ImplicitTerrain: a Continuous Surface Model for Terrain Data Analysis

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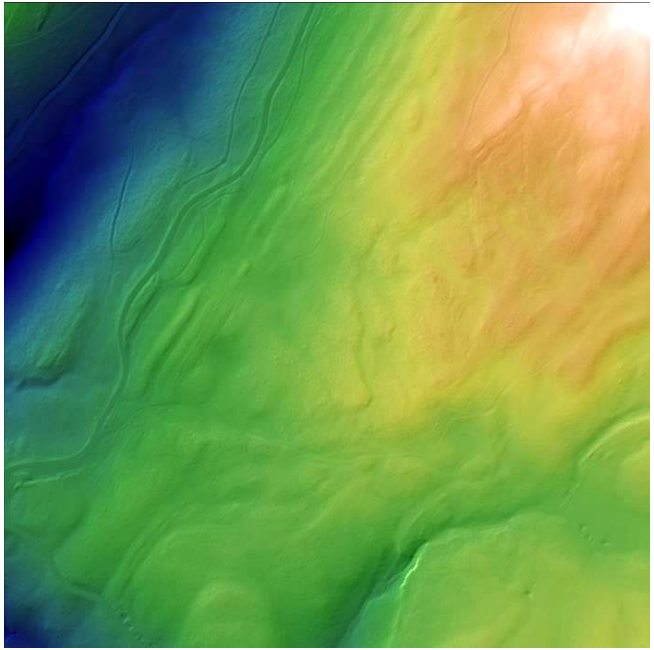
Digital Terrain Model (DTM)

Often used in geographical information systems (GISs) to model the Earth's **surface elevation and shape of the landscape**, to support various engineering, land-use planning, and environmental applications.

- Topographical analysis - Local
- Topological analysis - Global



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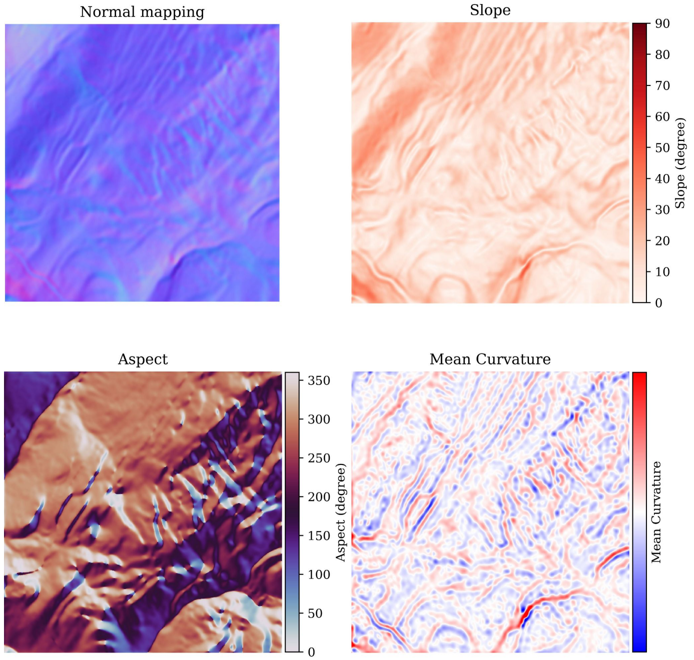
Topographical analysis based on **local surface gradients & 2nd-order derivatives**



