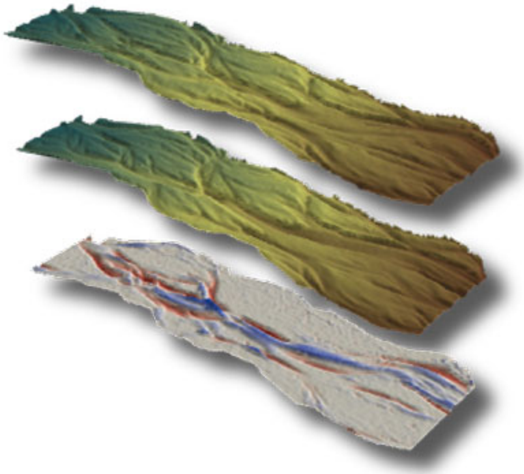
PRINCIPLES OF TOPOGRAPHIC CHANGE DETECTION

$\frac{\partial z}{\partial t}$ GCD



UtahState University
ECOGEOMORPHOLOGY & TOPOGRAPHIC ANALYSIS LABORATORY

NORTH ARROW RESEARCH

RIVERSCAPES CONSORTIUM

BY END OF HOUR

GCD = Geomorphic Change Detection
TCD = *Topographic* Change Detection

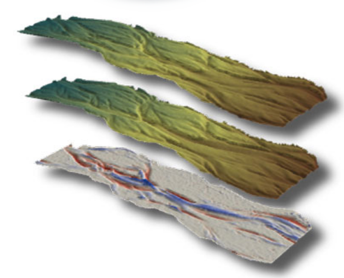
You should understand:

1. GCD techniques and how they are applied to monitoring rivers
2. How to account for unreliability uncertainties in DEMs
3. How to interpret DoDs

≈ ?

DoD ≠

DoD = DEM of Difference =

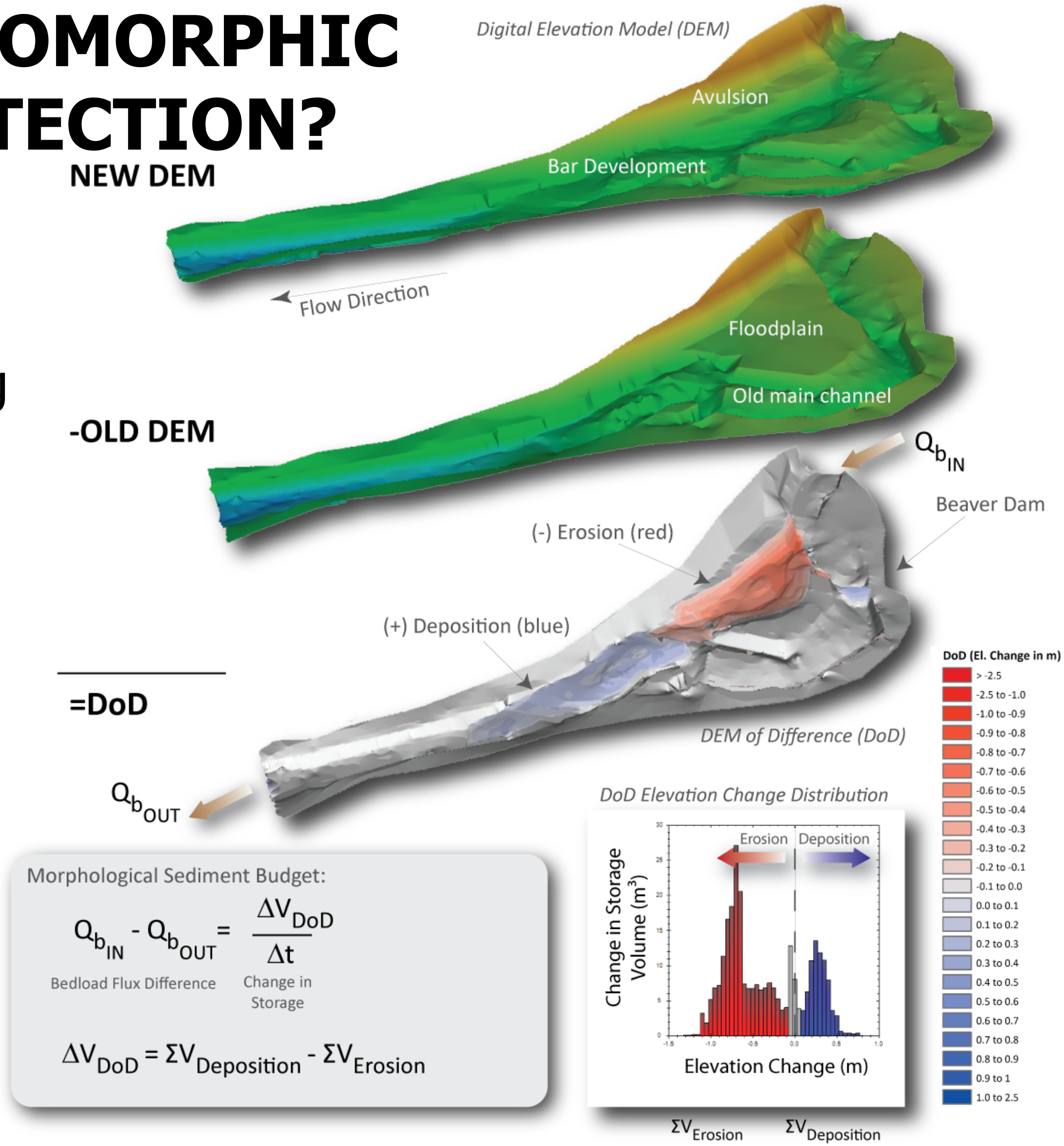


PRINCIPLES OF TOPOGRAPHIC CHANGE DETECTION

- At its heart TCD is a signal to noise problem
  - Best applied when signal is big and obvious and noise is negligible
  - Often applied when signal is small and obscured and noise is substantial
- Noise is estimated with error modelling & error propagation
- Apples to Apples Easiest
  - Orthogonality, Concurrency & Dimensional Divisibility
  - Allows this to be a simple subtraction problem with orthogonal rasters
  - Different survey methods okay if accounted for in error modelling
- Thresholding of changes allows separation of signals
  - Either discard or flag as 'do not trust' information below threshold
- Always start simple & conservative, and see if signal you are interested in is detectable. Invest in more complex methods if you believe signal is there, but is obscured…

WHAT IS GEOMORPHIC CHANGE DETECTION?

- Inferences about 'net' geomorphic changes resulting from erosion & deposition that are detectable despite noise…
- Inferences made with repeat topography… i.e.



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IN A PERFECT WORLD…

- The signal (the change we're trying to detect) is much greater than our noise….

$$\frac{\partial z}{\partial t} >> \delta(z)$$

- In many instances, the noise is of similar magnitude to our noise…

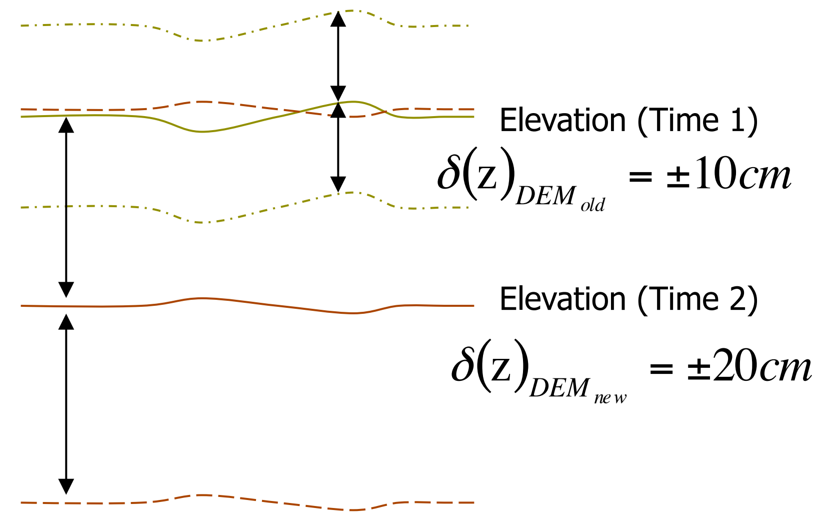
$$\frac{\partial z}{\partial t} \approx \delta(z)$$

- Better in places where vertical changes are large!

- LiDaR : +/- 10 to 25 cm (14 to 36 cm ${}_{min}LoD$)
- Terrestrial Laser Scanning: +/- 0.5 to 4 cm (0.7 to 6 cm ${}_{min}LoD$)

ERROR PROPAGATION

- Distinguish those changes that are real from noise
- Use standard Error Propagation



$$\delta(z) = \sqrt{\left(\delta(z)_{DEM_{old}}\right)^2 + \left(\delta(z)_{DEM_{new}}\right)^2}$$

e.g. $\delta(z) = \sqrt{(10)^2 + (20)^2} = 22.36$

22.36 cm ≈ 8.8 in

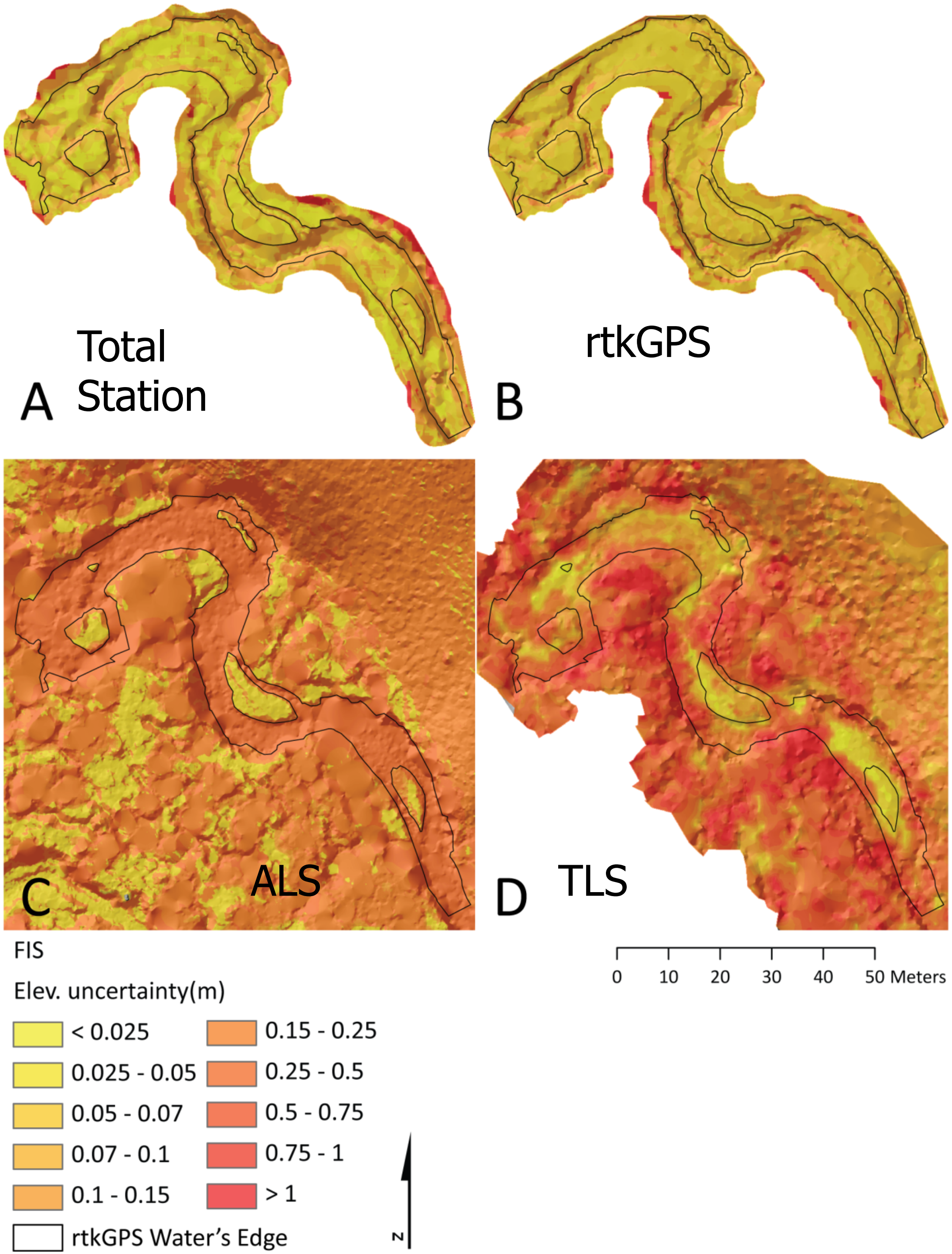
See

- Brasington et al (2000): *ESPL*
- Lane et al (2003): *ESPL*
- Brasington et al (2003): *Geomorphology*

EXAMPLES OF ERROR MODELS

- Greater extent on TLS & ALS
- ALS & TLS worthless in water
- ALS best on floodplain

From Bangen et al. (2014) Geomorphology
DOI: 10.1016/j.geomorph.2013.10.010



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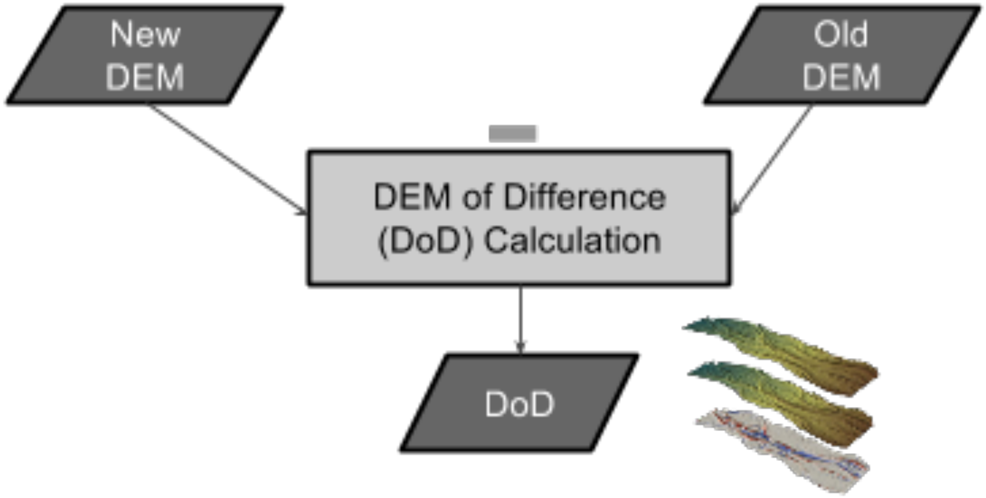
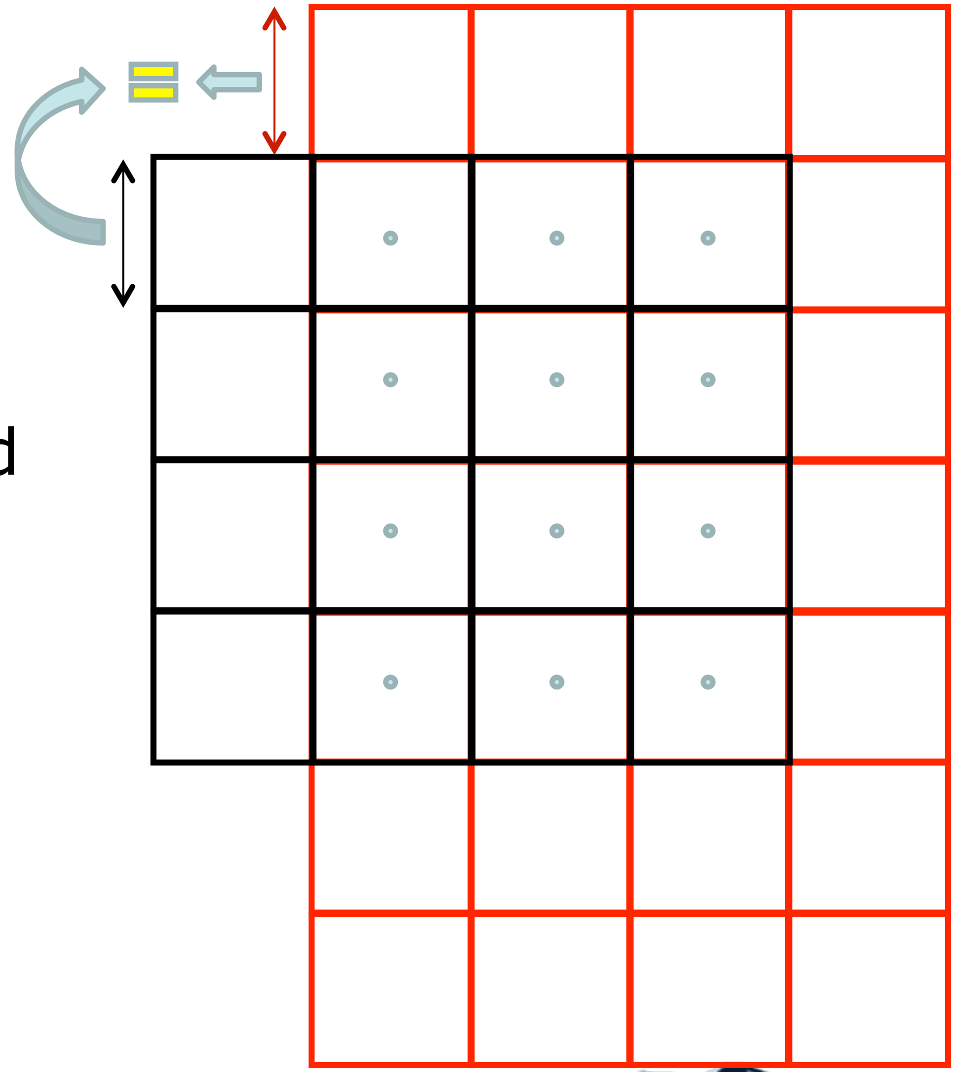
'SO… YOUR WHOLE CAREER IS A SIMPLE SUBTRACTION PROBLEM?'

