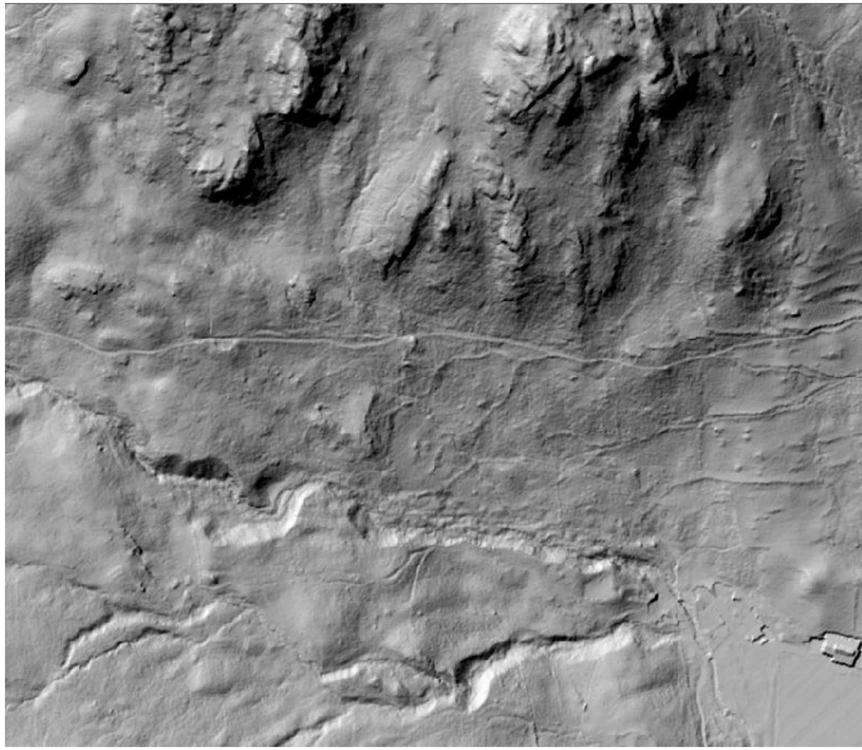
OS T50 DEM (terrain & objects)



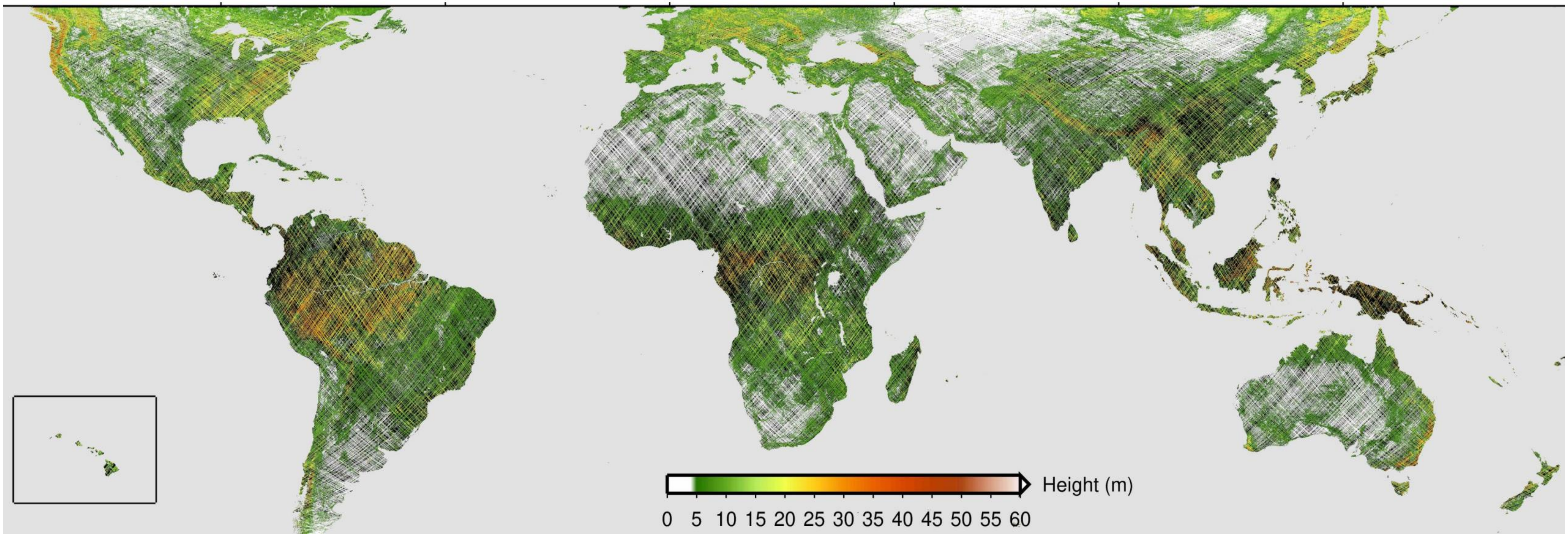
LiDAR 50cm DSM (terrain & objects)