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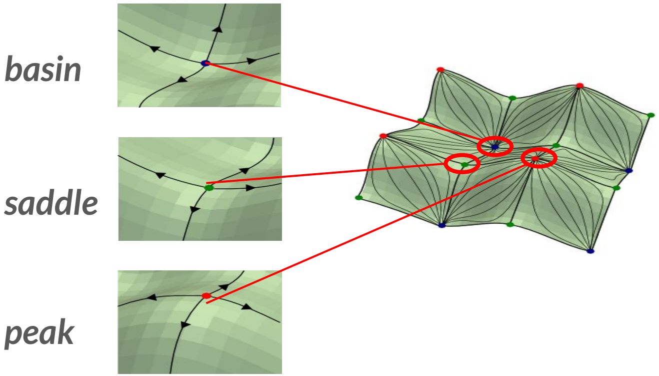
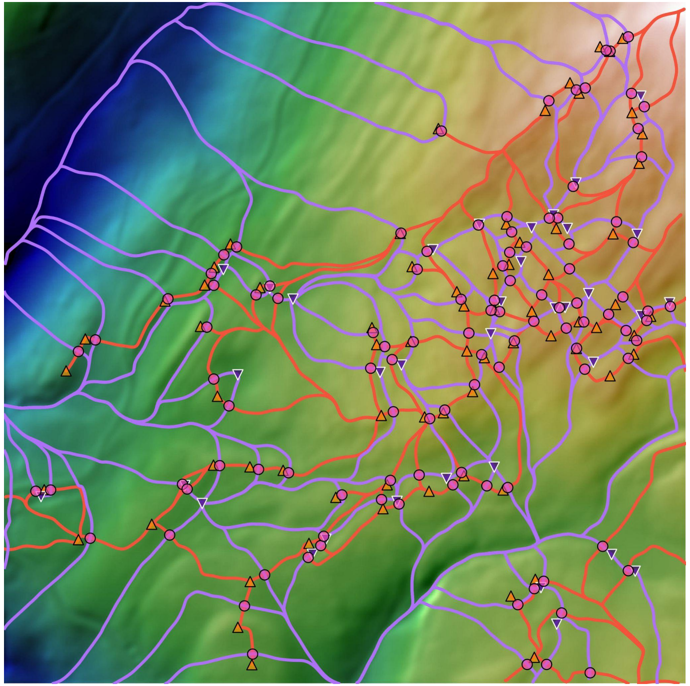
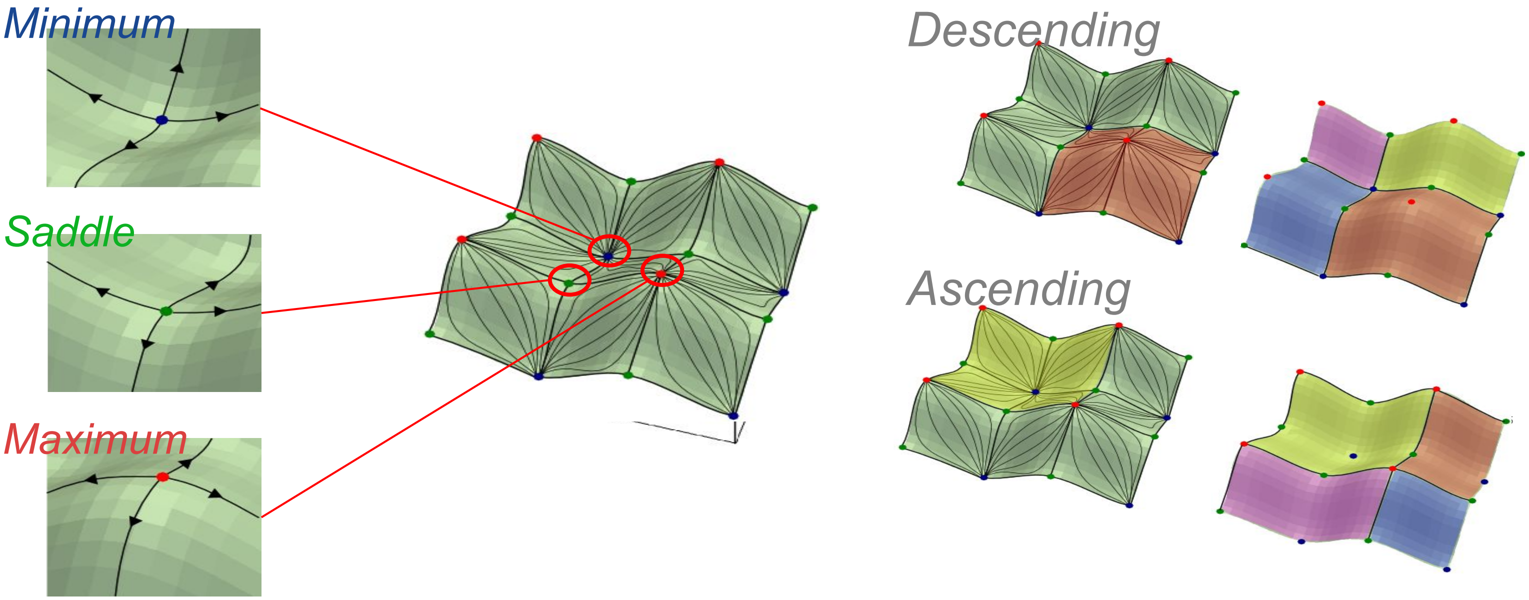
Topological analysis based on the overall shape of the surface, that can also be derived from **gradient.**





Basic Morse theory

- Consider a scalar field *f* defined over a compact domain



Critical points

Integral lines

Morse complexes

Digital Terrain Model (DTM)

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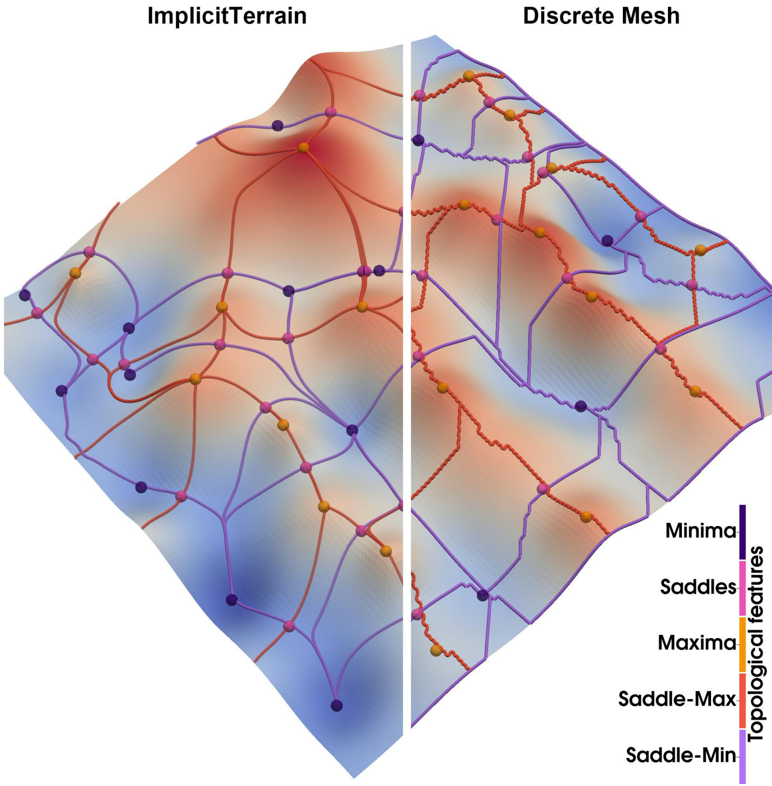
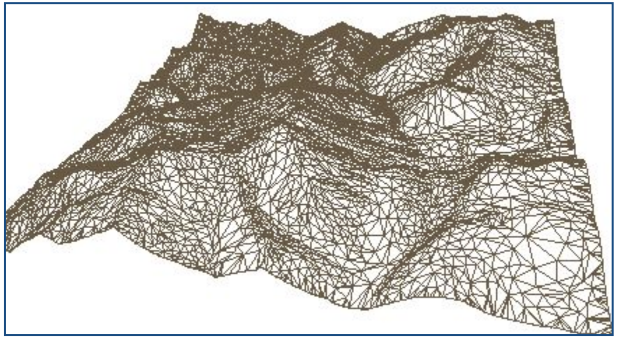
Key points & challenges:

- + Accurate surface elevation
- + Accurate surface derivatives
- + Support high resolution
- + Better 😊"easy-to-understand"

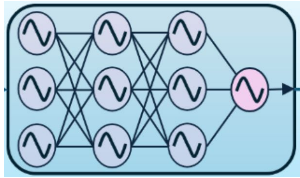
Motivation: Discrete Surface Models are Limited



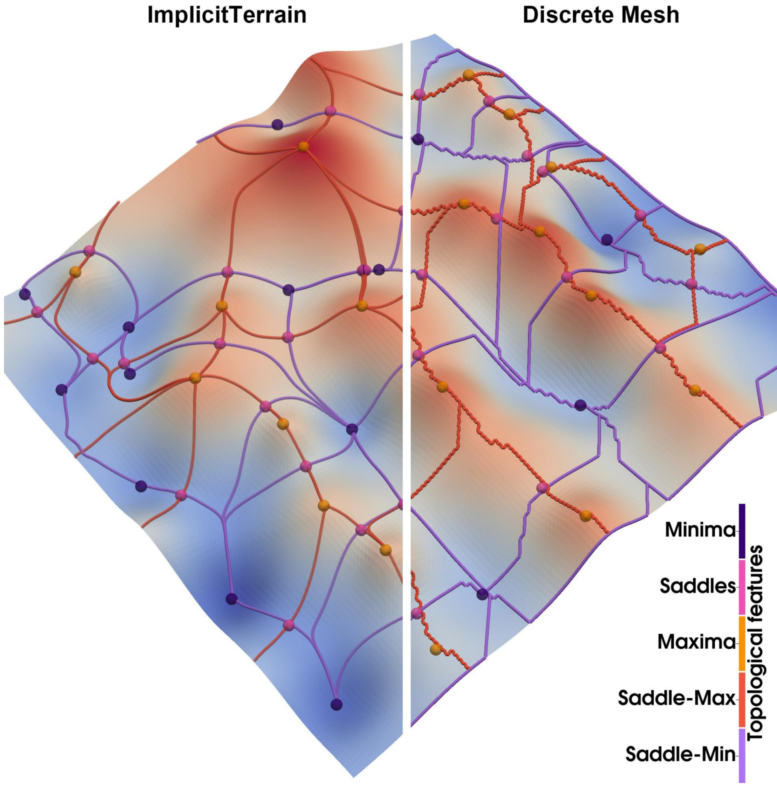
- Surface elevation and gradient quality is directly related to the number of vertices (grids or meshes).
- Surface gradient and high-order derivatives are **approximation** results.
- Analysis algorithms on these models are relatively **complex** with **special cases.**



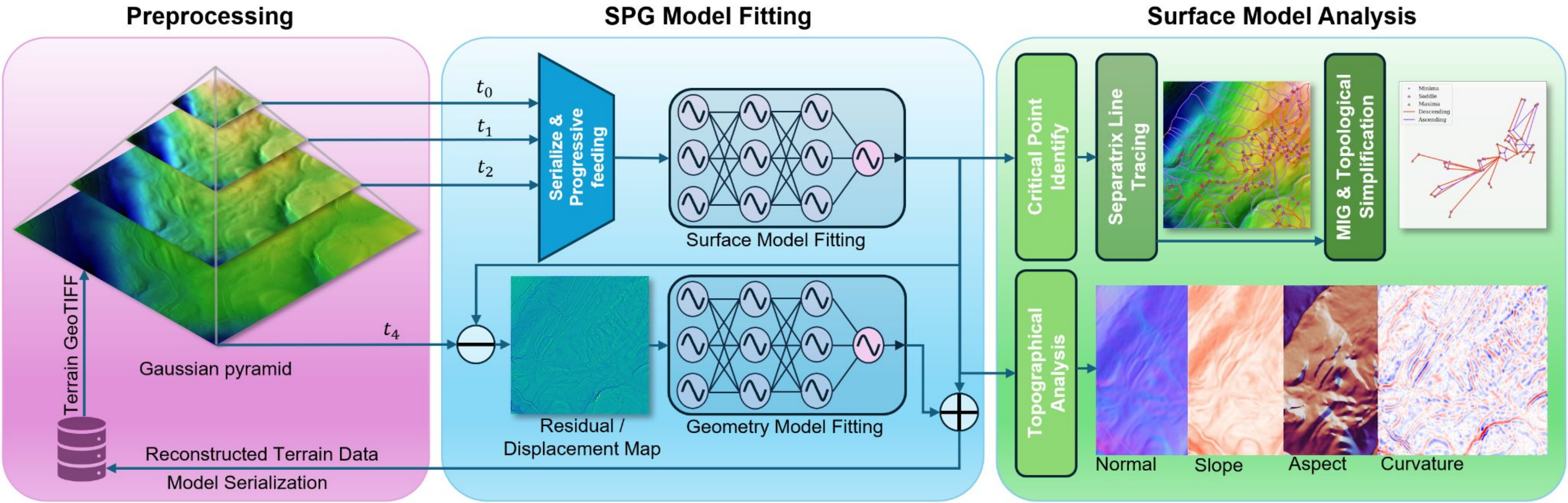
Motivation: A Smooth Implicit Surface Model