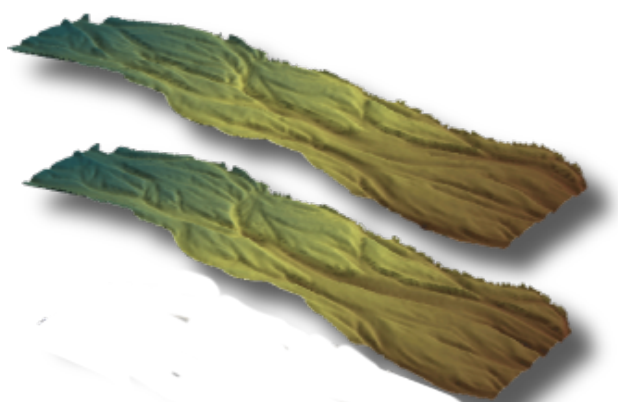
- $DoD = DEM_{new} - DEM_{old}$



ORTHOGONALITY

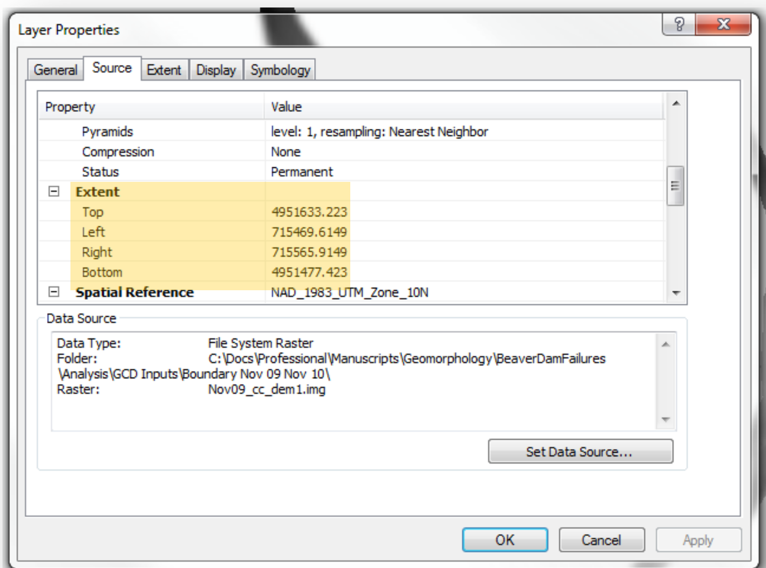
- Orthogonal rasters must:
  - Share exact same grid resolution
  - Share the exact same grid centers (i.e. aligned in both easting and northing)

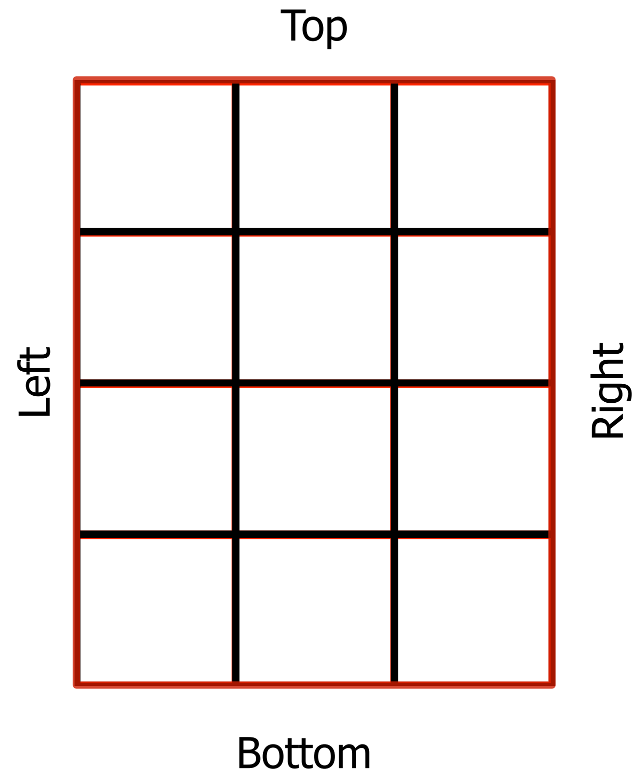




CONCURRENCY

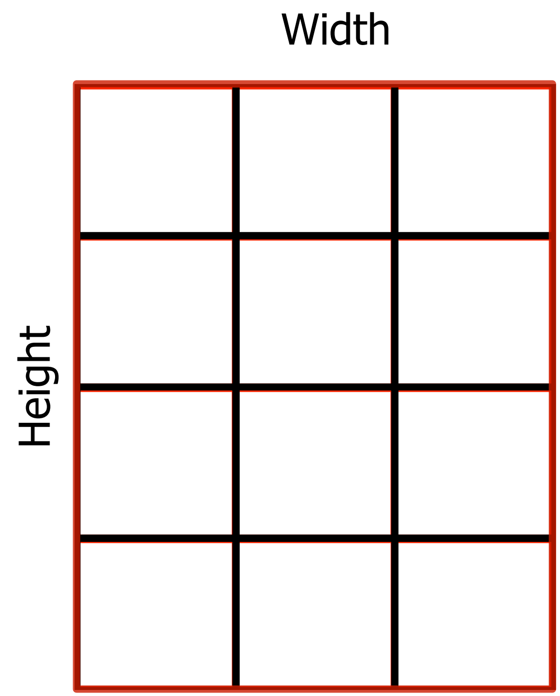
- Grids are orthogonal and:
  - Share *exact* same extents

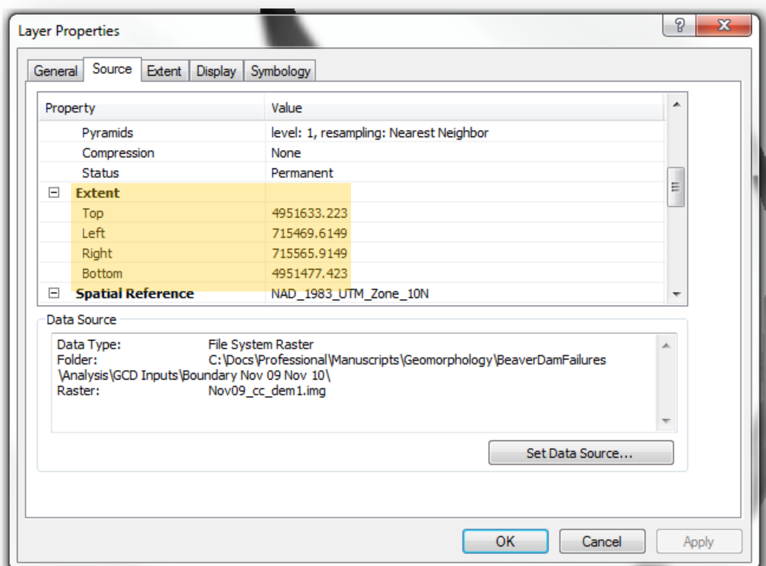




DIMENSIONAL DIVISIBILITY

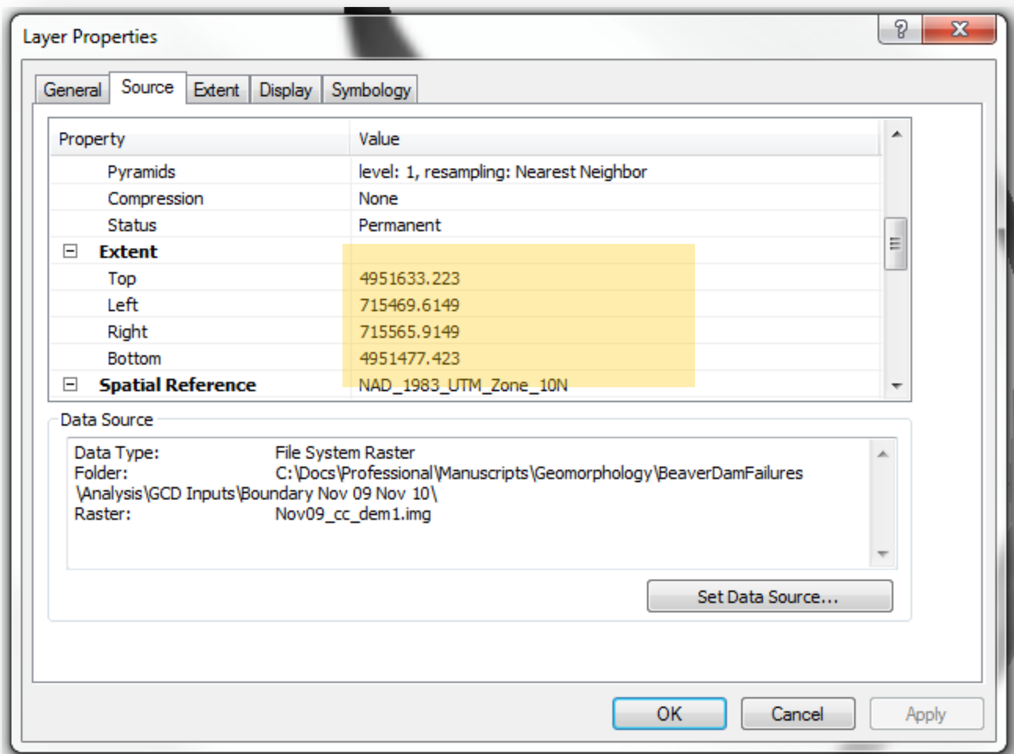
- Are width & height evenly divisible by cell resolution?
- If not:
  - Does cell resolution or number of rows and columns take the hit?





INTERNAL DIVISIBILITY CONSISTENCY

- The corner coordinates must be evenly divisible by the cell resolution.



- More restrictive then dimensional divisibility, but gives rise to nice rounded extents
- Who cares?

PRINCIPLES OF TOPOGRAPHIC CHANGE DETECTION

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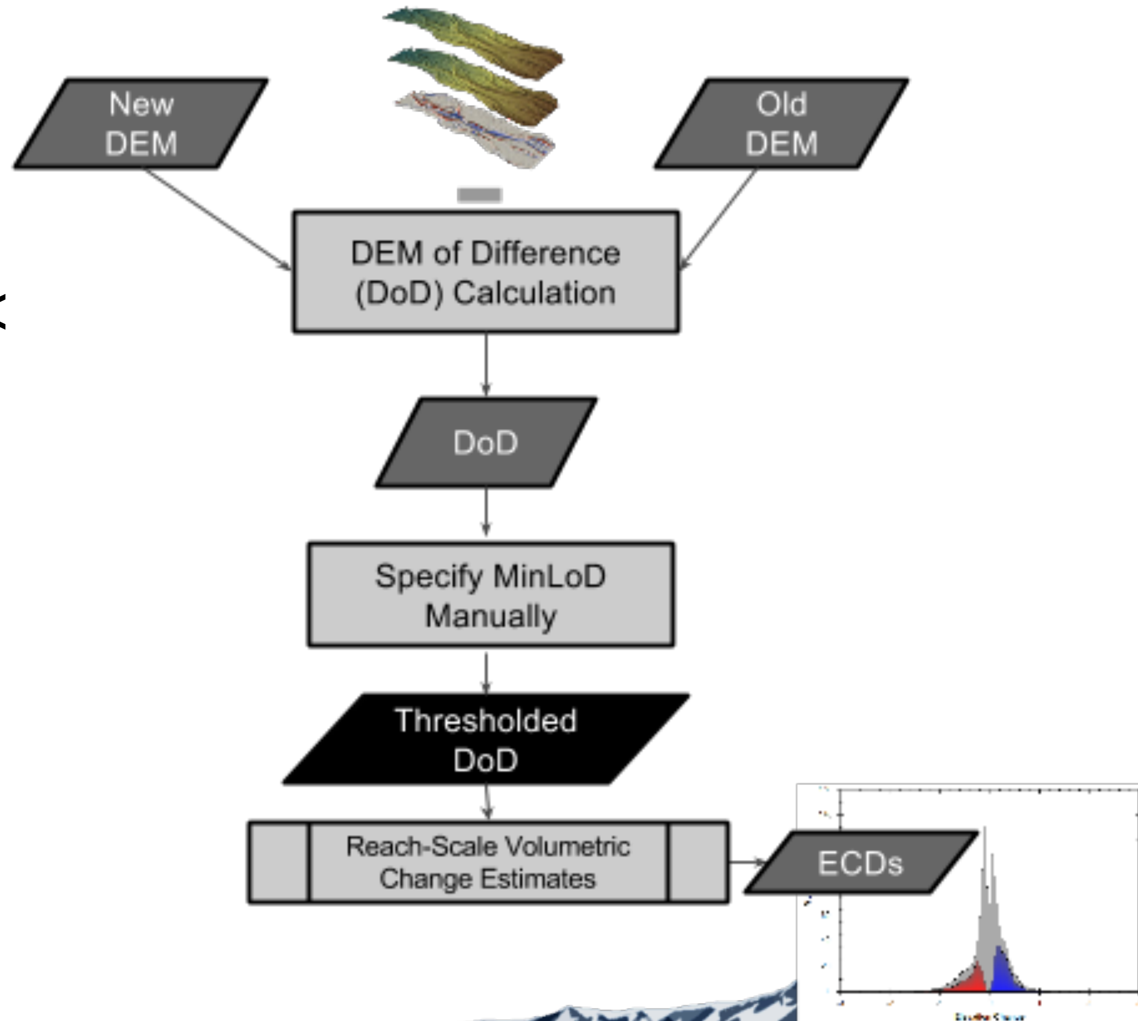
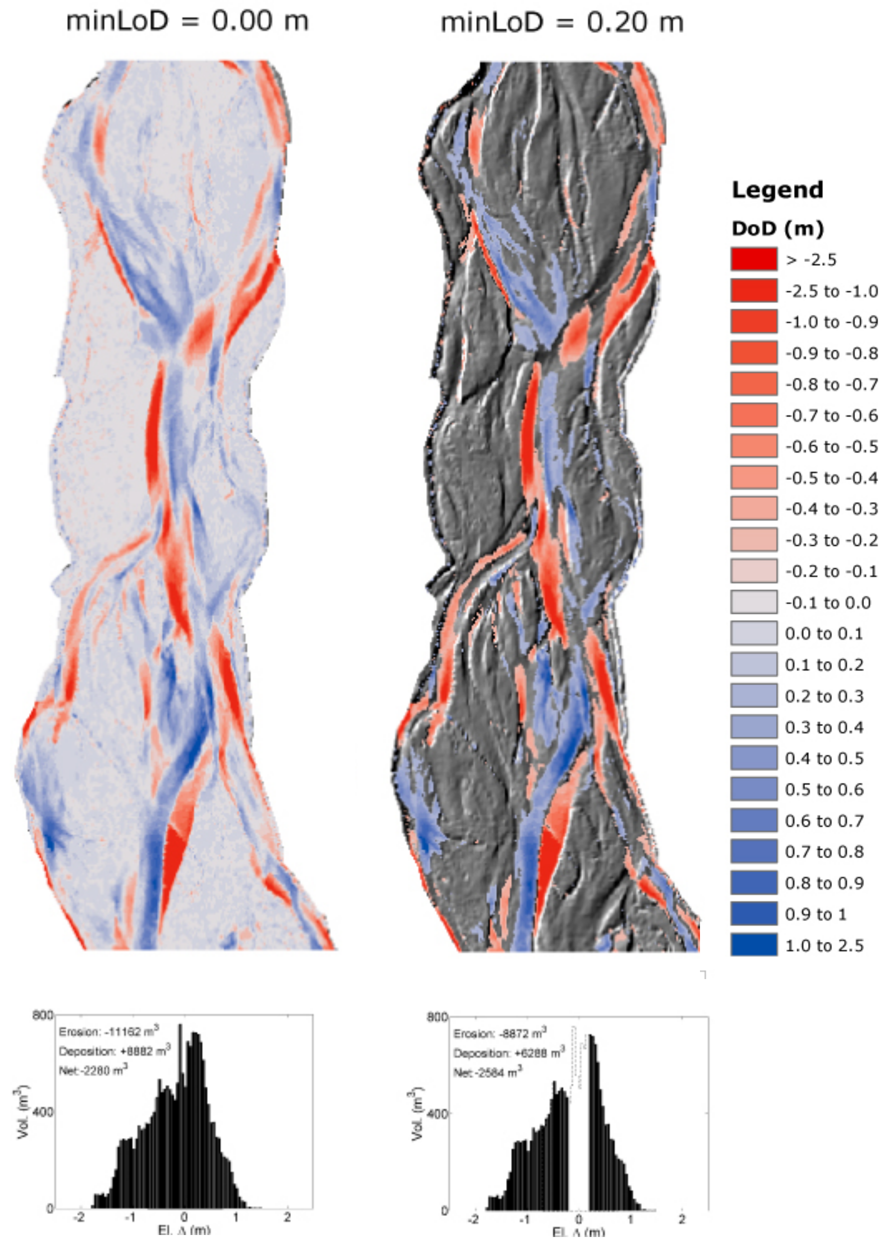
WHAT WE'RE DOING TO SIMPLE SUBTRACTION PROBLEM

- Just specifying a minimum level of detection ($_{min}$LoD)
- Throwing away DoD < $_{min}$LoD
- Calculating some summary statistics
- Multiplying cell by cell DoD by cell area to get volumes
- Looking at histograms of change (ECD)



THRESHOLDING… APPLIED SPATIALLY

- Does not matter whether the $_{min}$LoD is specified, or calculated from error propagation
- Just on a cell-by-cell basis!



