Quadtree Displacement Mapping with Height Blending

Practical Detailed Multi-Layer Surface Rendering

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Reality Pump

Outline

- Introduction
- Motivation
- Existing Solutions
- Quad tree Displacement Mapping
- Shadowing
- Surface Blending
- Conclusion

Introduction

- Next generation rendering
  - Higher quality per-pixel
    - More effects
    - Accurate computation
  - Less triangles, more sophistication
    - Ray tracing
    - Volumetric effects
    - Post processing
  - Real world details
    - Shadows
    - Lighting
    - Geometric properties

Surface rendering

- Surface rendering stuck at
  - Blinn/Phong
    - Simple lighting model
  - Normal mapping
    - Accounts for light interaction modeling
    - Doesn't exhibit geometric surface depth
  - Industry proven standard
    - Fast, cheap, but we want more…

Improvements

- Several titles tackled high quality surface rendering
  - Gears of War
    - Multiple custom materials
      - Different light properties
      - Additional geometric details
  - Crysis
    - Multiple custom surfaces
      - Exhibit natural phenomenon
        - Ice
        - Skin
        - Parallax mapped terrain features

Terrain surface rendering

- Rendering terrain surface is costly
  - Requires blending
    - With current techniques prohibitive
  - Blend surface exhibit high geometric complexity

Surface properties

- Surface geometric properties
  - Volume
  - Depth
  - Various frequency details
- Together they model visual clues
  - Depth parallax
  - Self shadowing
  - Light Reactivity

Surface Rendering

- Light interactions
  - Depends on surface microstructure
  - Many analytic solutions exists
    - Cook Torrance BDRF
- Modeling geometric complexity
  - Triangle approach
    - Costly
      - Vertex transform
      - Memory
    - More useful with Tessellation (DX 10.1/11)
  - Ray tracing

Motivation

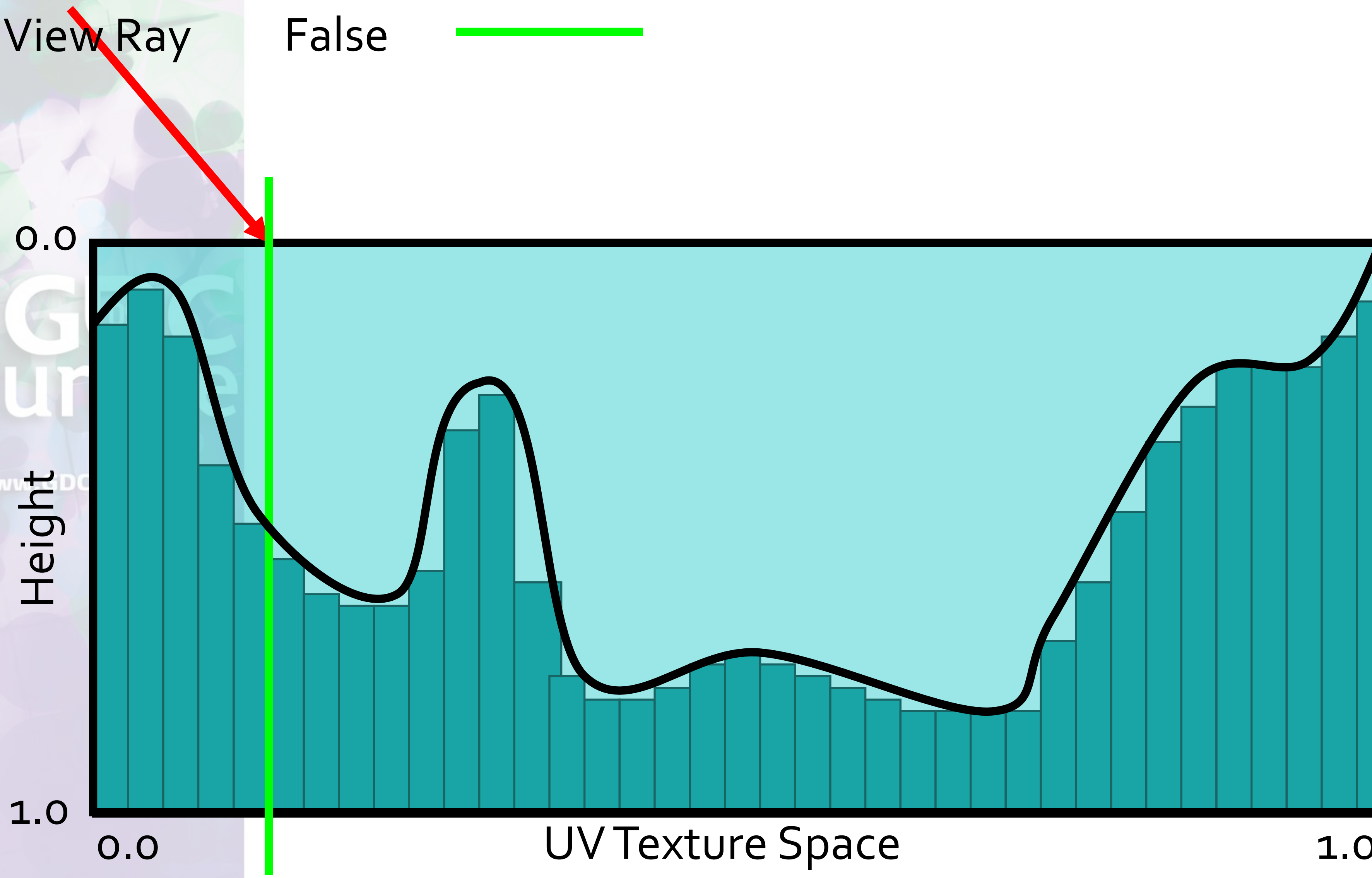
- Render different surfaces
  - Terrains
  - Objects
  - Dynamic Objects
    - Fluid/Gas simulation
- Do it fast
  - Current Hardware
  - Consoles (X360)
  - Scalable for upcoming GPUs
- Minimize memory usage
  - Preferably not more than standard normal mapping
  - Consoles are limited