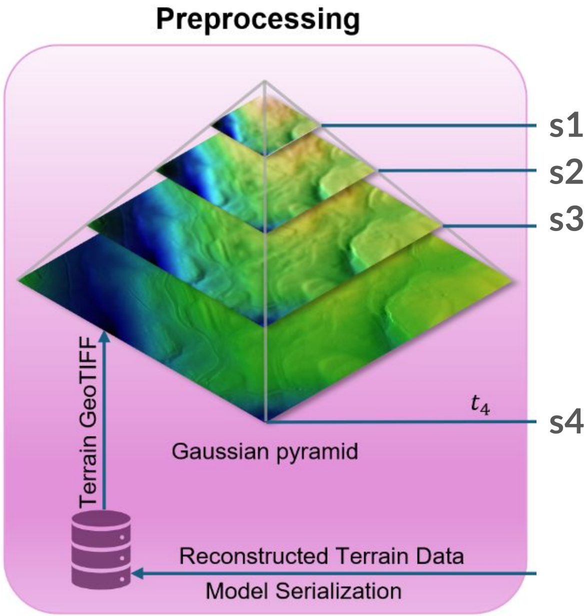
- Terrain surface as a **2D scalar function.**
- **Implicit Neural Representation (INR)** based on ***Coordinate-based Network*** brings analysis back to the continuous world.
- **C-n continuous** surface model.
- Surface quality depends on **number of params**.
- **"Over-smoothness" of INR is not a problem!**



ImplicitTerrain: Pipeline Overview

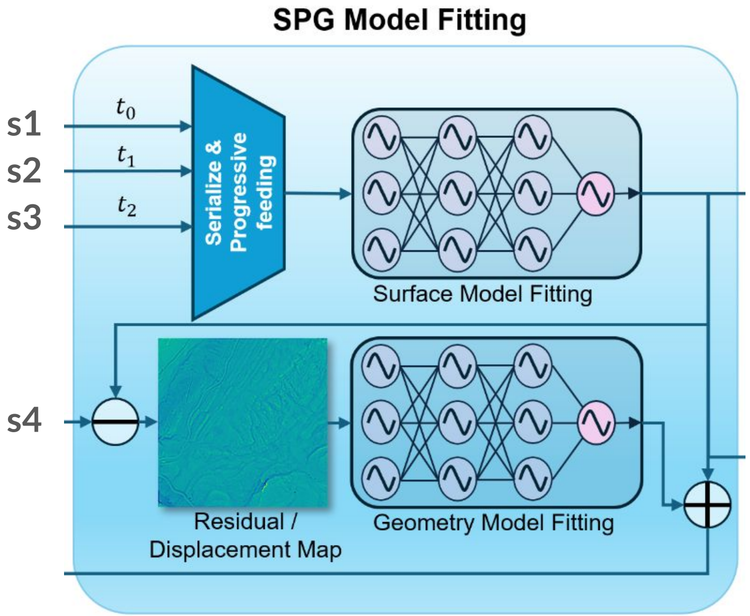


ImplicitTerrain: Preprocessing



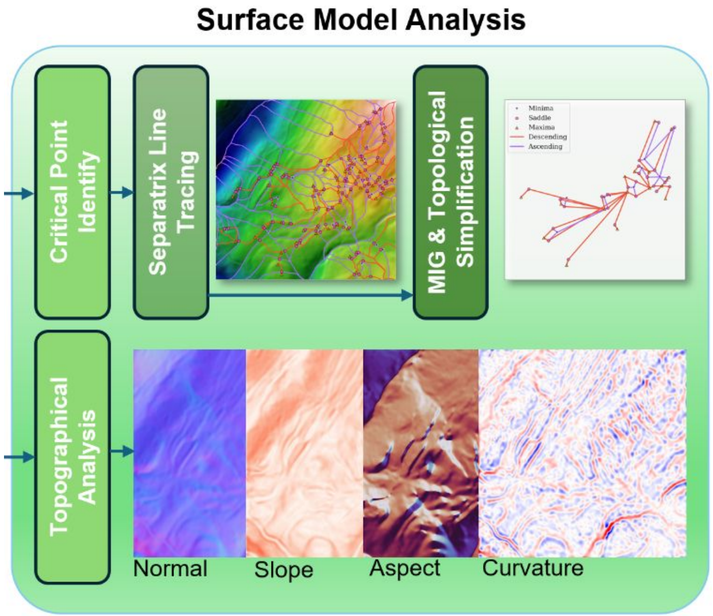
- **High-resolution**: 1000 x 1000 Raster data of digital elevation information of 1km^2 terrain
- **Progressive fitting from *low-freq* to *high-freq* signals**