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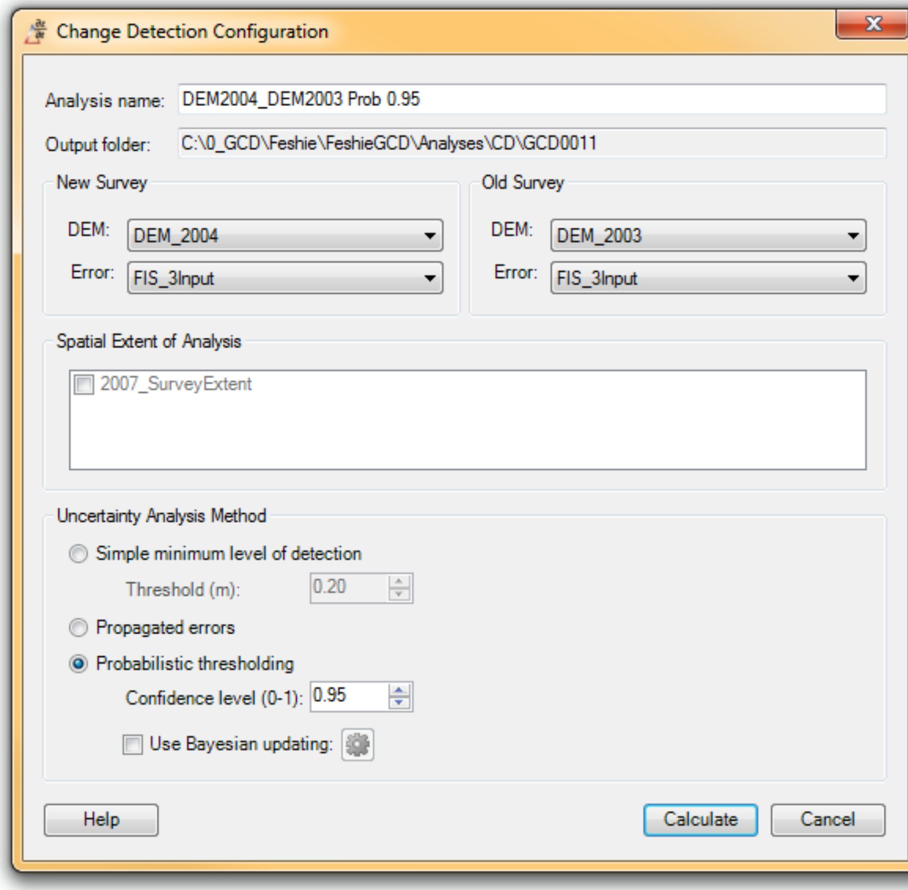
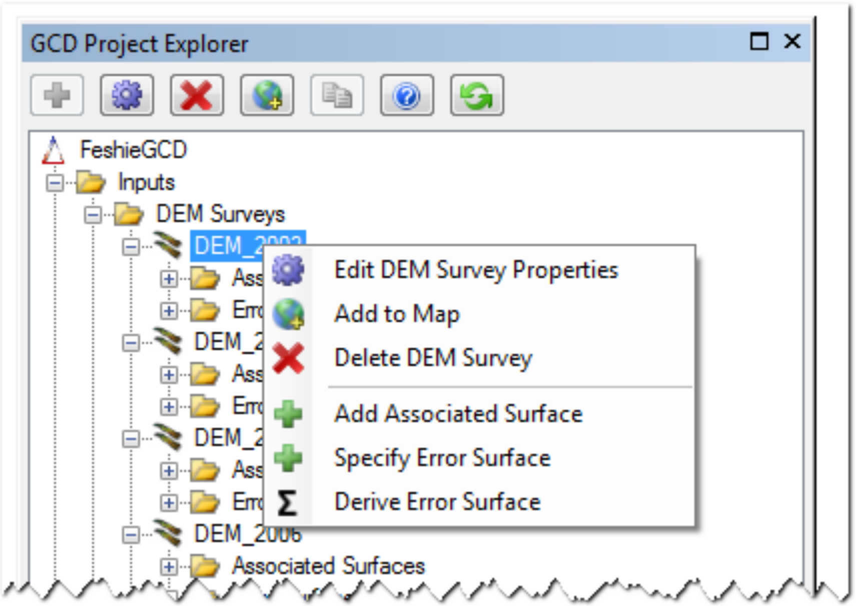
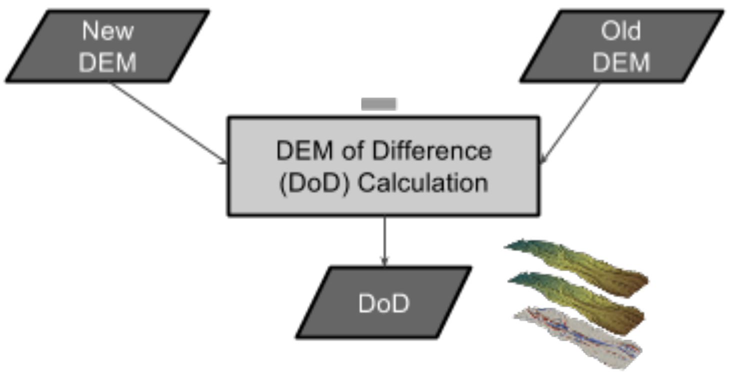
GCD THRESHOLDING

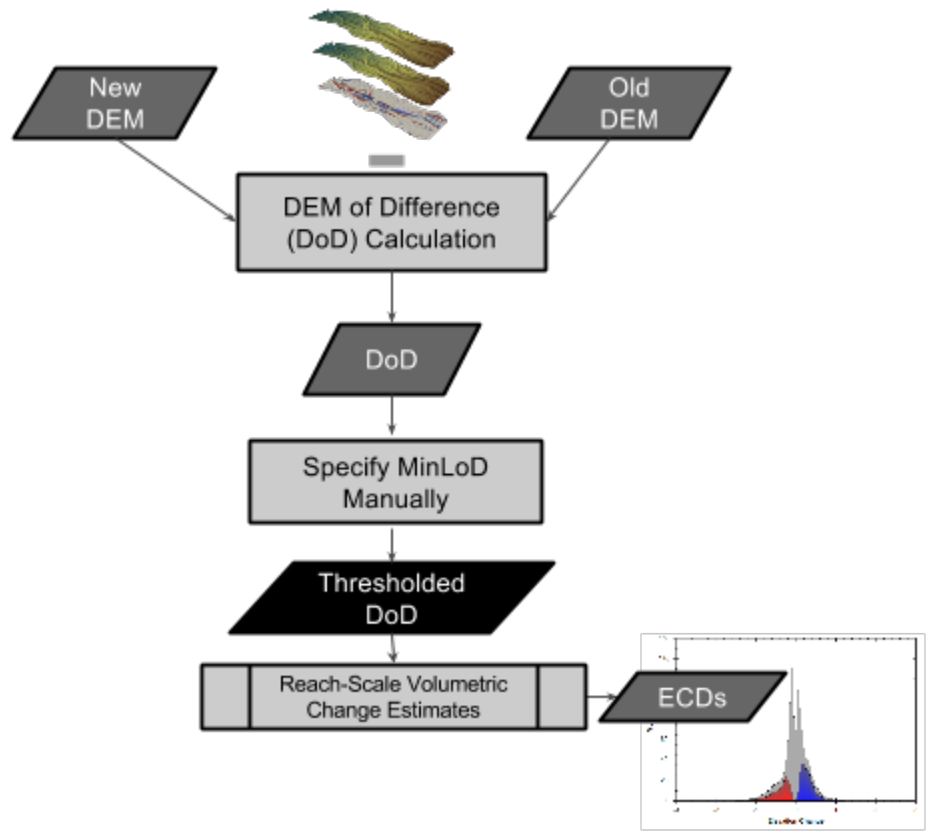
1. **Simple defined $_{min}$LoD**
2. Propagated Errors
3. Probabilistic Confidence Interval



ALL WE DID IN PREVIOUS EXERCISE…

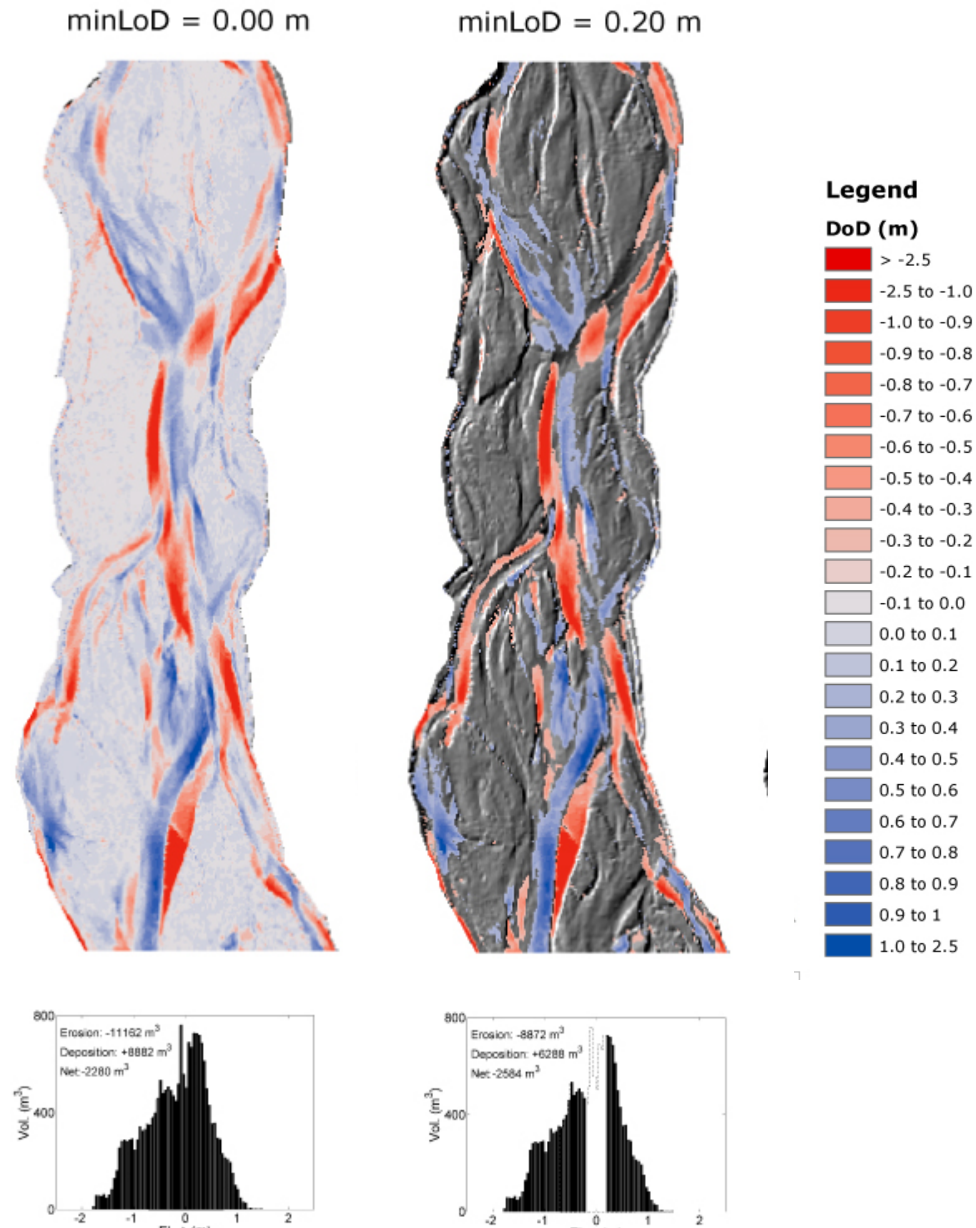




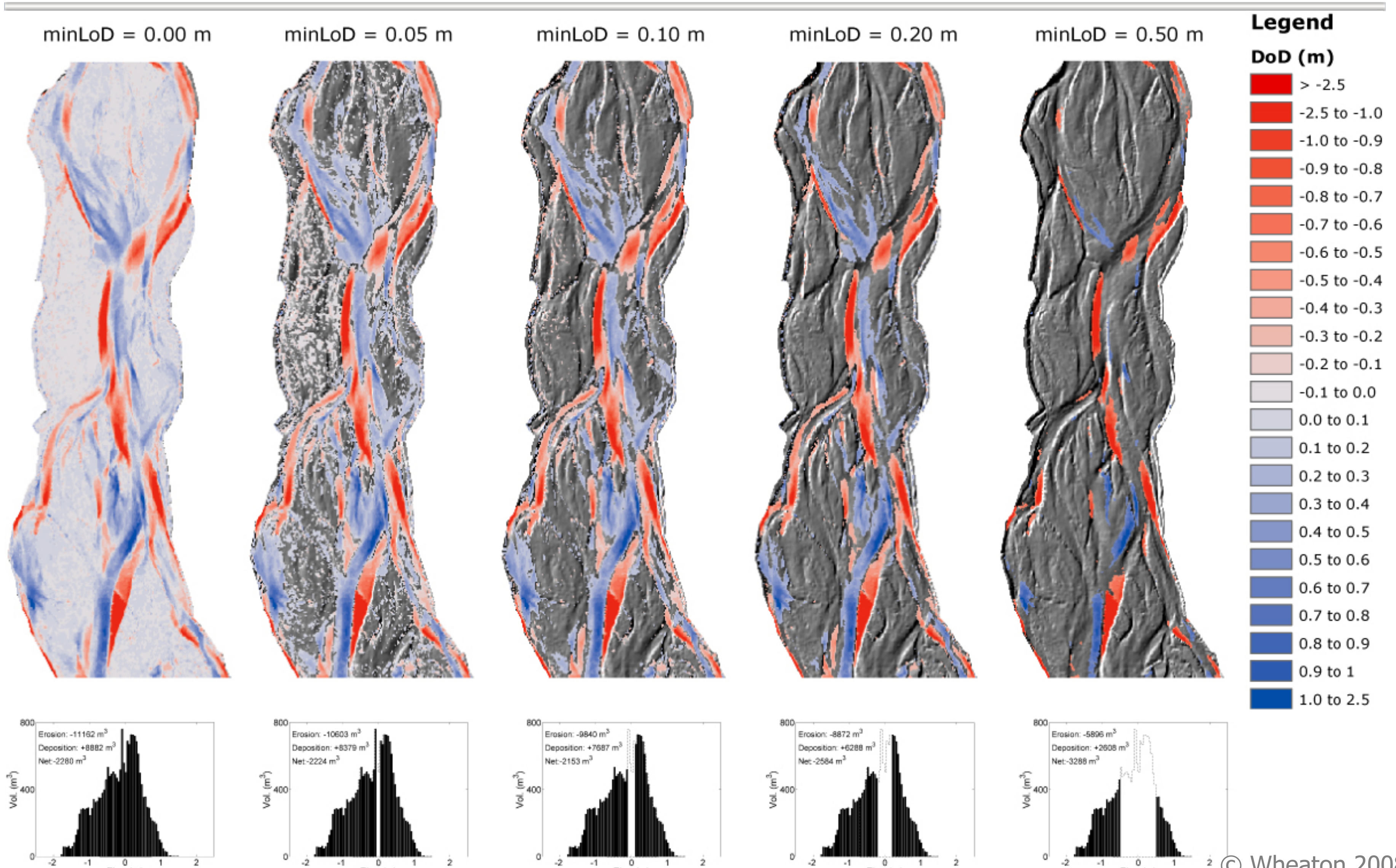


APPLICATION OF A $_{MIN}$LoD

- You take original DoD, and remove all changes <= $_{min}$LoD
- For example +/- 20 cm



VARYING $_{min}$LoD THRESHOLDS



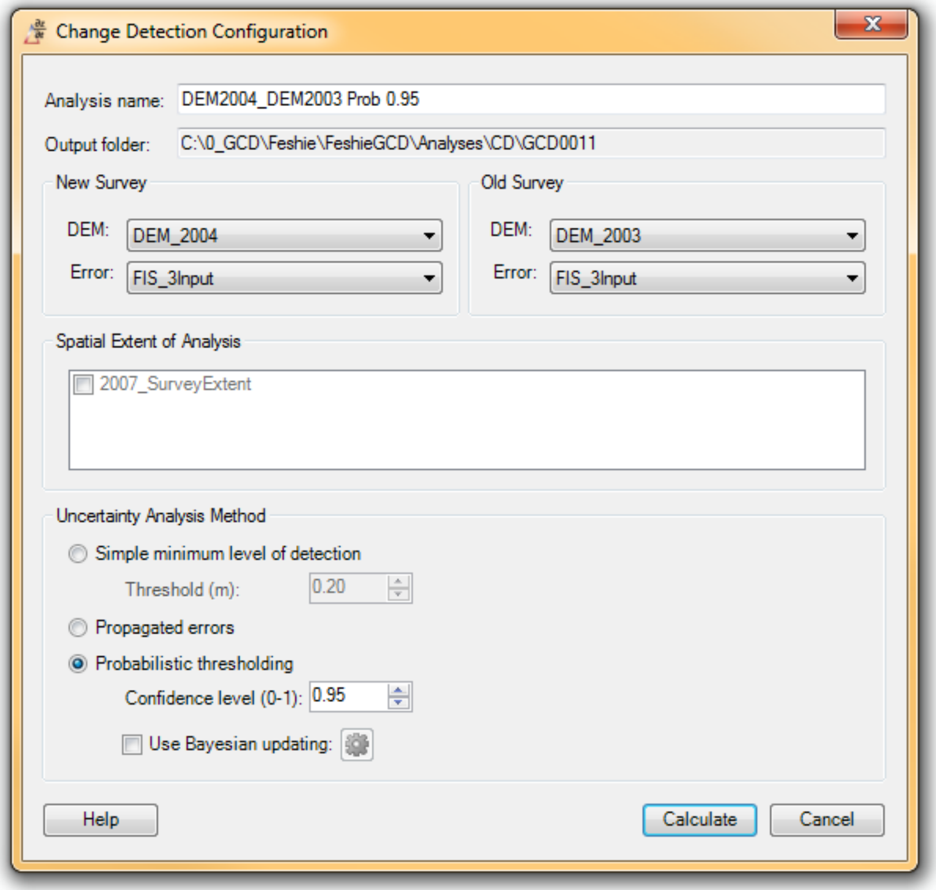
EXERCISE: VARYING $_{MIN}$LOD

C:\0_GCD\Excercises\G_Thresholding

1. Start new ArcMap Document
2. Create new GCD Project called 'Feshie_Threshold' in I
3. Load 2 DEMs provided as surveys
4. Do Change Detections with following minLoDs:
   - 0 cm, 5 cm, 10 cm, 20 cm, 50 cm
5. Compare the outputs (maps, summaries, elevation change distributions)…

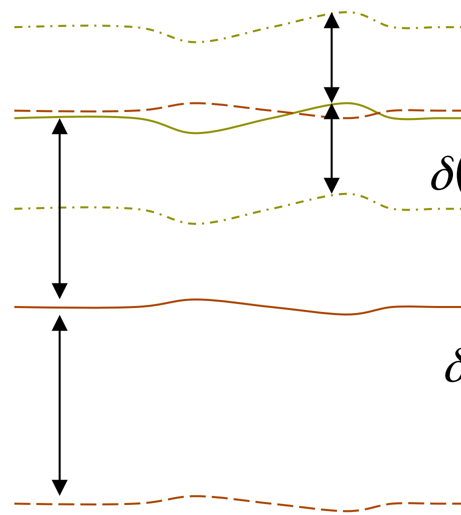
GCD THRESHOLDING

1. Simple defined $_{min}$LoD
2. **Propagated Errors**
3. Probabilistic Confidence Interval



$_{\text{MIN}}$LoD USING ERROR PROPAGATION

- Distinguish those changes that are real from noise
- Use standard Error Propagation
- DEM Errors can vary temporally and spatially



$$\delta(z) = \sqrt{\left(\delta(z)_{DEM_{old}}\right)^2 + \left(\delta(z)_{DEM_{new}}\right)^2}$$