LiDAR 1 m DEM (terrain only)



Global applications: forest canopy height mapping from the ISS



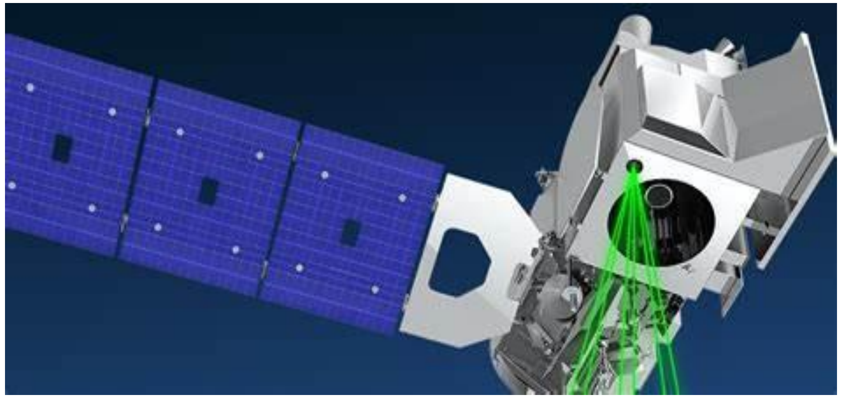
Source: NASA Global Ecosystem Dynamics Investigation (GEDI) 2019+ https://glad.umd.edu/dataset/gedi/

Potapov, et al., 2021. Mapping global forest canopy height through integration of GEDI and Landsat data, Remote Sensing of Environment, 253, 112165, ISSN 0034-4257, https://doi.org/10.1016/j.rse.2020.112165.

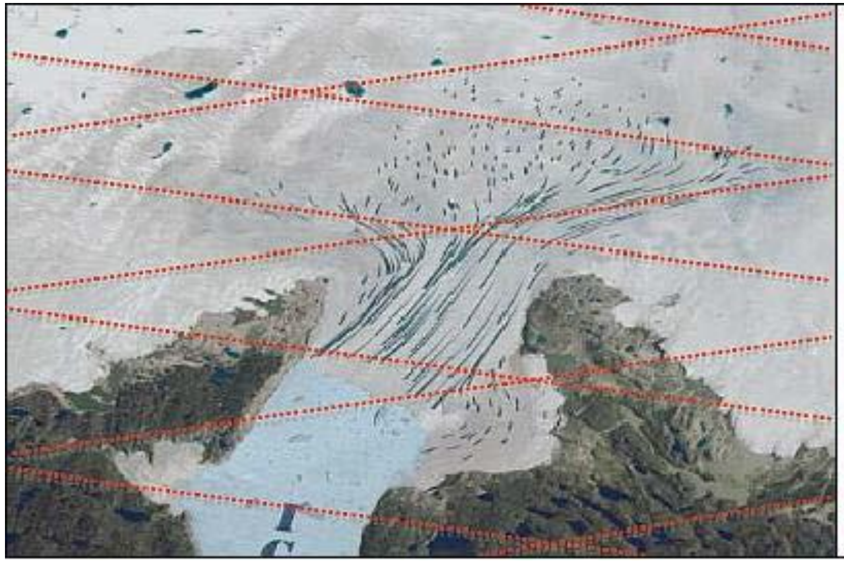
Global applications: Topography & canopy from ICESat-2