ImplicitTerrain: Surface-plus-Geometry Model Fitting



- **Progressive fitting from *low-freq* to *high-freq* signals**
- Terrain surface analyses need pre-process the data (**down-sample, smoothing, ...**)
- Cascaded **surface model** (3, 256, sin) and **geometry model** (3, 256, sin)

ImplicitTerrain: Surface Model Analysis



- Derivatives calculated via **back propagation**
- **Topological and topographical features can be derived just following their definitions**
  - E.g., Critical point = function 1st-order derivative equals zero
  - E.g., Mean curvature:

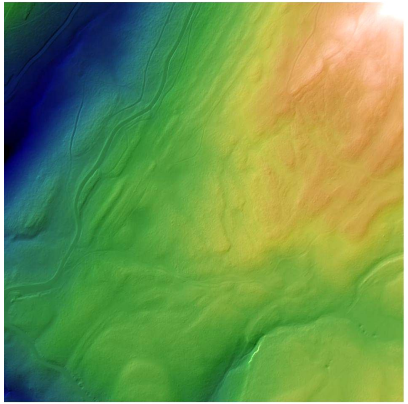
$$H = \frac{(1+f_y^2)f_{xx} - 2f_x f_y f_{xy} + (1+f_x^2)f_{yy}}{2(1+f_x^2+f_y^2)^{3/2}} \qquad (5)$$

ImplicitTerrain: Experiment Results

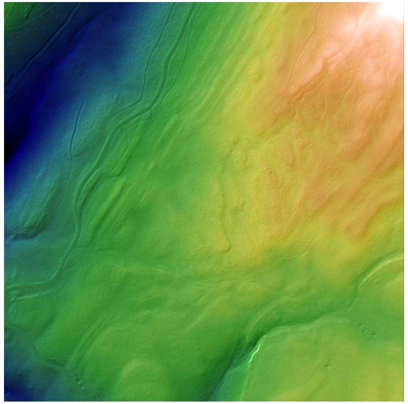
Name	Sizes (MBs)	Size ratio	Ψ_s PSNR	Ψ_s SSIM	Freq diff $\times 10$	Grad norm diff $\times 10$	Grad direction diff (rad) $\times 10$	SPG PSNR	SPG SSIM
Swiss_1	1.51/7.6	0.20	64.85	0.9999	1.49 ± 2.31	0.54 ± 0.52	0.62 ± 1.10	67.08	0.9999
Swiss_2	1.51/7.6	0.20	60.53	0.9998	0.95 ± 2.08	0.77 ± 1.00	0.61 ± 0.77	52.34	0.9992
Swiss_3	1.51/7.6	0.20	59.75	0.9998	0.13 ± 0.29	0.86 ± 1.05	0.72 ± 1.02	58.93	0.9997
Swiss_3	1.51/7.6	0.20	62.54	0.9999	0.17 ± 0.32	0.56 ± 0.61	0.46 ± 0.57	66.59	0.9999

Table 2. Numerical evaluation of the fitting results of the real-world terrain. **Sizes** are the total model sizes and the input raster size, and **Size ratio** is their ratio. Ψ_s **PSNR** and Ψ_s **SSIM** are the fitting accuracy of the surface model to the smoothed data. **SPG PSNR** and **SPG SSIM** are the fitting accuracy of the SPG model to the original input. For the surface model, **Freq diff** is the mean and standard deviation of the frequency domain difference. **Grad norm/direction diff**s are the mean and standard deviation of the difference of gradient norm and direction between $\nabla\Psi_s$ and the estimated image gradient from I_s. $\times 10$ denotes the scaling factor for better numerical representation.

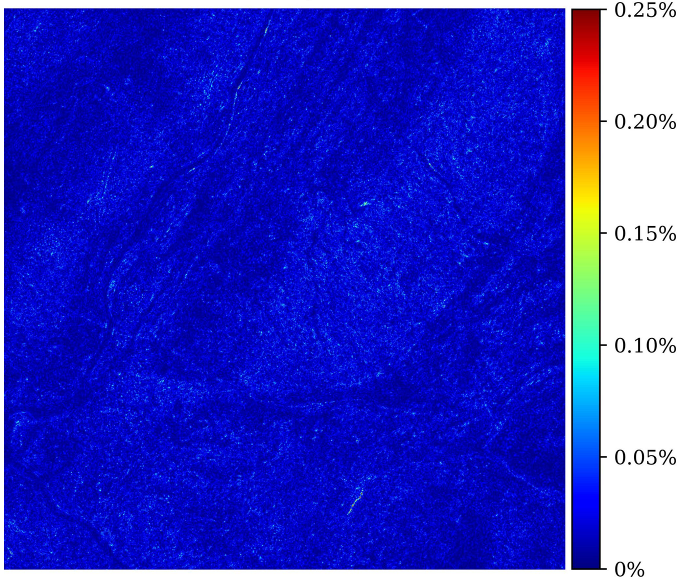
Input data.