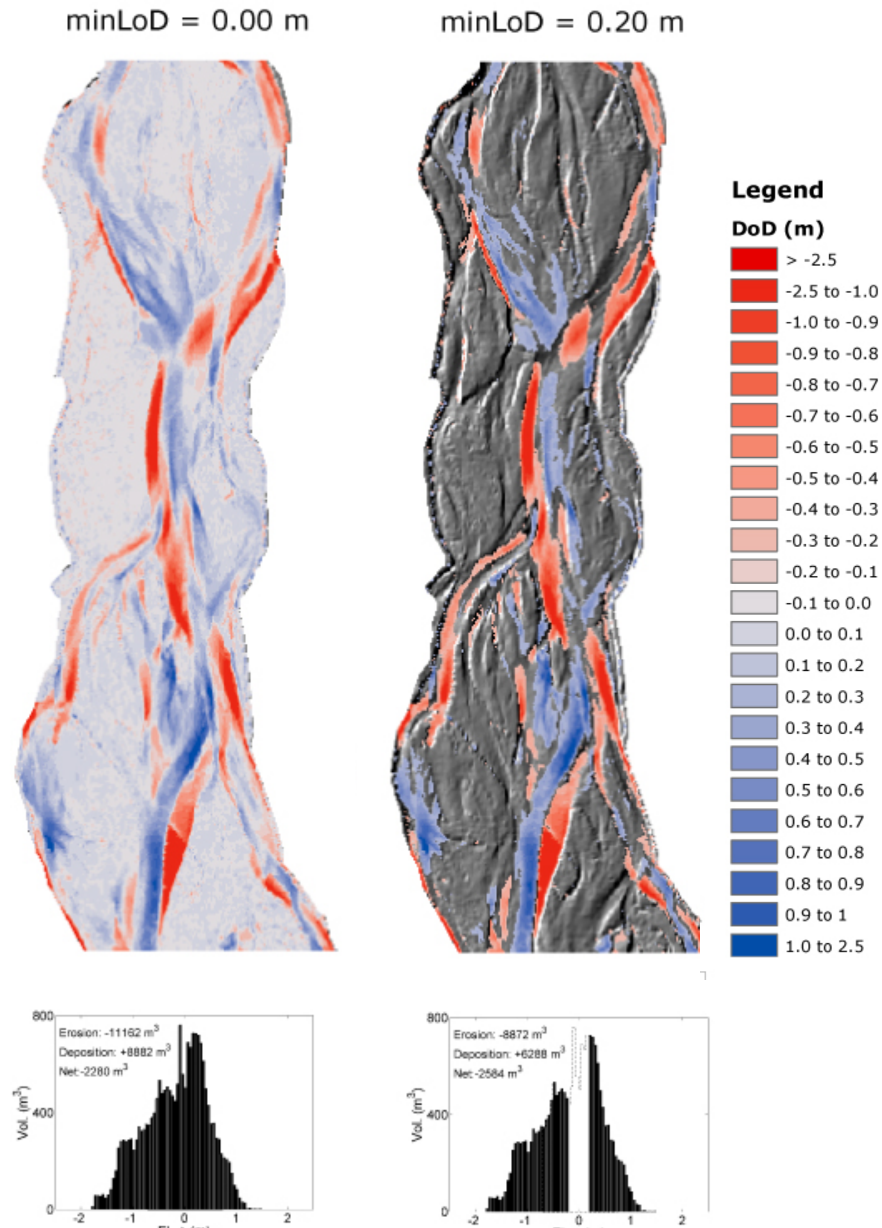
e.g. $\delta(z) = \sqrt{(10)^2 + (20)^2} = 22.36$

22.36 cm ≈ 8.8 in

See
- Brasington et al (2000): *ESPL*
- Lane et al (2003): *ESPL*
- Brasington et al (2003): *Geomorphology*

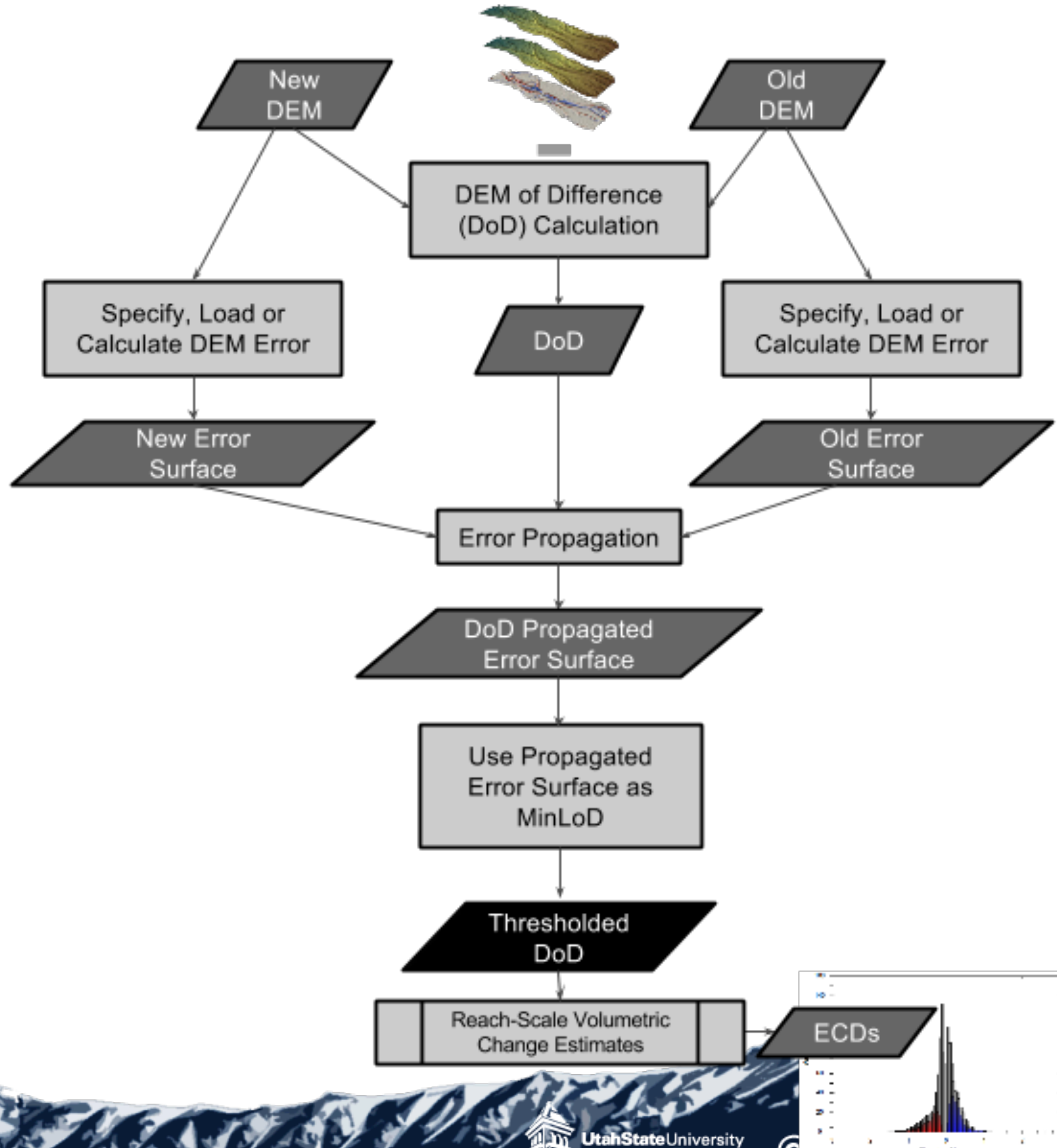
ERROR PROPAGATION GETS APPLIED SAME WAY AS $_{MIN}$LoD

- Does not matter whether the $_{min}$LoD is specified, or calculated from error propagation
- Just on a cell-by-cell basis!
- In background a perror grid is produced

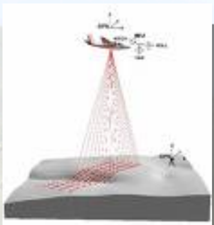


OUR REVISED WORKFLOW: PROPAGATED

- Just *come up with* separate estimates of error for DEM_{new} & DEM_{old} & propagate using square root of the sum of the square of the errors in quadrature…



WHAT ARE TYPICAL ERRORS?

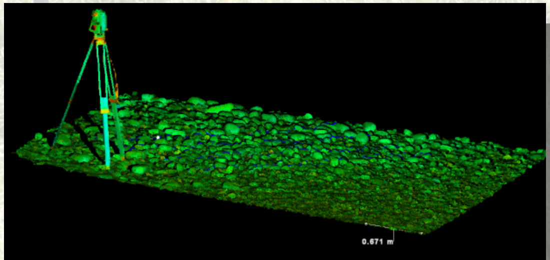


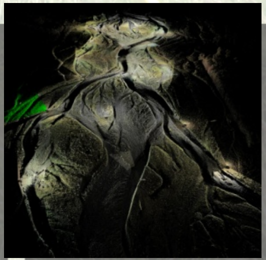
Remotely Sensed or Aerial Surveys

- LiDaR : +/- 12 to 25 cm
- Aerial Photogrammetry : +/- 10 to 15 cm

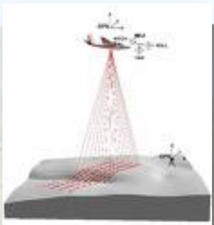
Ground-Based Surveys

- Total Station Surveys : +/- 2 to 10 cm
- GPS: : +/- 3 to 12 cm
- Terrestrial Laser Scanning: +/- 0.5 to 4 cm





SO WHAT WOULD PROPAGATED ERRORS BE?



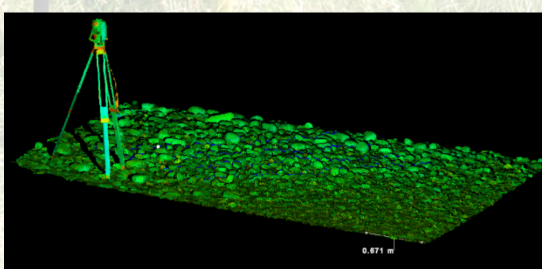
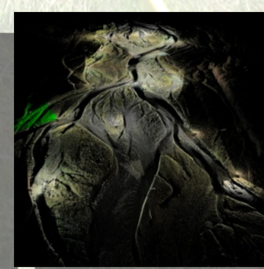
Remotely Sensed or Aerial Surveys

- LiDaR : +/- 12 to 25 cm (17 to 36 cm $_{min}$LoD)
- Aerial Photogrammetry : +/- 10 to 15 cm(14 to 22 cm $_{min}$LoD)



Ground-Based Surveys

- Total Station Surveys : +/- 2 to 10 cm (3 to 14 cm $_{min}$LoD)
- GPS: : +/- 3 to 12 cm (4 to 17 cm $_{min}$LoD)
- Terrestrial Laser Scanning: +/- 0.5 to 4 cm (0.7 to 6 cm $_{min}$LoD)

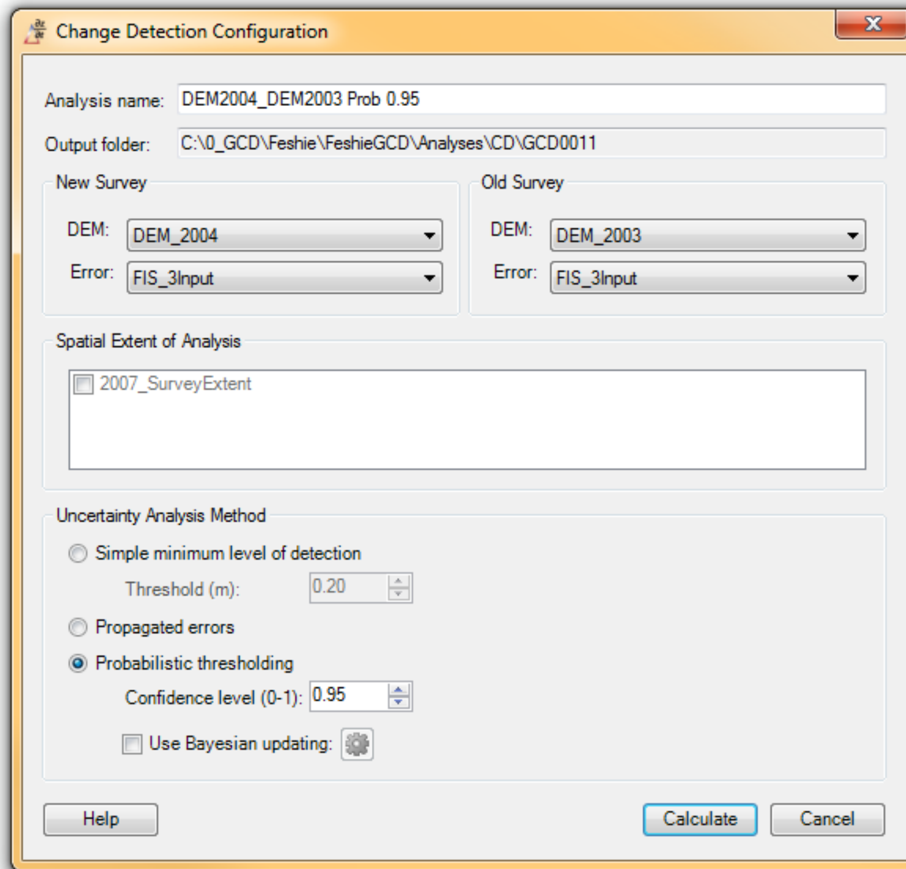

EXERCISE: PROPAGATED ERROR

C:\0_GCD\Excercises\G_Thresholding

1. In Same ArcMap Document
2. Go to each DEM Survey, and derive spatially uniform error surface for rtkGPS
3. Do Change Detections with Propagated Error
4. Compare the outputs (maps, summaries, elevation change distributions)…

GCD THRESHOLDING

1. Simple defined $_{min}$LoD
2. Propagated Errors
3. **Probabilistic Confidence Interval**



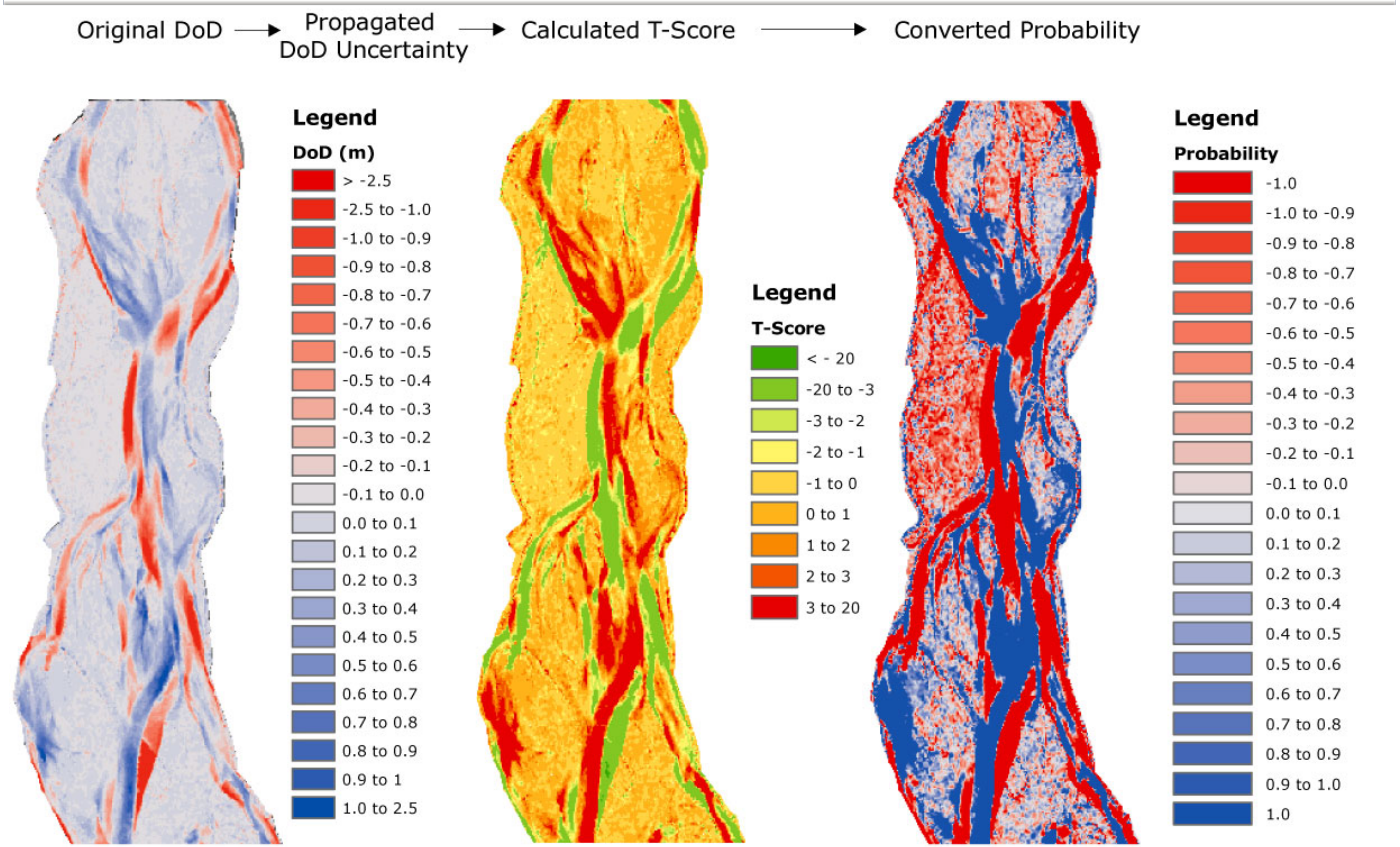
HOW COULD I REPRESENT AS PROBABILITY?