Motivation

- Our solution should support
  - Accurate depth at all angles
  - Self shadowing
  - Ambient Occlusion
  - Fast and accurate blending

Existing Solutions

- Depth complexity
  - Calculate correct surface depth
    - Find correct view ray – height field intersection
  - Compute lighting calculation using calculated depth offset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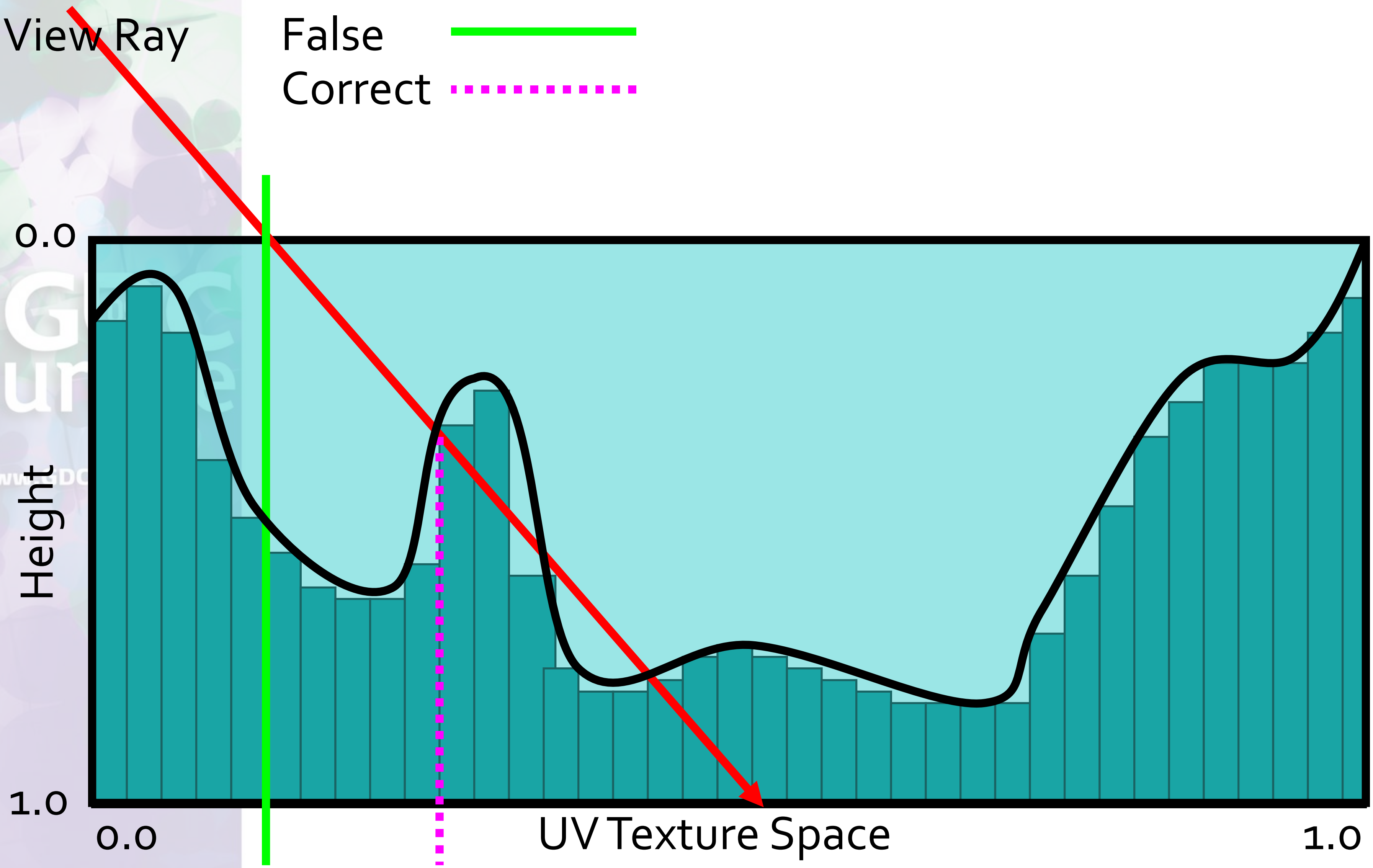
0.0
1.0
Height
0.0
UV Texture Space
1.0