Reconstructed data.



PSNR: 67.082 dBs, SSIM: 0.9999



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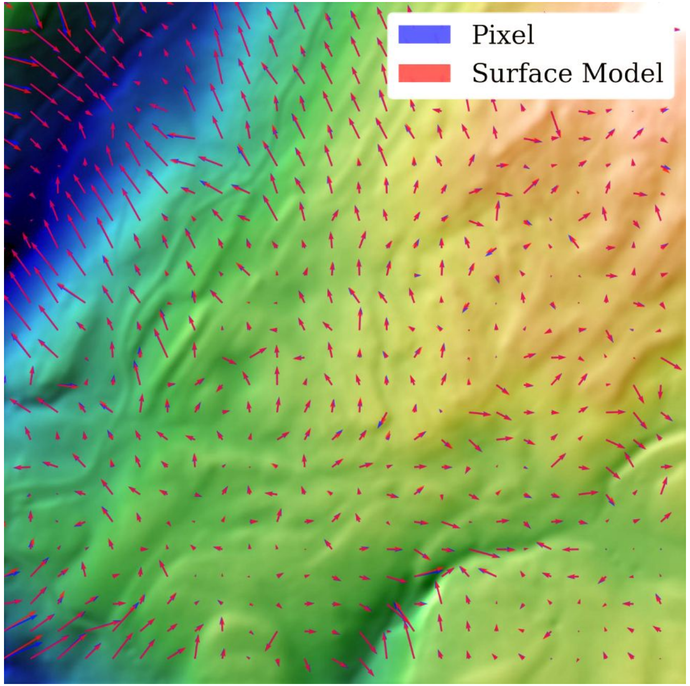

- Accurate gradient field reconstruction

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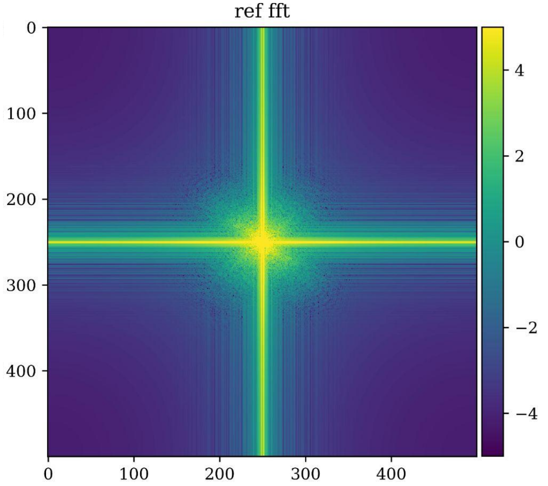