- Using inferential statistics, we'll calculate a t-score
- σ_{DoD} is the characteristic uncertainty
  - In this case σ_{DoD} = $_{min}$LoD

$$t = \frac{\left| z_{DEM_{new}} - z_{DEM_{old}} \right|}{\sigma_{DoD}}$$

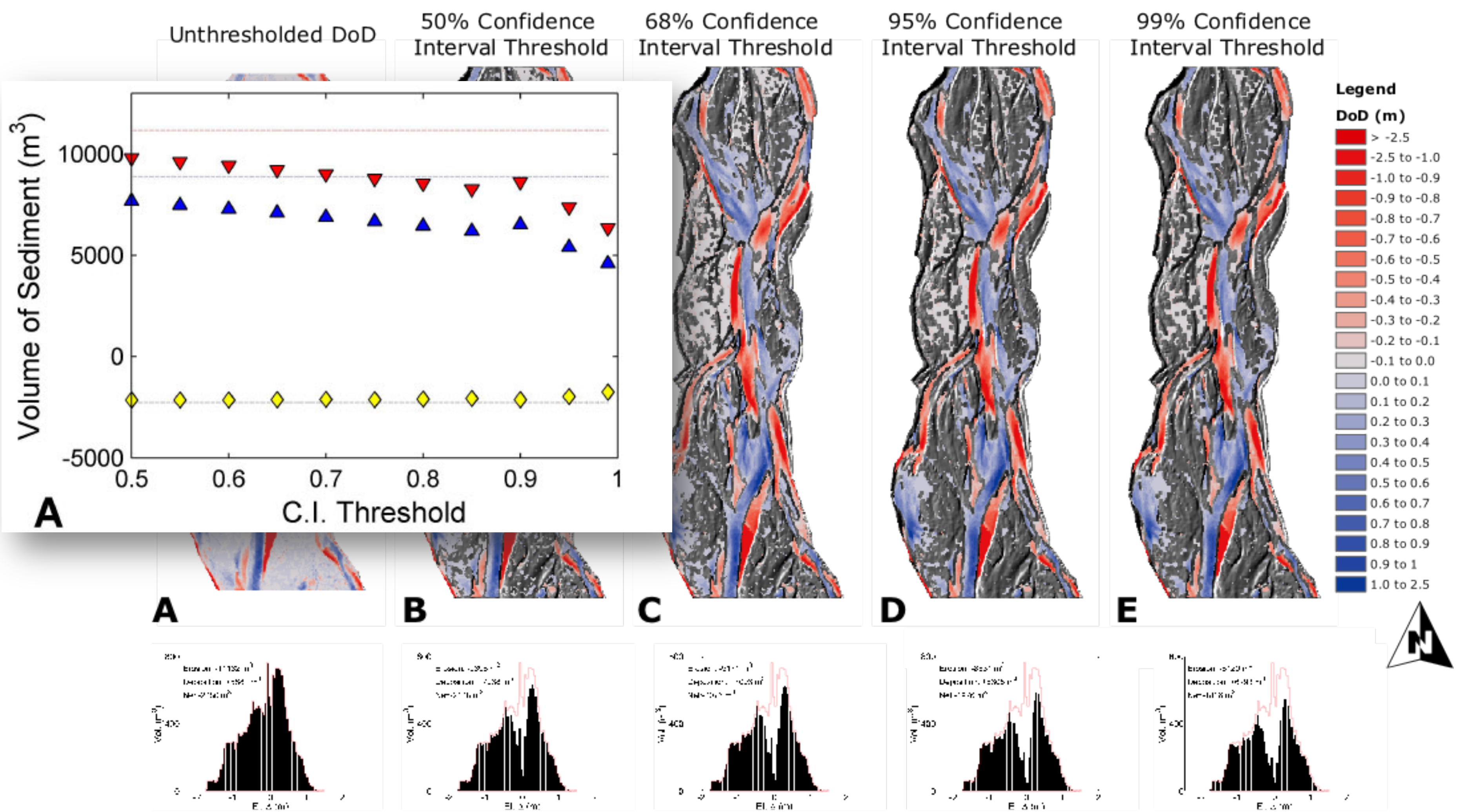
- Just the ratio of actual change to $_{min}$LoD change
- Assuming two-tailed test, t is significant at:
  - 68% confidence limit when t= 1
  - 95% confidence limit when t=1.96

PROBABILITY THAT CHANGE IS REAL

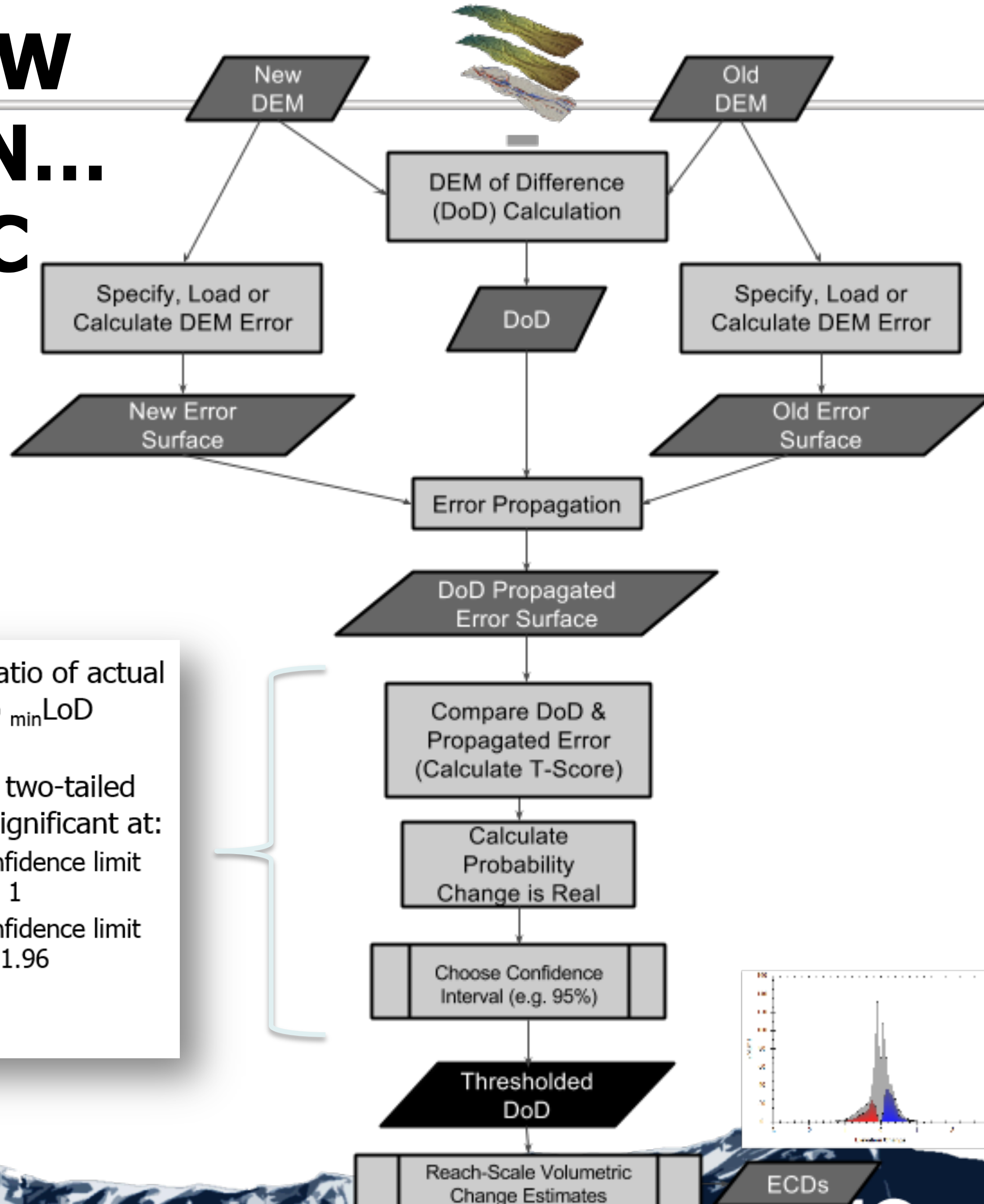


Even when ${}_{min}$LoD is spatially constant, probability varies in space… why?

SENSITVITY OF THRESHOLD?



OUR WORKFLOW REVISED AGAIN… PROBABILISTIC



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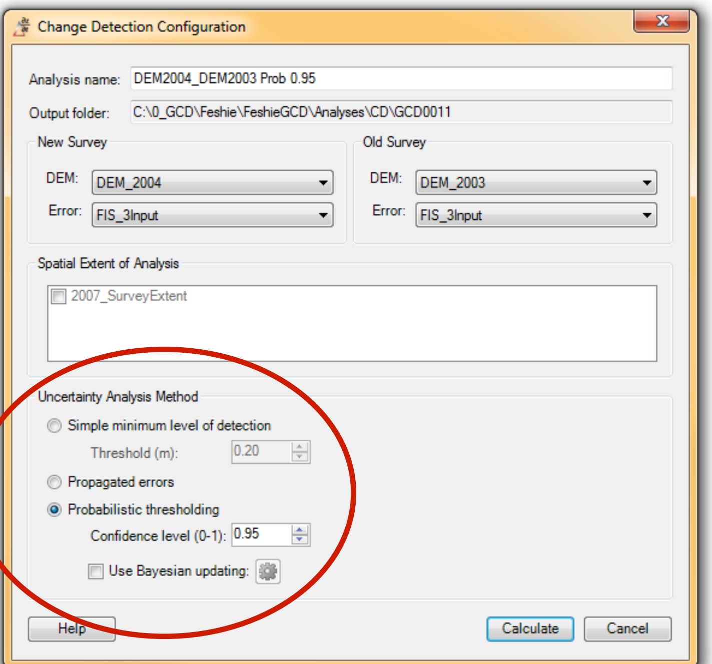
EXERCISE: VARYING PROB.

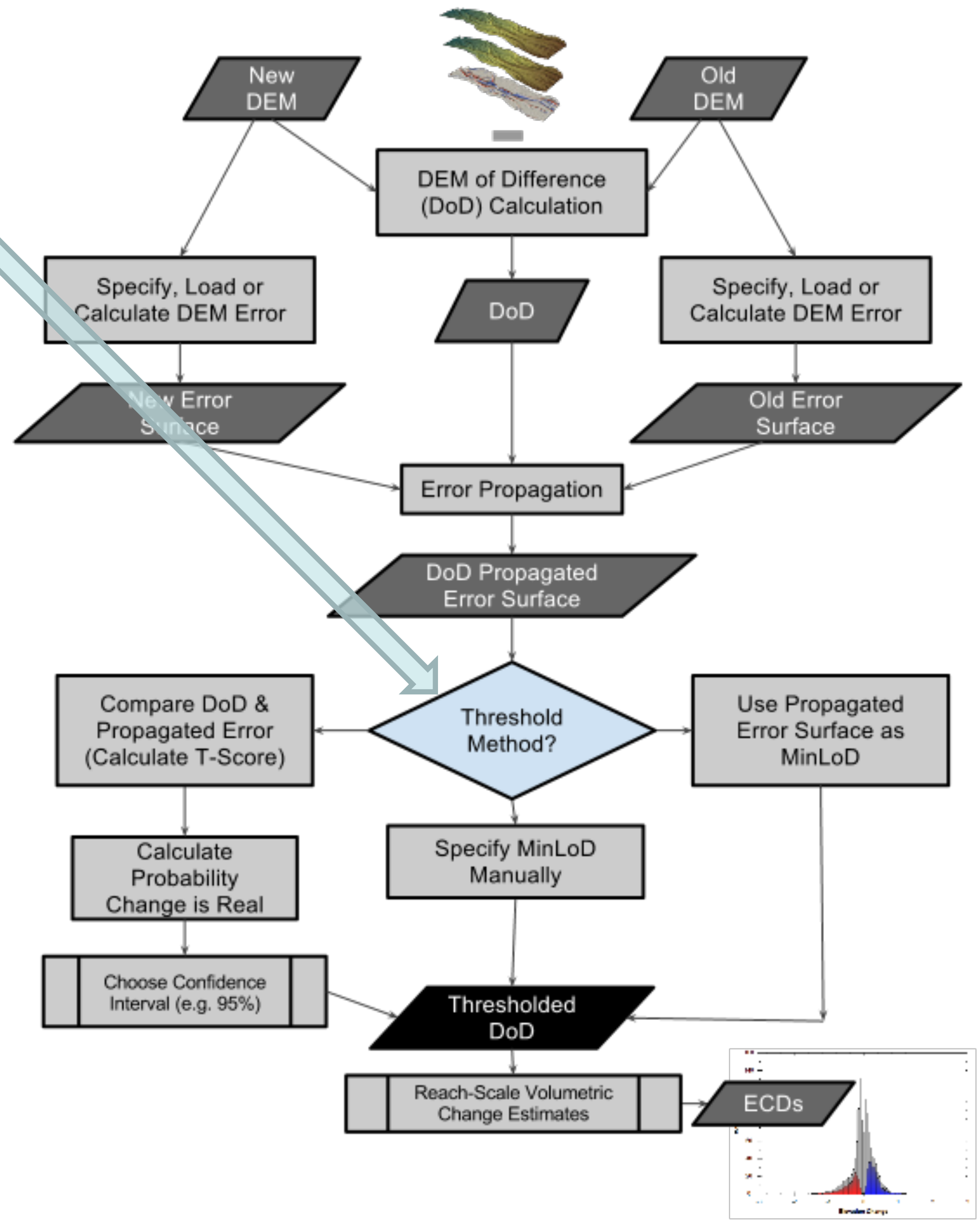
C:\0_GCD\Excercises\G_Thresholding

1. In Same ArcMap Document
2. Do Change Detections with Propagated Error for following probabilities:
    1. 99%, 95%, 90%, 80%, 66% and 50%
3. Compare the outputs (maps, summaries, elevation change distributions)…

WHERE DOES THIS FIT IN GCD?

- Choosing the Threshold Method is a choice:





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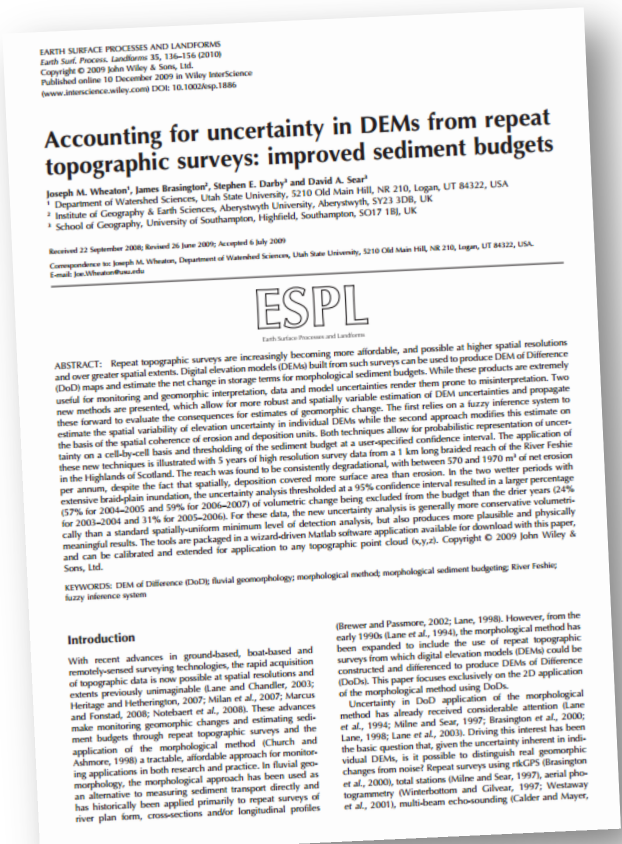
FUZZY ERROR MODELLING …

How important is DEM uncertainty in impacting our ability to detect geomorphic change?



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Earth Surf. Process. Landforms 35, 136–156 (2010)

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Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets

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ESPL
Earth Surface Processes and Landforms

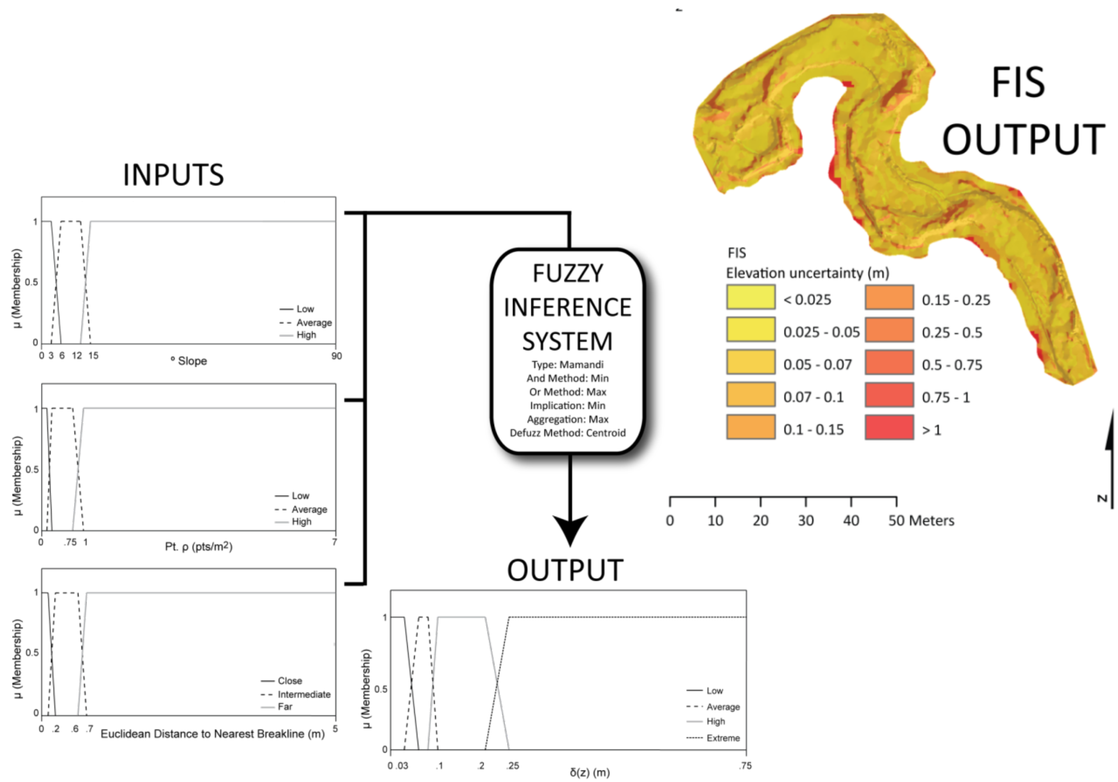
ABSTRACT: Repeat topographic surveys are increasingly becoming more affordable, and possible at higher spatial resolutions and over greater spatial extents. Digital elevation models (DEMs) built from such surveys can be used to produce DEM of Difference (DoD) maps and estimate the net change in storage terms for morphological sediment budgets. While these products are extremely useful for monitoring and geomorphic interpretation, data and model uncertainties render them prone to misinterpretation. Two new methods are presented, which allow for more robust and spatially variable estimation of DEM uncertainties and propagate these forward to evaluate the consequences for estimates of geomorphic change. The first relies on a fuzzy inference system to estimate the spatial variability of elevation uncertainty in individual DEMs while the second approach modifies this estimate on the basis of the spatial coherence of erosion and deposition units. Both techniques allow for probabilistic representation of uncertainty on a cell-by-cell basis and thresholding of the sediment budget at a user-specified confidence interval. The application of these new techniques is illustrated with 5 years of high resolution survey data from a 1 km long braided reach of the River Feshie in the Highlands of Scotland. The reach was found to be consistently degradational, with between 570 and 1970 m^3 of net erosion per annum, despite the fact that spatially, deposition covered more surface area than erosion. In the two wetter periods with extensive braid-plain inundation, the uncertainty analysis thresholded at a 95% confidence interval resulted in a larger percentage (57% for 2004–2005 and 59% for 2006–2007) of volumetric change being excluded from the budget than the drier years (24% for 2003–2004 and 31% for 2005–2006). For these data, the new uncertainty analysis is generally more conservative volumetrically than a standard spatially-uniform minimum level of detection analysis, but also produces more plausible and physically meaningful results. The tools are packaged in a wizard-driven Matlab software application available for download with this paper, and can be calibrated and extended for application to any topographic point cloud (x,y,z). Copyright © 2009 John Wiley & Sons, Ltd.