https://icesat-2.gsfc.nasa.gov/icesat-2-data

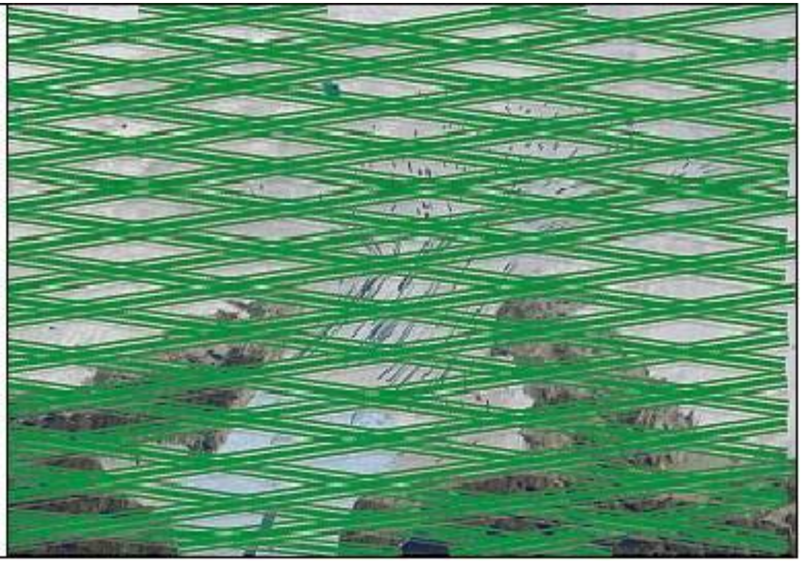
- Measure melting ice sheets and investigate how this effects sea level rise
- Measure mass changes of ice sheets and glaciers
- Estimate variations of sea ice thickness
- Measure the height of vegetation in forests and other ecosystems worldwide



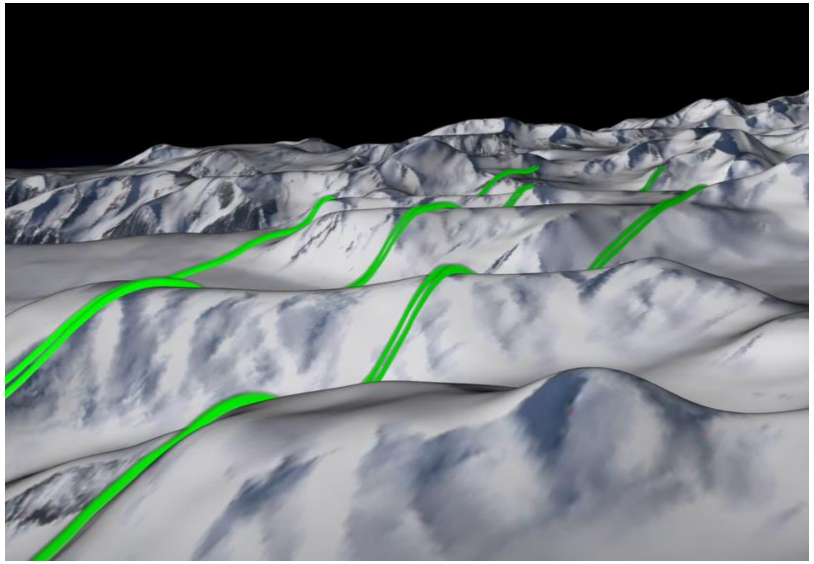
ICESat-1 (single laser beam)