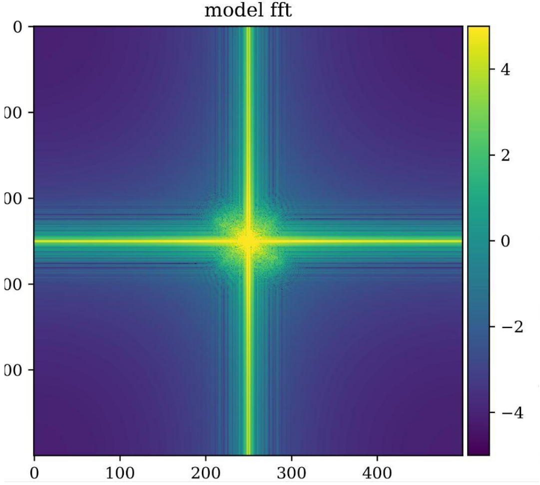

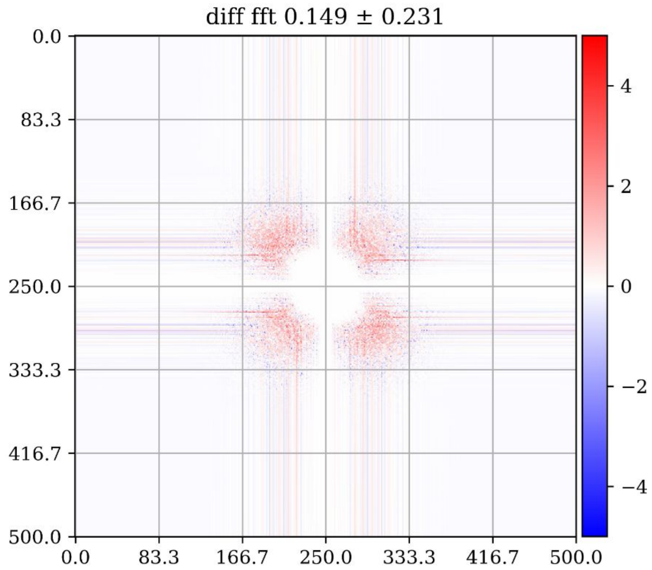

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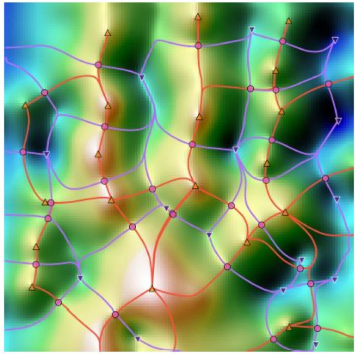
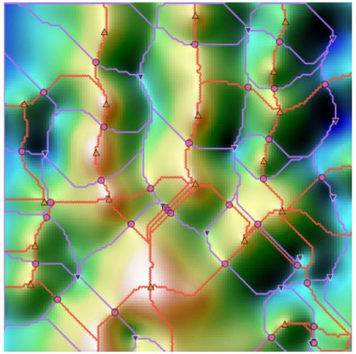
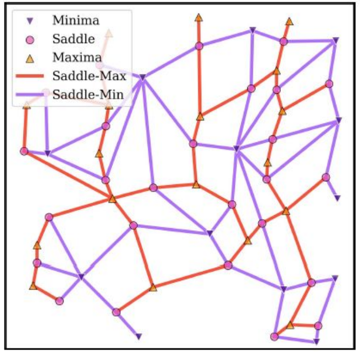


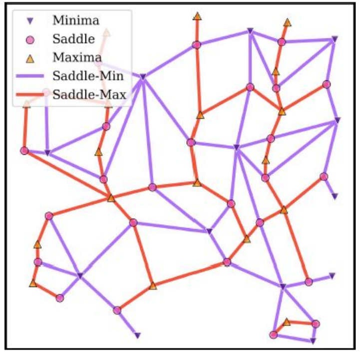
(a) Separatrix lines - ImplicitTerrain.



(b) Separatrix lines - *Forman method.*



(c) MIG - ImplicitTerrain.



(d) MIG - *Forman method.*

Figure 4. Comparison of topological analysis results of the synthetic terrain. Node colors and shapes represent the critical point types and the edge colors represent the separatrix lines as in the legend of (c) and (d). Better viewed in the digital version.

Name	**precision**	**recall**	$F_{0.5}$ **score**	WS_{ratio}
Synth_{ours}	1.00	1.00	1.00	0.68
Swiss_1	0.90	0.96	0.91	0.17
Swiss_2	0.91	0.831	0.89	0.31
Swiss_3	0.89	0.78	0.87	0.69
Swiss_4	0.91	0.83	0.89	0.35

Table 1. Topological analysis results of the synthetic and real-world terrain. WS_{ratio} between $[0, 1]$ indicates the MIGs from both methods are well aligned.

ImplicitTerrain: Experiment Results

- On par noise robustness, also benefiting from the smoothing pre-processing
- Surface **gradient field** is more robust to noise than discrete method -> **MIG structure preserved**

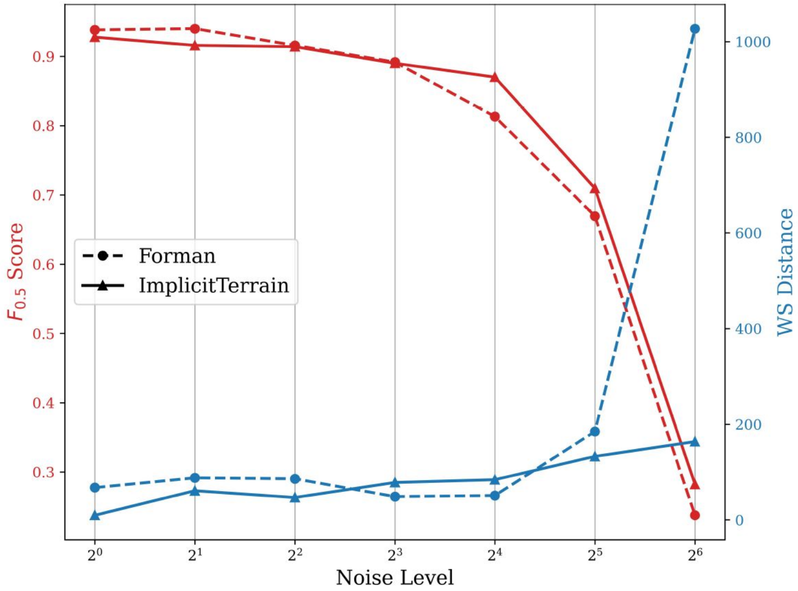
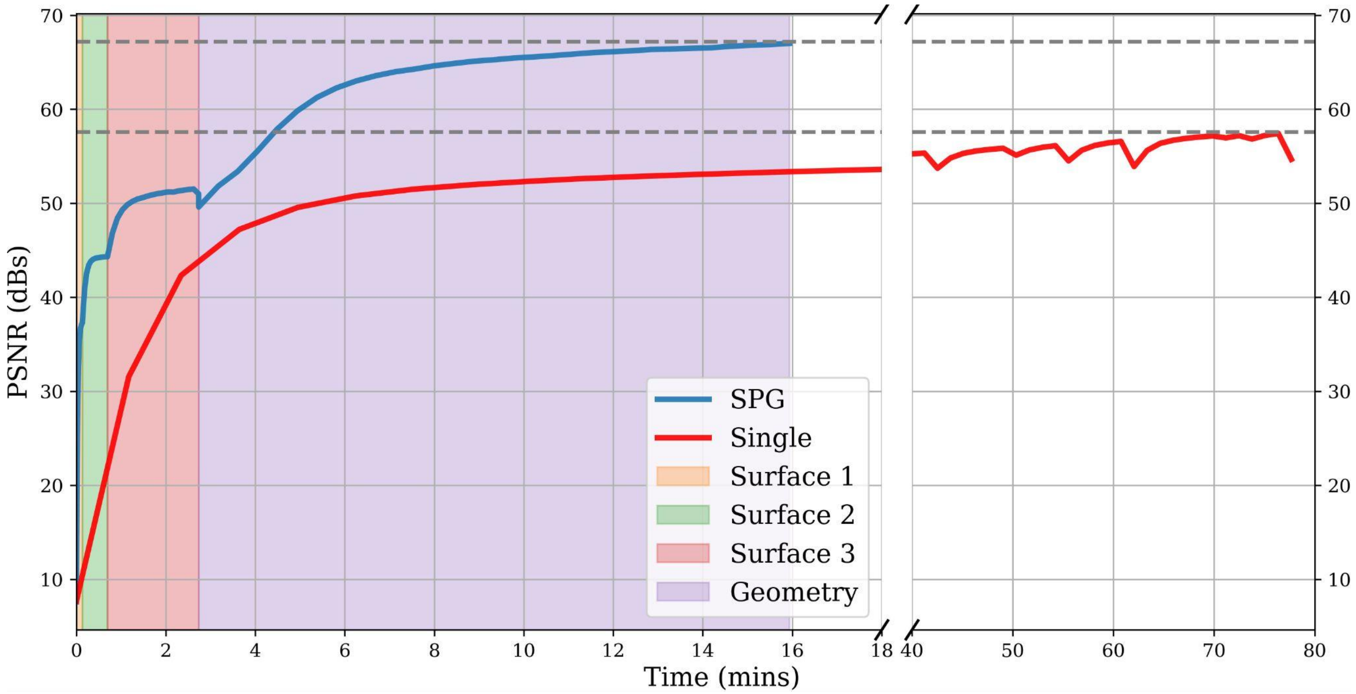