KEYWORDS: DEM of Difference (DoD); fluvial geomorphology; morphological method; morphological sediment budgeting; River Feshie; fuzzy inference system

Introduction

With recent advances in ground-based, boat-based and remotely-sensed surveying technologies, the rapid acquisition of topographic data is now possible at spatial resolutions and extents previously unimaginable (Lane and Chandler, 2003; Heritage and Hetherington, 2007; Milan *et al.*, 2007; Marcus and Fonstad, 2008; Notebaert *et al.*, 2008). These advances make monitoring geomorphic changes and estimating sediment budgets through repeat topographic surveys and the application of the morphological method (Church and Ashmore, 1998) a tractable, affordable approach for monitoring applications in both research and practice. In fluvial geomorphology, the morphological approach has been used as an alternative to measuring sediment transport directly and has historically been applied primarily to repeat surveys of river plan form, cross-sections and/or longitudinal profiles (Brewer and Passmore, 2002; Lane, 1998). However, from the early 1990s (Lane *et al.*, 1994), the morphological method has been expanded to include the use of repeat topographic surveys from which digital elevation models (DEMs) could be constructed and differenced to produce DEMs of Difference (DoDs). This paper focuses exclusively on the 2D application of the morphological method using DoDs.

Uncertainty in DoD application of the morphological method has already received considerable attention (Lane *et al.*, 1994; Milne and Sear, 1997; Brasington *et al.*, 2000; Lane, 1998; Lane *et al.*, 2003). Driving this interest has been the basic question that, given the uncertainty inherent in individual DEMs, is it possible to distinguish real geomorphic changes from noise? Repeat surveys using rtkGPS (Brasington *et al.*, 2000), total stations (Milne and Sear, 1997), aerial photogrammetry (Winterbottom and Gilvear, 1997; Westaway *et al.*, 2001), multi-beam echo-sounding (Calder and Mayer,



From
DOI: 10.1002/esp.1886

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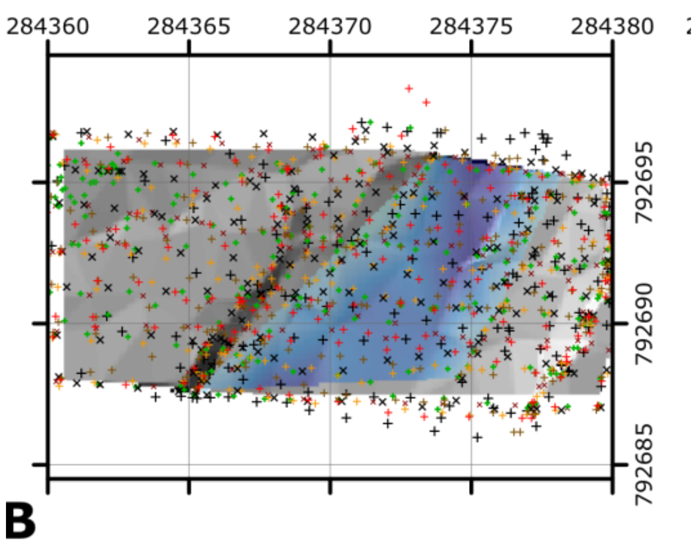
@ FHC THE FLUVIAL HABITATS CENTER

A SIMPLE TWO RULE FUZZY INFERENCE SYSTEM…

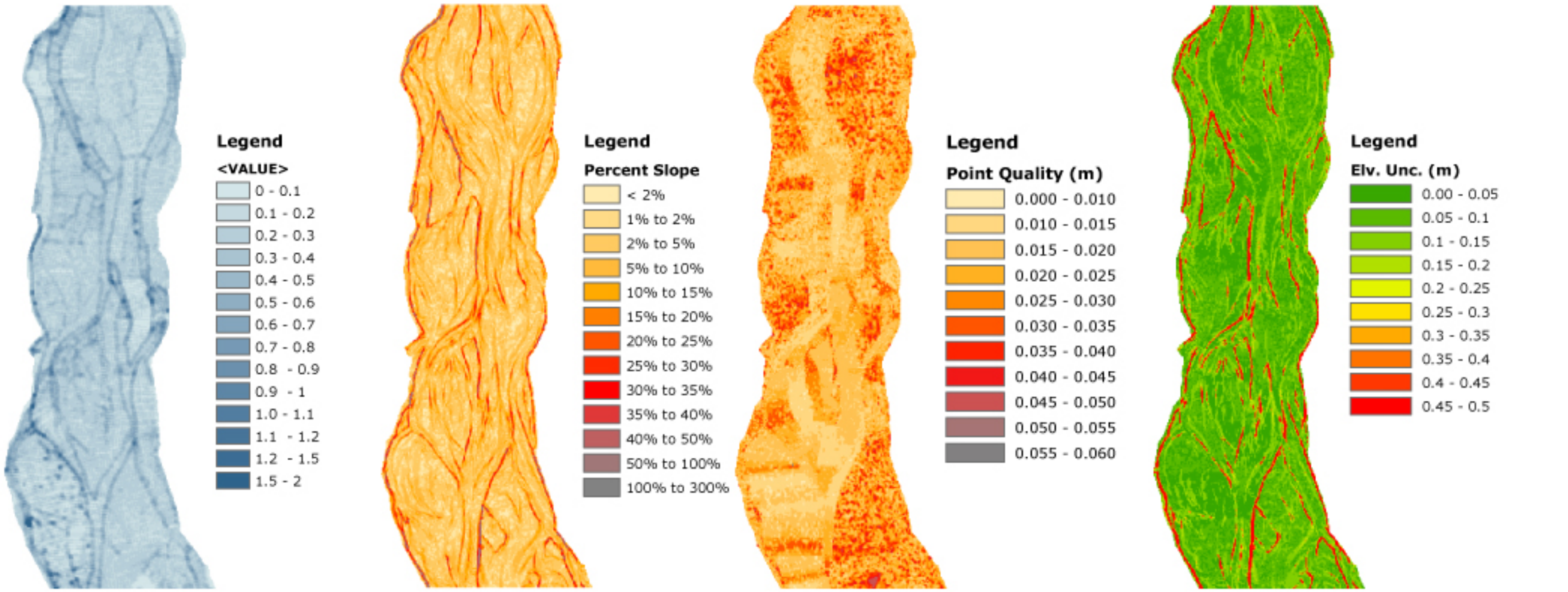
- Given a point cloud
- Relationship between topographic complexity (slope) and sampling (point density)



Rule:	Inputs		Output
	Slope %	Pt. ρ m/pts^2	$\delta(z)$ m
1	Low	Low	Average
2	Low	Medium	Low
3	Low	High	Low
4	Medium	Low	High
5	Medium	Medium	High
6	Medium	High	Average
7	High	Low	Extreme
8	High	Medium	High
9	High	High	High

DOI: 10.1002/esp.1886

SPATIALLY VARIABLE ERROR MODELLING



FIS Input 1 (Point Density) + FIS Input 2 (Slope) + FIS Input 3 (GPS Quality) = FIS Surface (El. Unc (m))

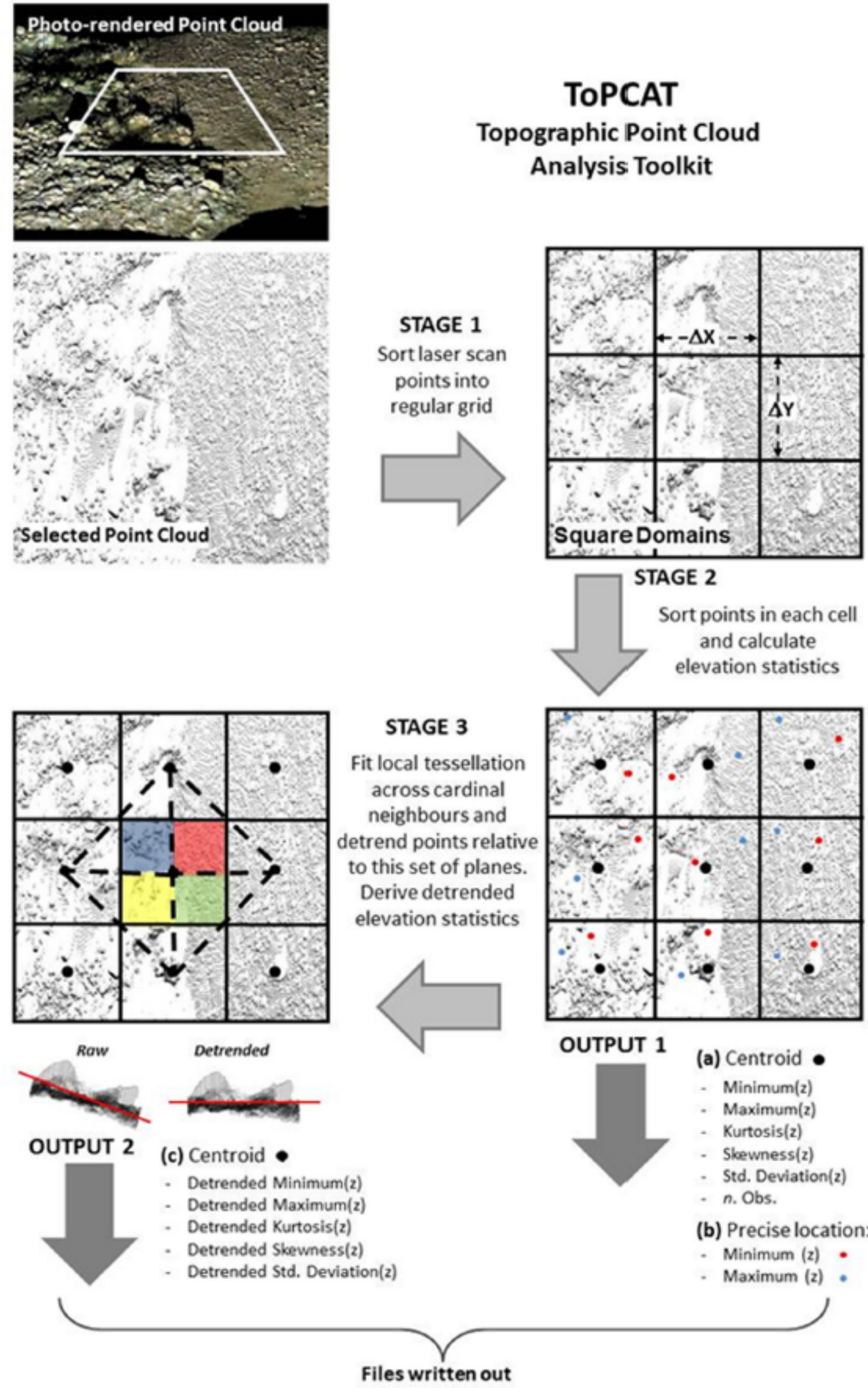
- Readily tractable now!
- FIS, needs to be minimally survey method specific and output should be locally calibrated

DOI: 10.1002/esp.1886

STATISTICAL METHODS

- **To**pographic **P**oint **C**loud **A**nalysis **T**oolkit (ToPCAT; formerly PC-Tools)
- Look at statistical estimates of variance for elevation
  - Absolute Zmin & Zmax
  - Zmean
  - range
  - stdev - The aboslutle σ
  - sk - Skew
  - n - Count of number of points in cell (i.e. point density)

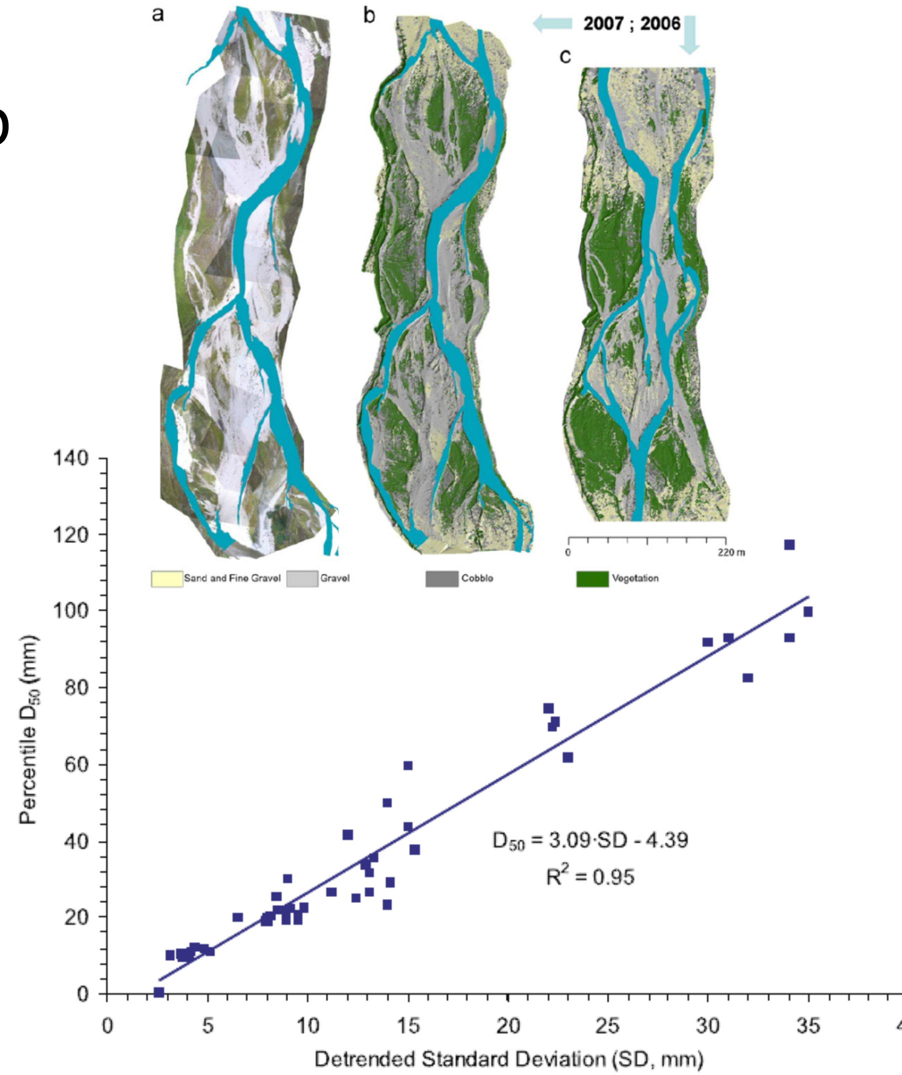
See: Brasington, J., Vericat, D., Rychkov, I., 2012. Modeling river bed morphol roughness, and surface sedimentology using high resolution terrestrial laser scanning. Water Resources Research 48. DOI: 10.1029/2012wr012223.



DETRENDED STD. DEV RELATES TO ROUGHNESS

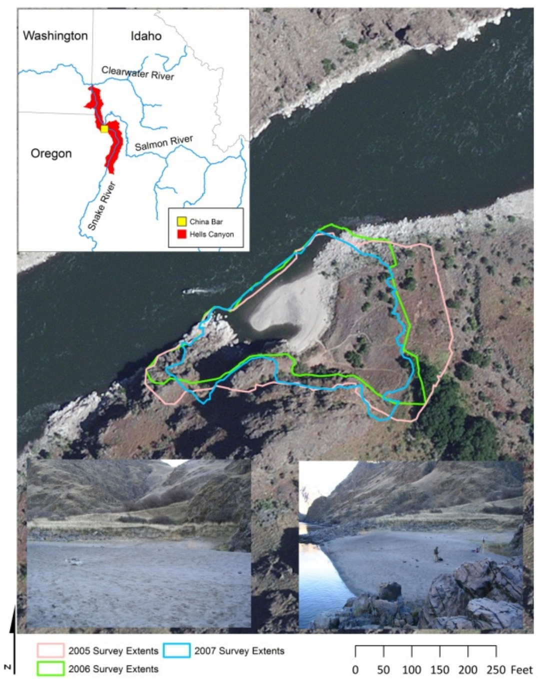
- Simple empirical relationship to convert detrended σ to grain size & roughness…

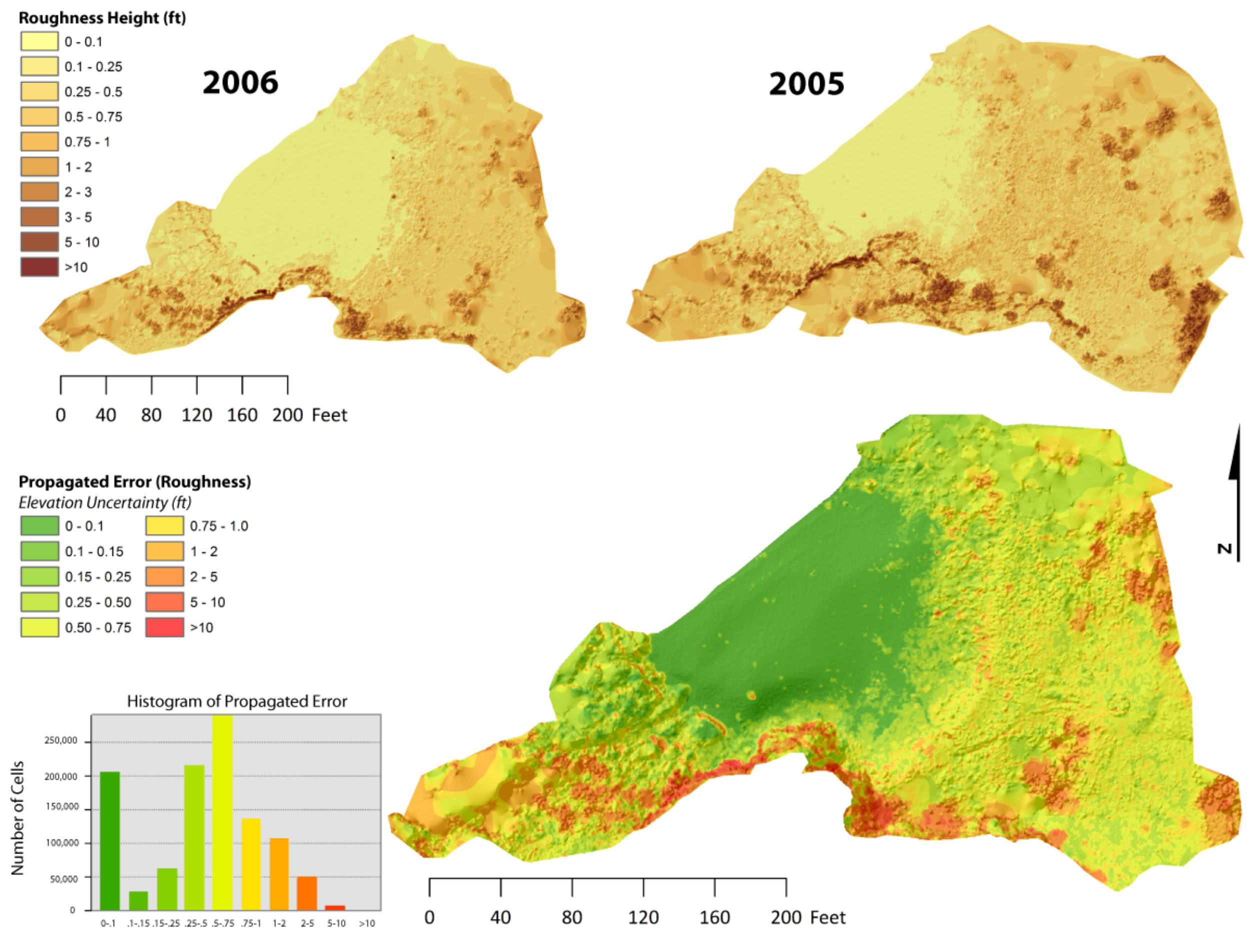
Fig. 3. Measuring patch-scale grain size distribution median (D_{50}) by method of pebble counts.