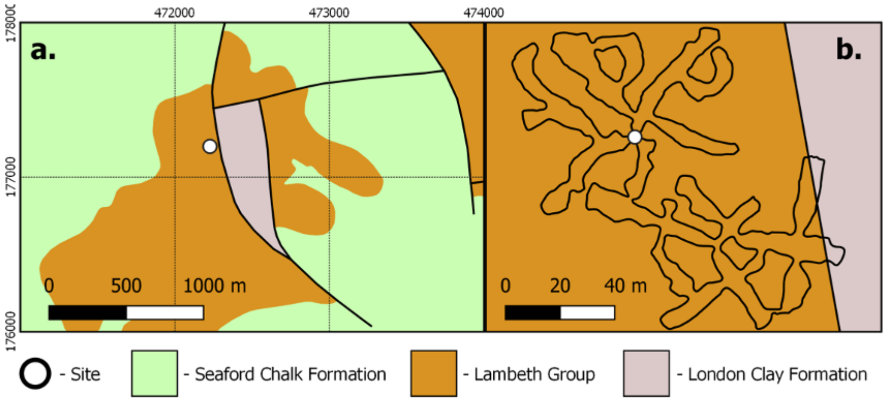
ICESat-2 (6 laser beams)



ICESat-2



Ground based applications: automated fracture mapping using hand-held LiDAR, in Emmer Green Chalk Mine

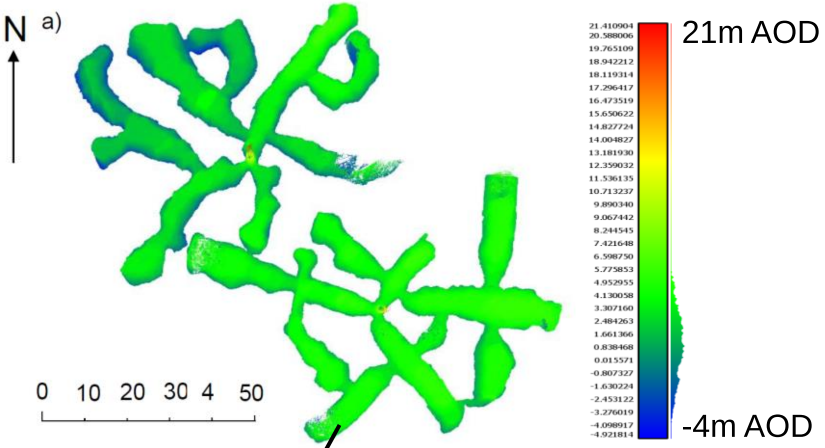


- Mine 20m below ground level
- Many chambers hazardous and unmappable
- Situated next to fault 'pull-apart' structure
- Within the Seaford Chalk Formation - relatively pure chalk with flint bands

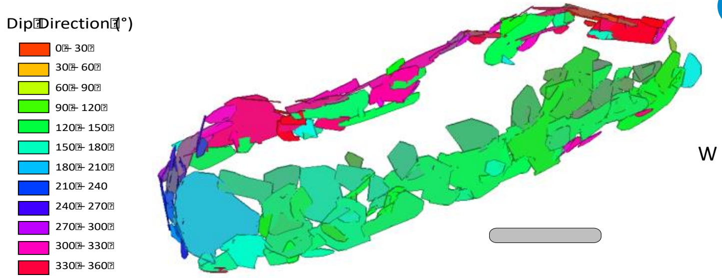
GeoSLAM Zeb-Revo User Guide; (Eyre et al., 2016; Nocerino et al., 2017).