Figure 8. Comparison of noise robustness. *Forman method* and ImplicitTerrain comparison via $F_{0.5}$ score and Wasserstein distance of the Swiss_1 w.r.t. noise level.

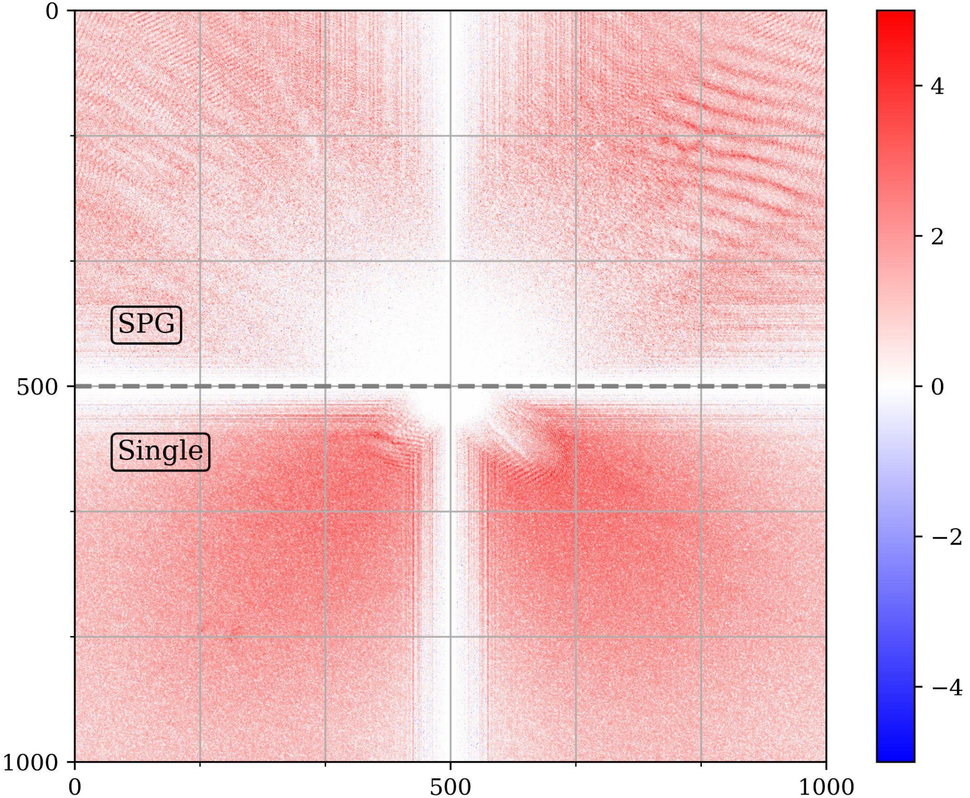
Ablation: SPG model vs. single model

- 4x faster fitting
- Much better accuracy (67 dBs vs. 58 dBs)
- Even faster (30x) if only surface model needed



Ablation: SPG model vs. single model

- Frequency domain comparison illustrates the **higher efficiency of model parameter usage**



Thank you!

ImplicitTerrain: a Continuous Surface Model for Terrain Data Analysis

Q & A

For more details, please visit our project website:
https://fengyee.github.io/implicit-terrain/

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