View Ray
False
Correct
0.0
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Height
0.0
UV Texture Space
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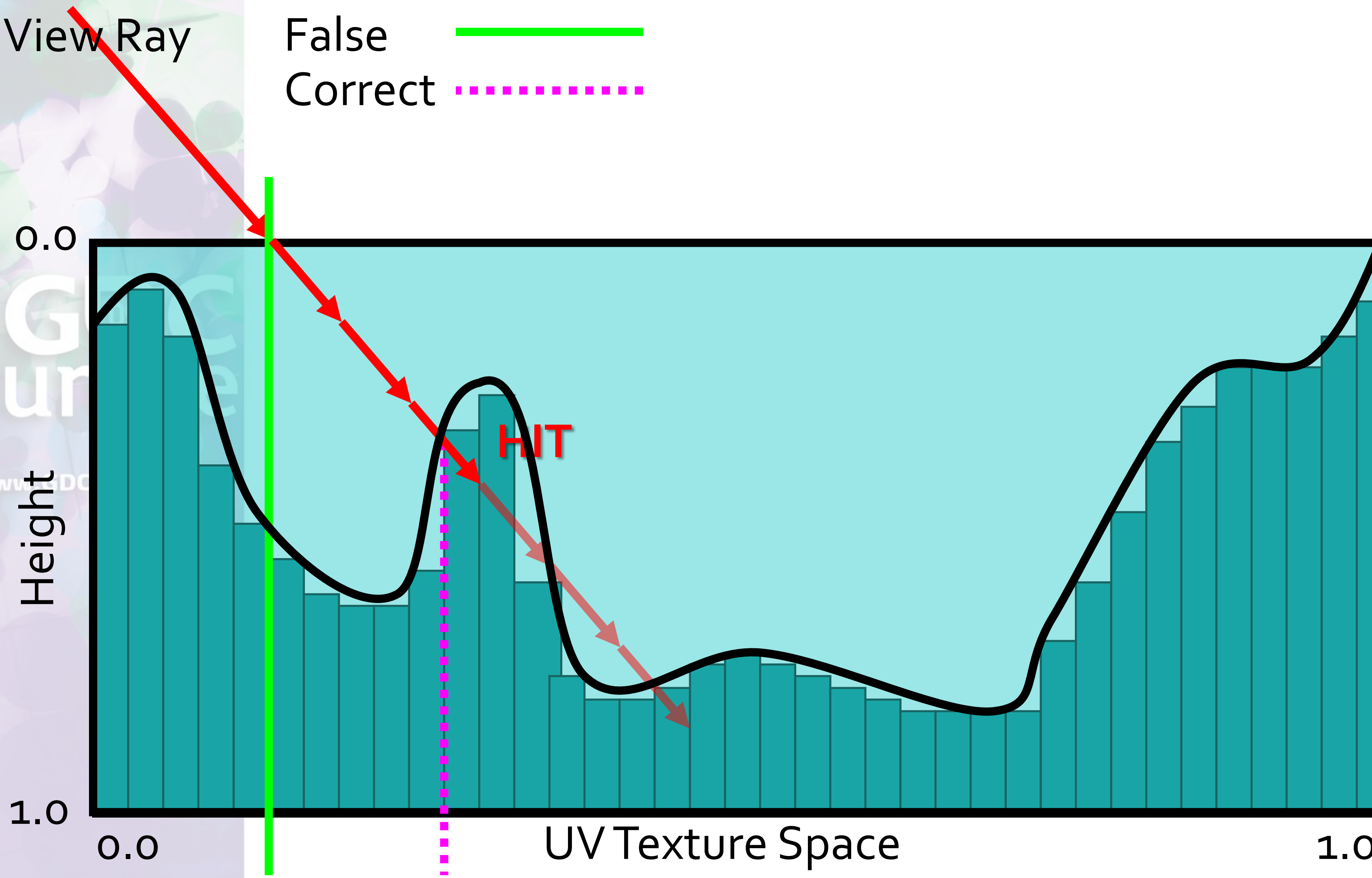
Online methods

- Perform ray tracing using height field data only
- Additional memory footprint
  - 1x8 bit texture
  - May use alpha channel
  - DXT5 – OK!
    - Remember about alpha interpolation!