IF ROUGHNESS IS LIMITING…

- Roughness itself can be used an error model for some point clouds





- Use roughness as proxy for error…

4 'CLASSICS' IN YOUNG FIELD OF RASTER GCD

- Lane SN, Chandler JH and Richards KS. 1994. Developments in Monitoring and Modeling Small-Scale River Bed Topography. *Earth Surface Processes and Landforms*. 19(4): 349-368. DOI: 10.1002/esp.3290190406.
- McLean DG and Church M. 1999. Sediment transport along lower Fraser River - 2. Estimates based on the long-term gravel budget. *Water Resources Research.* 35(8): 2549-2559.
- Lane SN, Westaway RM and Hicks DM. 2003. Estimation of erosion and deposition volumes in a large, gravel-bed, braided river using synoptic remote sensing. *Earth Surface Processes and Landforms.* 28(3): 249-271. DOI: 10.1002/esp.483.
- Brasington J, Langham J and Rumsby B. 2003. Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport. *Geomorphology*. 53(3-4): 299-316. DOI: 10.1016/S0169-555X(02)00320-3.

TWO TIME DEPENDENT ESTIMATES OF ERROR… PROPAGATED INTO EACH OTHER

- Why are error models different?
- Propagated error used to compare against DoD and calculate T-Score…

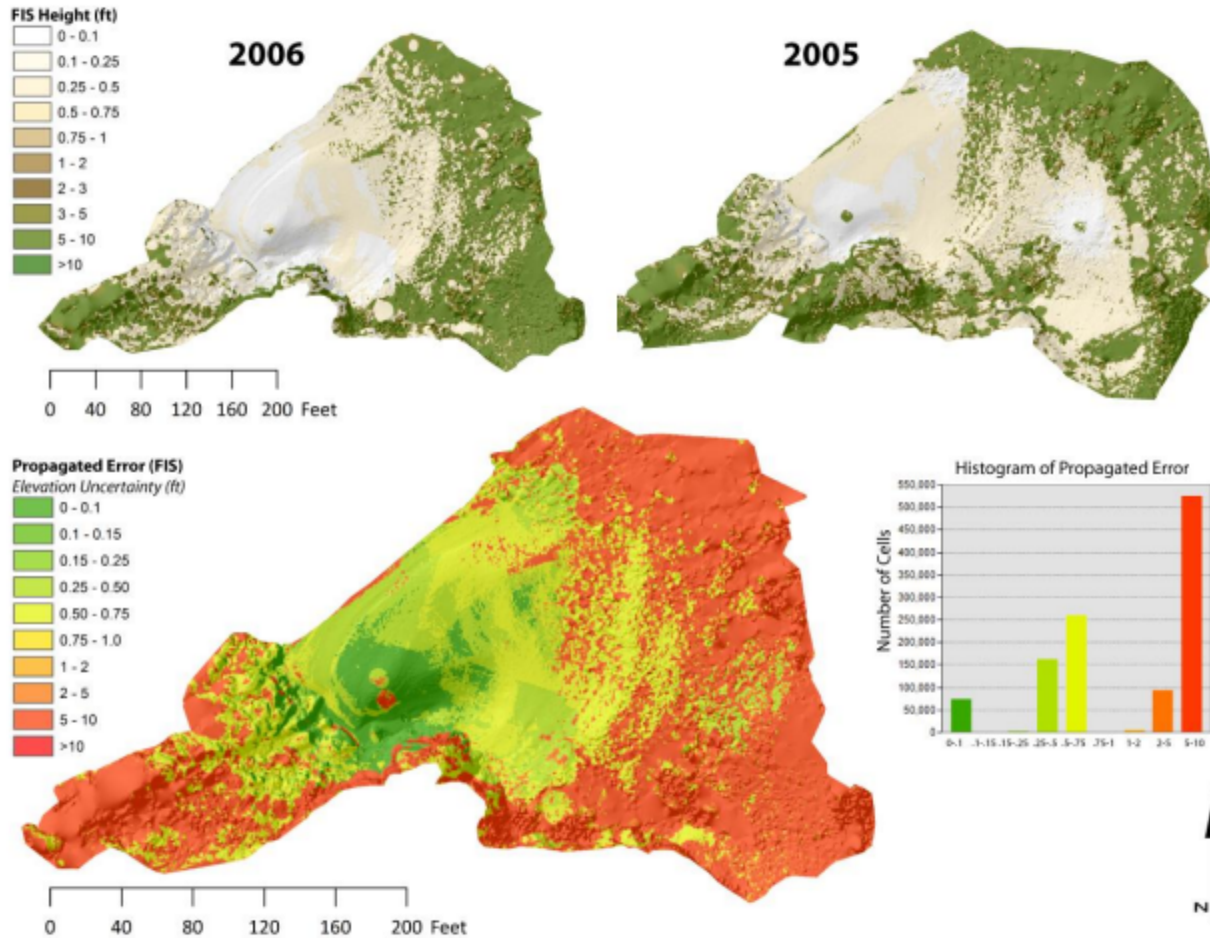
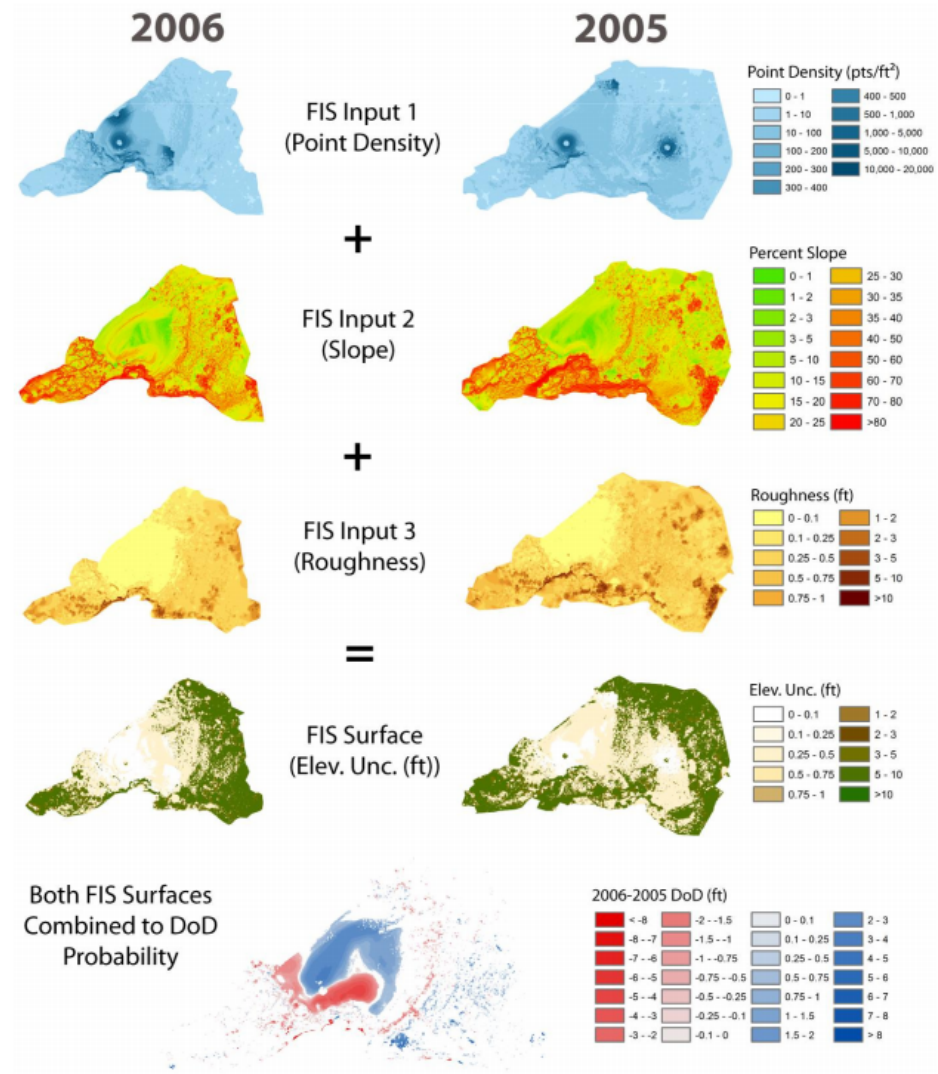


Figure 51 - – Propagated error surface produced from 2006 and 2005 FIS rasters for China Bar.

EXAMPLE OF HOW TO GET THERE…

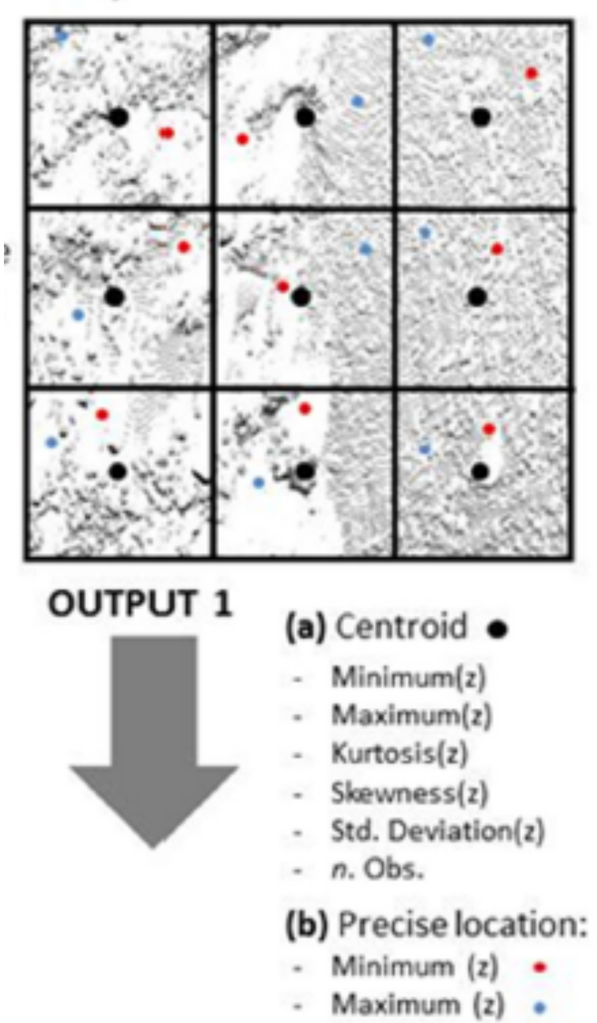
Rule	Inputs→ Slope	Point Density	Roughness	Output Elevation Uncertainty
1	Low	Sparse	Smooth (sand)	Average
2	Low	Medium	Smooth (sand)	Average
3	Low	Dense	Smooth (sand)	Low
4	Medium	Sparse	Smooth (sand)	High
5	Medium	Medium	Smooth (sand)	Average
6	Medium	Dense	Smooth (sand)	Low
7	High	Sparse	Smooth (sand)	High
8	High	Medium	Smooth (sand)	Average
9	High	Dense	Smooth (sand)	Average
10	Low	Sparse	Rough (Gravel/Cobble)	High
11	Low	Medium	Rough (Gravel/Cobble)	Average
12	Low	Dense	Rough (Gravel/Cobble)	Average
13	Medium	Sparse	Rough (Gravel/Cobble)	Extreme
14	Medium	Medium	Rough (Gravel/Cobble)	High
15	Medium	Dense	Rough (Gravel/Cobble)	Average
16	High	Sparse	Rough (Gravel/Cobble)	Extreme
17	High	Medium	Rough (Gravel/Cobble)	High
18	High	Dense	Rough (Gravel/Cobble)	Average
19	Low	Sparse	Very Rough (Boulder/Veg)	Extreme
20	Low	Medium	Very Rough (Boulder/Veg)	Extreme
21	Low	Dense	Very Rough (Boulder/Veg)	High
22	Medium	Sparse	Very Rough (Boulder/Veg)	Extreme
23	Medium	Medium	Very Rough (Boulder/Veg)	Extreme
24	Medium	Dense	Very Rough (Boulder/Veg)	High
25	High	Sparse	Very Rough (Boulder/Veg)	Extreme
26	High	Medium	Very Rough (Boulder/Veg)	Extreme
27	High	Dense	Very Rough (Boulder/Veg)	Extreme



From: Leary et al. (2012)

DECIMATION of BIG POINT CLOUDS…

- **To**pographic **P**oint **C**loud **A**nalysis **T**oolkit (ToPCAT; formerly PC-Tools)
- Can be used to go from 1000's to 10,000's of points per square meter to 1 to 10…
- Absolute zMin can be extracted in a window of defined size… That can be used to model elevation

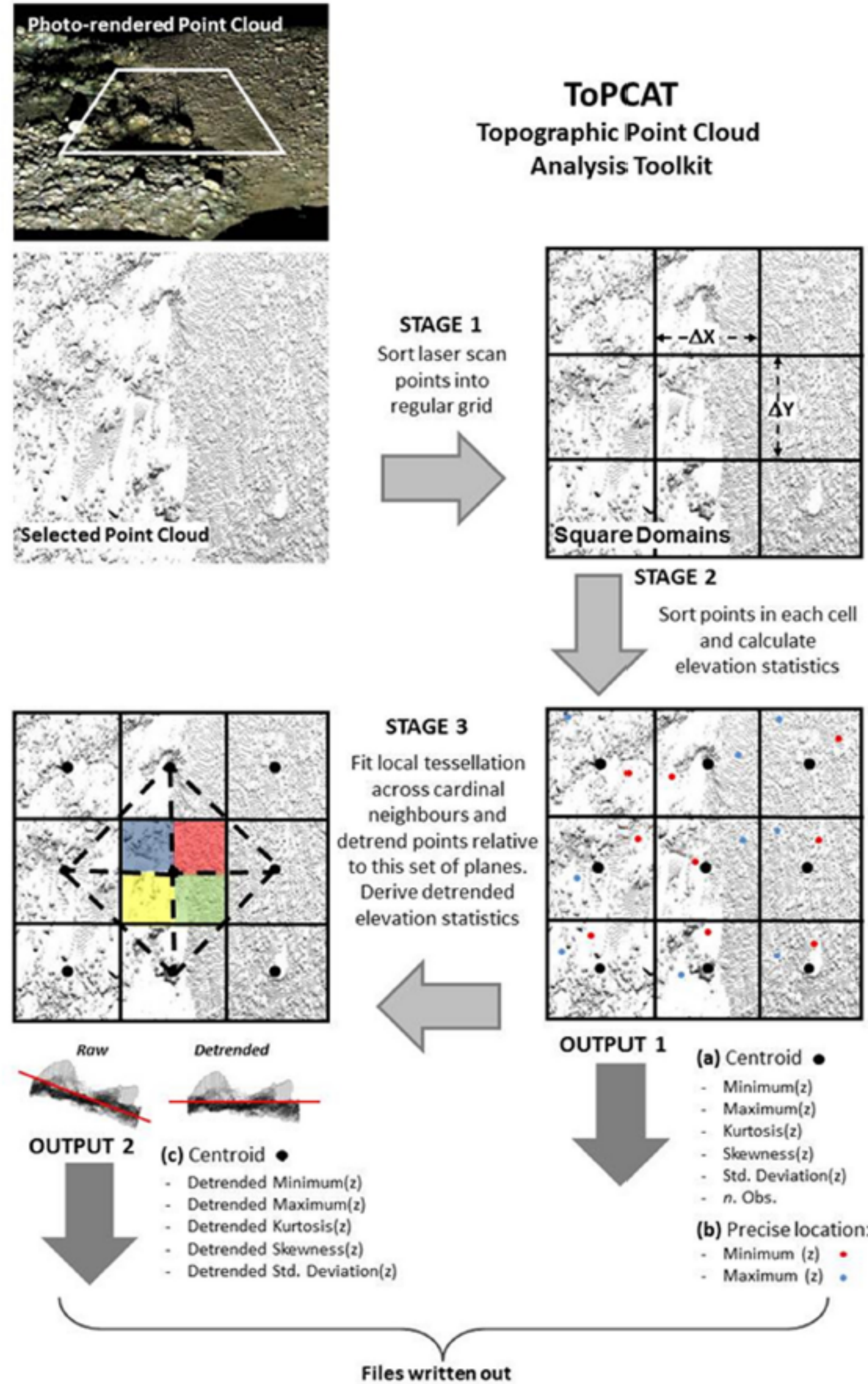


See: Brasington, J., Vericat, D., Rychkov, I., 2012. Modeling river bed morphology, roughness, and surface sedimentology using high resolution terrestrial laser scanning. Water Resources Research 48. DOI: 10.1029/2012wr012223.