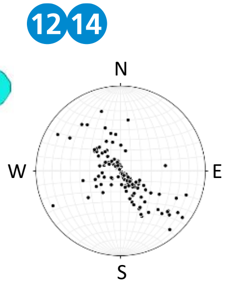
Specification	Specification
Maximum Range	30 m in optimal conditions 15-20 m outside
Points per Scan Line	432
Field of View	270 x 360
Scan Rate	43200 points / s
Scan Range Noise	30 mm
Laser Wavelength	905 nm
Scanner Line Speed	100 Hz
Laser Head Rotation Speed	0.5 Hz
Scanner Weight	1.0 kg
Scanner Dimensions	86 x 113 x 287 mm
Operating Time (Battery Life)	4 hours continuous use

New accurate map of the chalk mine



Structural analysis





- Data collection with the Zeb-Revo LiDAR easily and rapid
- Easy extraction of facet statistics to assess dip direction
- Large number of very tiny facets which are not geologically significant
- Some cavern walls are major facets but some are artificial
- Automated classification challenging
- Successful in producing accurate cavern map

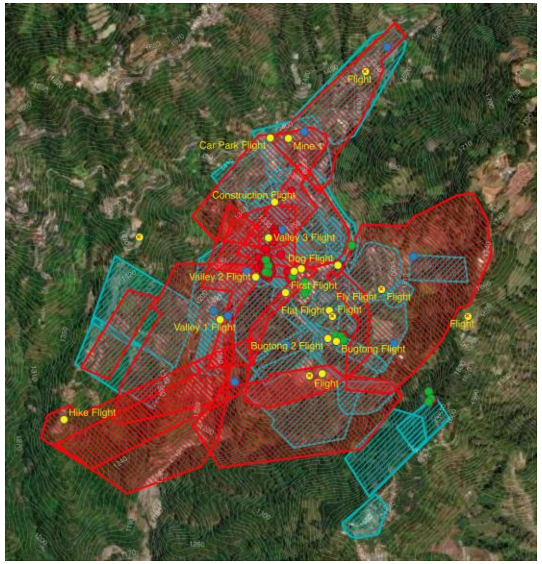
MSc student Olivia Rhind

Mapping abandoned mine site beneath forest in Philippines

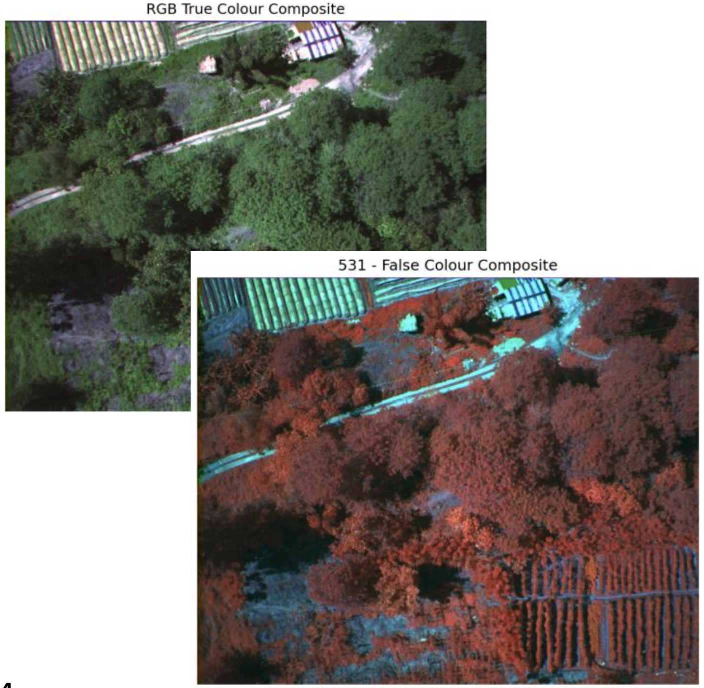
Plancherel, Brita Parado, Mason, Rasheed & Graham

DJI Matrice 300 with LiDAR payload

- Mine processing site now overgrown and completely vegetated (largely invisible)
- Outputs Bare Earth DTM
- Vegetation canopy data
- Orthorectified RGB image mosaic