POINT CLOUD STATS

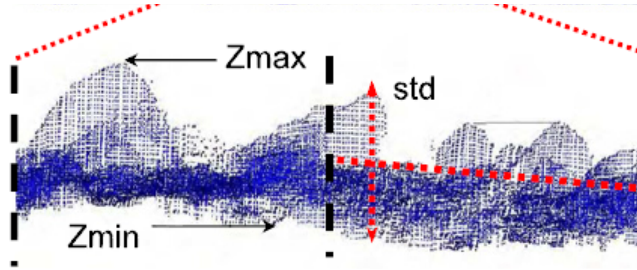
- **To**pographic **P**oint **C**loud **A**nalysis **T**oolkit (ToPCAT; formerly PC-Tools)
- Look at statistical estimates of variance for elevation
  - Absolute z_{min} & z_{max}
  - z_{mean}
  - `range`
  - `stdev` - The absolute σ
  - `sk` - Skew
  - `n` - Count of number of points in cell (i.e. point density)

See: Brasington, J., Vericat, D., Rychkov, I., 2012. Modeling river bed morphol roughness, and surface sedimentology using high resolution terrestrial laser scanning. Water Resources Research 48. DOI: 10.1029/2012wr012223.



HOW IT WORKS…

- Locally detrended stats, relative to a best-fit plane surface through the point cloud
  - `Zmean_det, stdev-det, sk-det, k det`



http://code.google.com/p/point-cloud-tools/

66 *I. Rychkov et al. / Computers & Geosciences 42 (2012) 64–70*

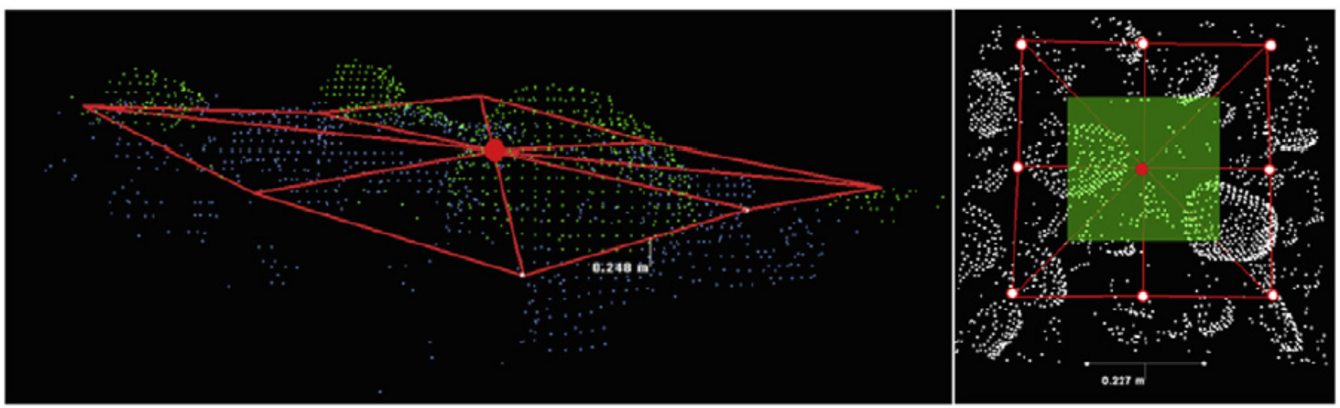
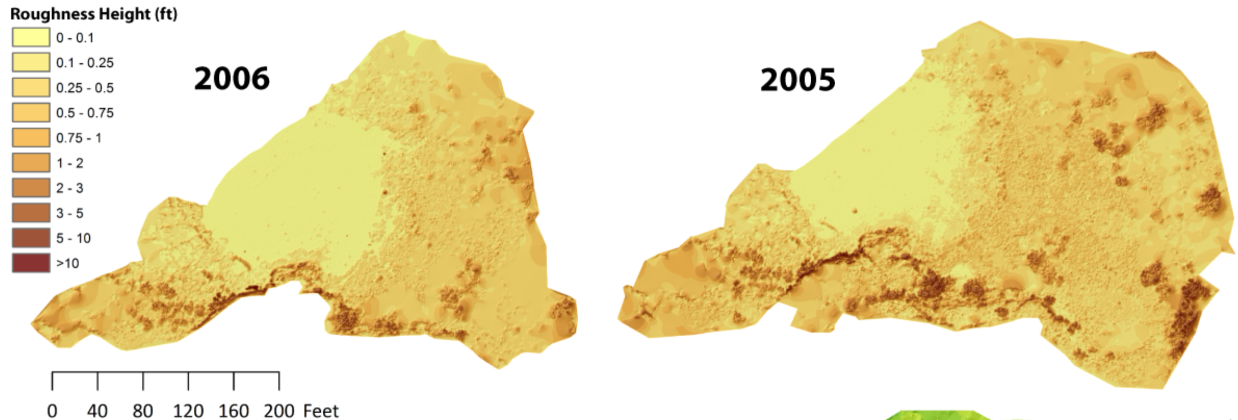


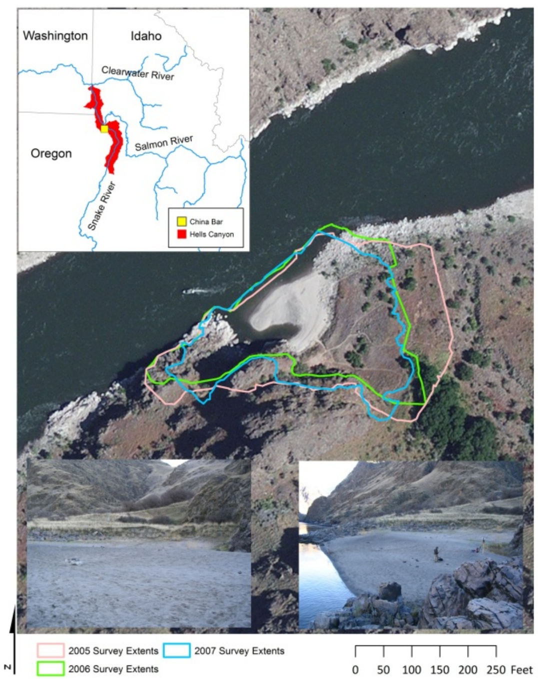
Fig. 2. Triangular mesh laid over grid cells. Green mask represents the current cell. Vertices can be central elevations, centroids or points of minimum elevations. Vertices from neighboring cells are connected by red lines. 3D (left image) and top (right image) views. The facets of the mesh give the local ground slopes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

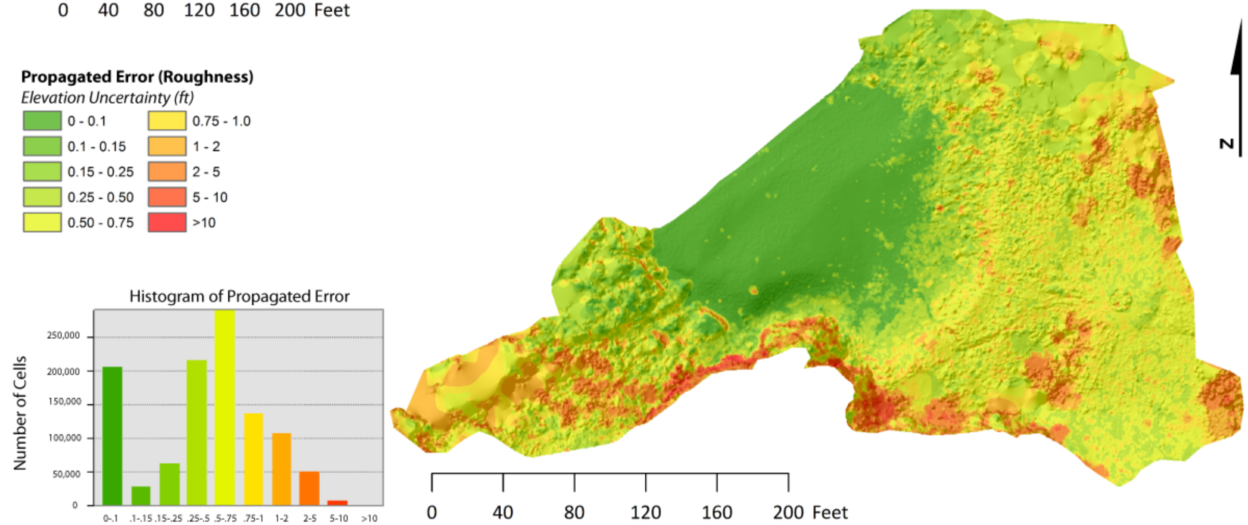
See: Rychkov I, Brasington J and Vericat D. (2012). DOI: 10.1016/j.cageo.2012.02.011

A SANDBAR EXAMPLE…

- Roughness changes through time



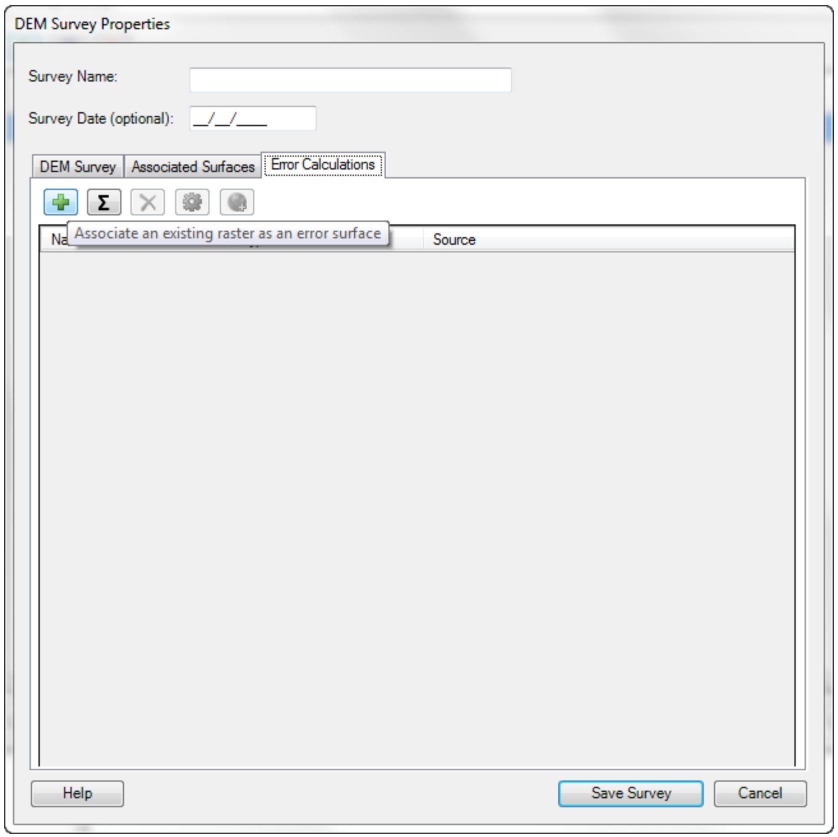


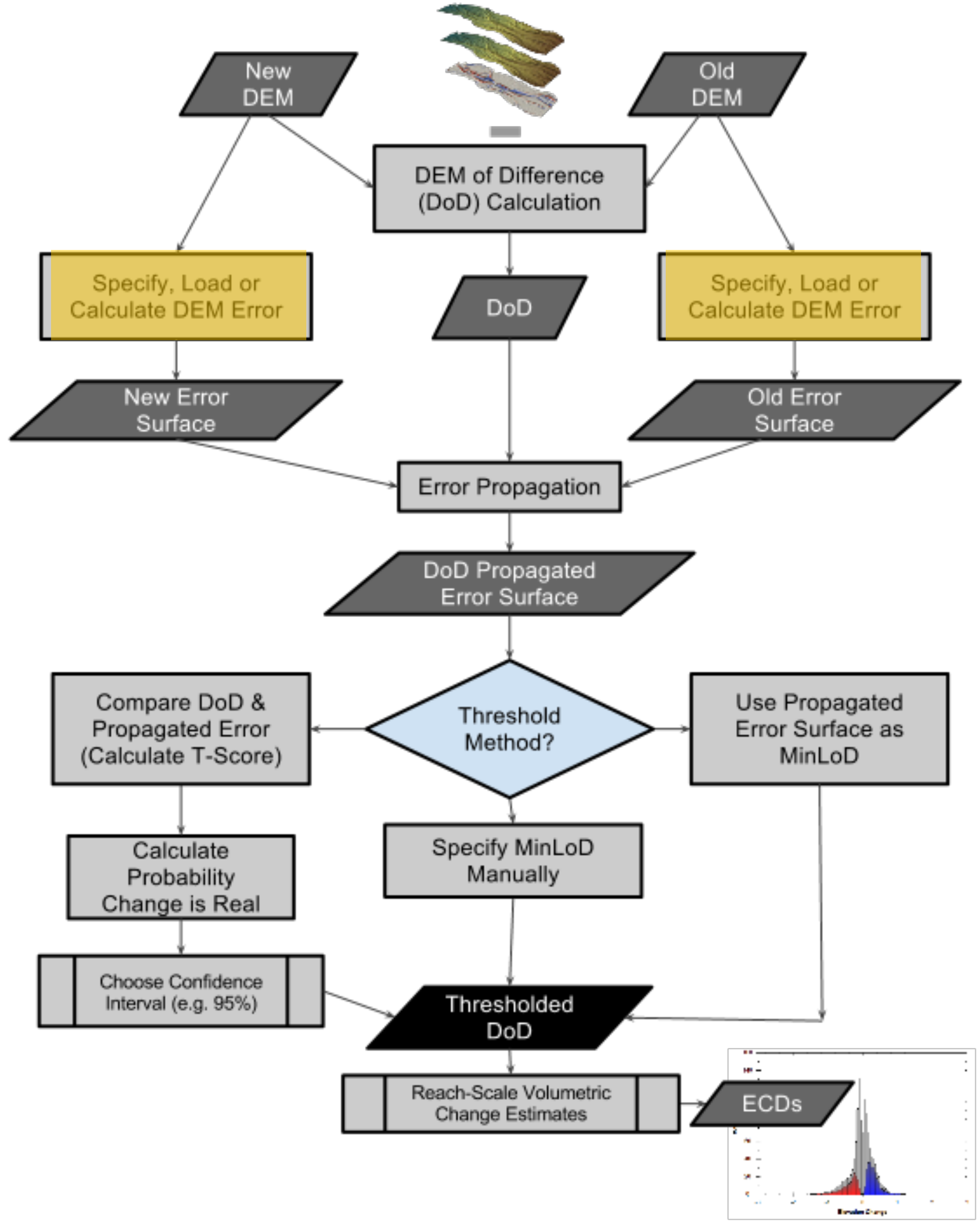


- Use detrended standard deviation as proxy for roughness and/or error…

ADD ROUGHNESS AS ERROR SURFACE

- New DEM Error
- Old DEM Error





ALTERNATIVES... PySESA

- PySESA – Python program for spatially explicit spectral analysis

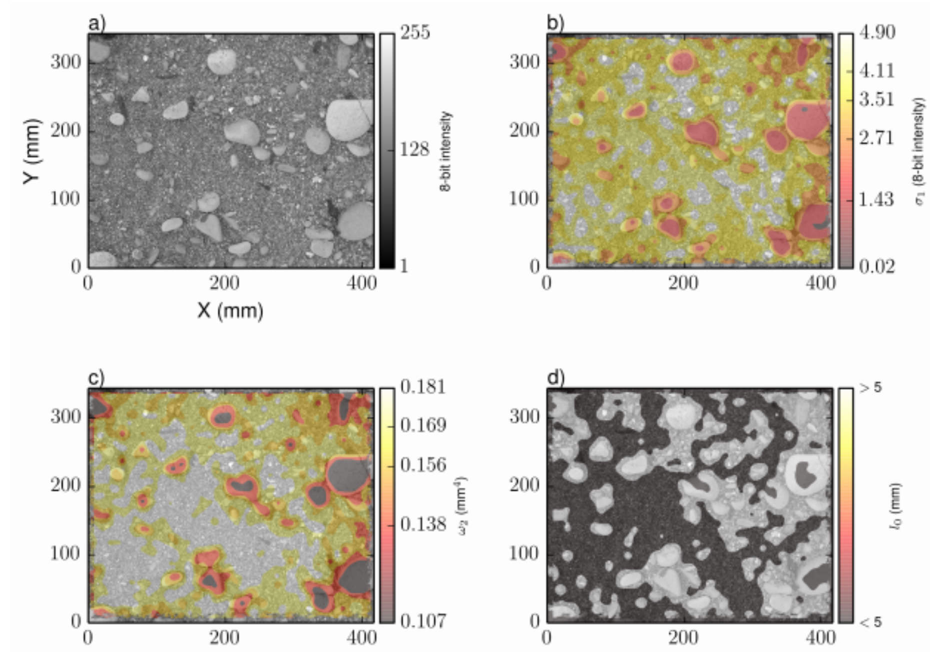


Figure 10: a) 8-bit greyscale intensity image of coarse sand, gravel and pebbles; b) greyscale image overlain by contour map of spectral RMS amplitude, σ_1 (equation 15); c) greyscale image overlain by contour map of spectral strength, ω_2 (equation 12); and d) greyscale image overlain by binary map of where integral lengthscale, l_0 (equation 11) is < (dark) and >5 (light) mm.

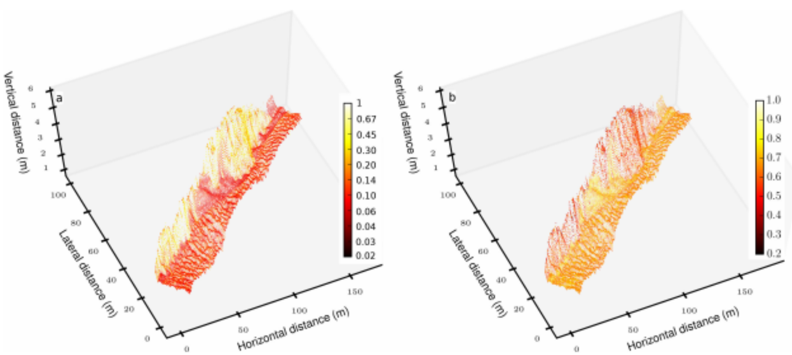


Figure 8: The point cloud shown in Figure 7a, decimated to a 0.25 × 0.25m regular grid by the PySESA program, and colour-coded by: a) spectral root-mean-square variation in amplitude, σ (m); and b) spectral strength ω_2 (m^4).

PySESA Website: https://dbuscombe-usgs.github.io/pysesa/index.html
PYSEA Source code: https://github.com/dbuscombe-usgs/pysesa

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(USGS GCMRC)