Multiple survey grids with both UAVs

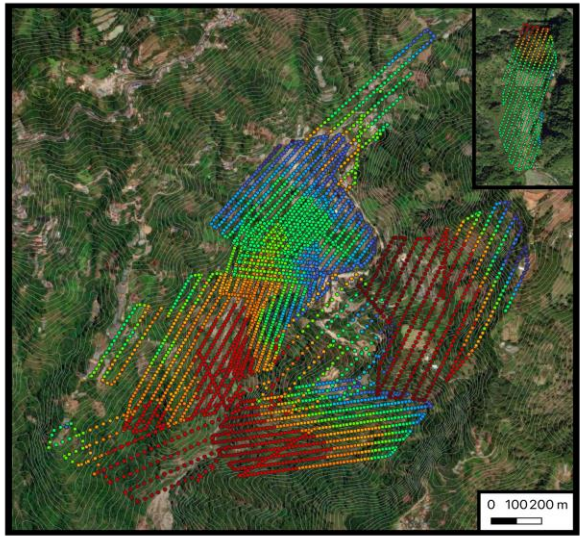


DJI Phantom4 with MultiSpectral payload (MSci student Arron Graham)

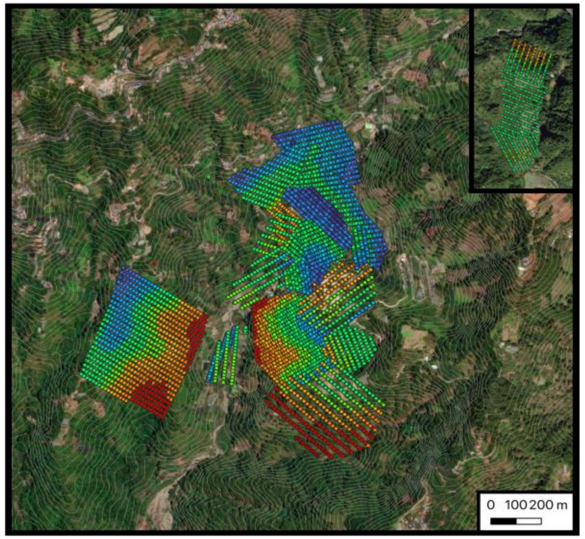
Getting local kids involved

New accurate mapping from both UAVs

Matrice 300



Phantom4



Aircraft height above ground (m)

- < 30
- 30 - 60
- 60 - 70
- 70 - 80
- 80 - 90
- 90 - 100
- 100 - 130
- 130 - 150
- 150 - 175
- 175 - 200
- 200 - 250
- 250 - 300

5.5 LiDAR Summary

- Active sensing, using reflections of coherent IR energy, and based on return time and direction.
- Operated mainly in VNIR part of spectrum (sometimes Green).
- Uses a coherent laser beam of low divergence for precision over long distances between source and target
- Three modes of operation – discrete, full waveform & photon counting.
- Can be operated from airborne, spaceborne and ground based platforms
- Distance between source and target object = (Speed of Light x Time of Flight)/ 2
- Produces a point cloud, consisting of x,y & z positions and intensity of reflections from each object
- Returns are recorded when intensity exceeds a predefined system threshold.
- Multiple returns are recorded (usually 1-5). Last returns are important for detecting the ground – and these are used to extract the Bare Earth terrain
- Point cloud, can be used to extract canopy height, internal canopy geometry, estimate biomass, extract Bare Earth information and building information, overhead power lines (from the earlier returns)
- Bare Earth terrain (DTM) can be used for a variety of applications – from very local (ground, UAV or aircraft) to global (spaceborne)
- LiDAR offers the highest vertical precision achievable (better than any photogrammetry), and variable spatial (horizontal) precision based on altitude (flying height) and flight speed (sampling frequency).