Relief mapping

- Relief mapping (Policarpo 2005)
  - Performs intersection calculation by linear search in 2D height field space
  - Refines the result by binary search near the point of possible hit

Linear search with static step length



Linear Search

- Linear search in each step
  - Check if ray over height field
  - If YES
    - Move the ray by const distance
  - If NOT
    - Stop and go to Binary Search

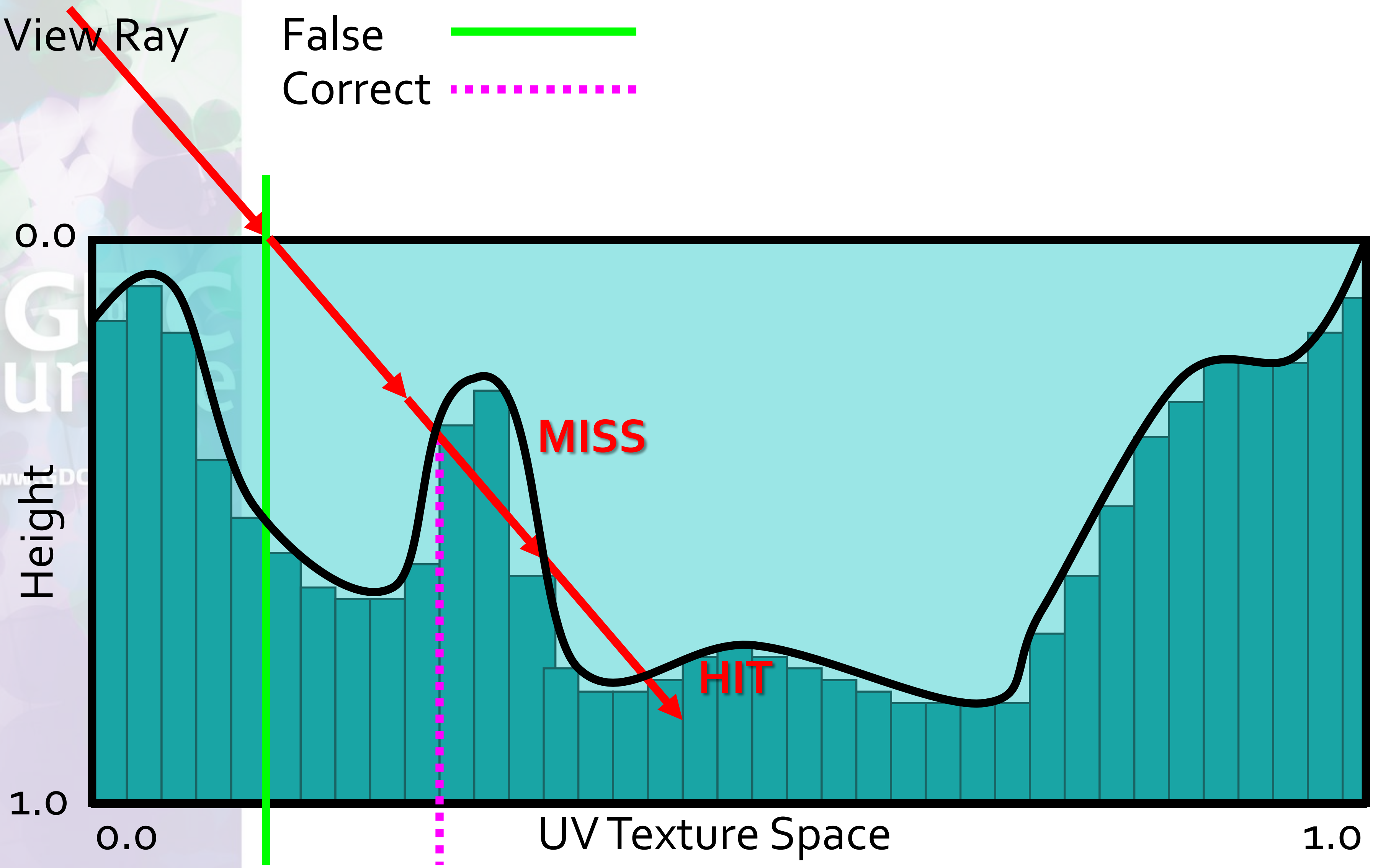
Linear Search

- Capped by max iterations
- Dynamic early out on stop condition
- Utilizes independent reads and linear filtering
  - Hardware optimized
- Fast for small number of iterations

Linear Search

- Drawbacks
  - Slow convergence
  - Prone to aliasing
    - With large steps may miss height field features
  - Scales bad with high resolution height fields
    - Worst case iteration count is n*sqrt(2) for n texel height field

Linear search with static step length



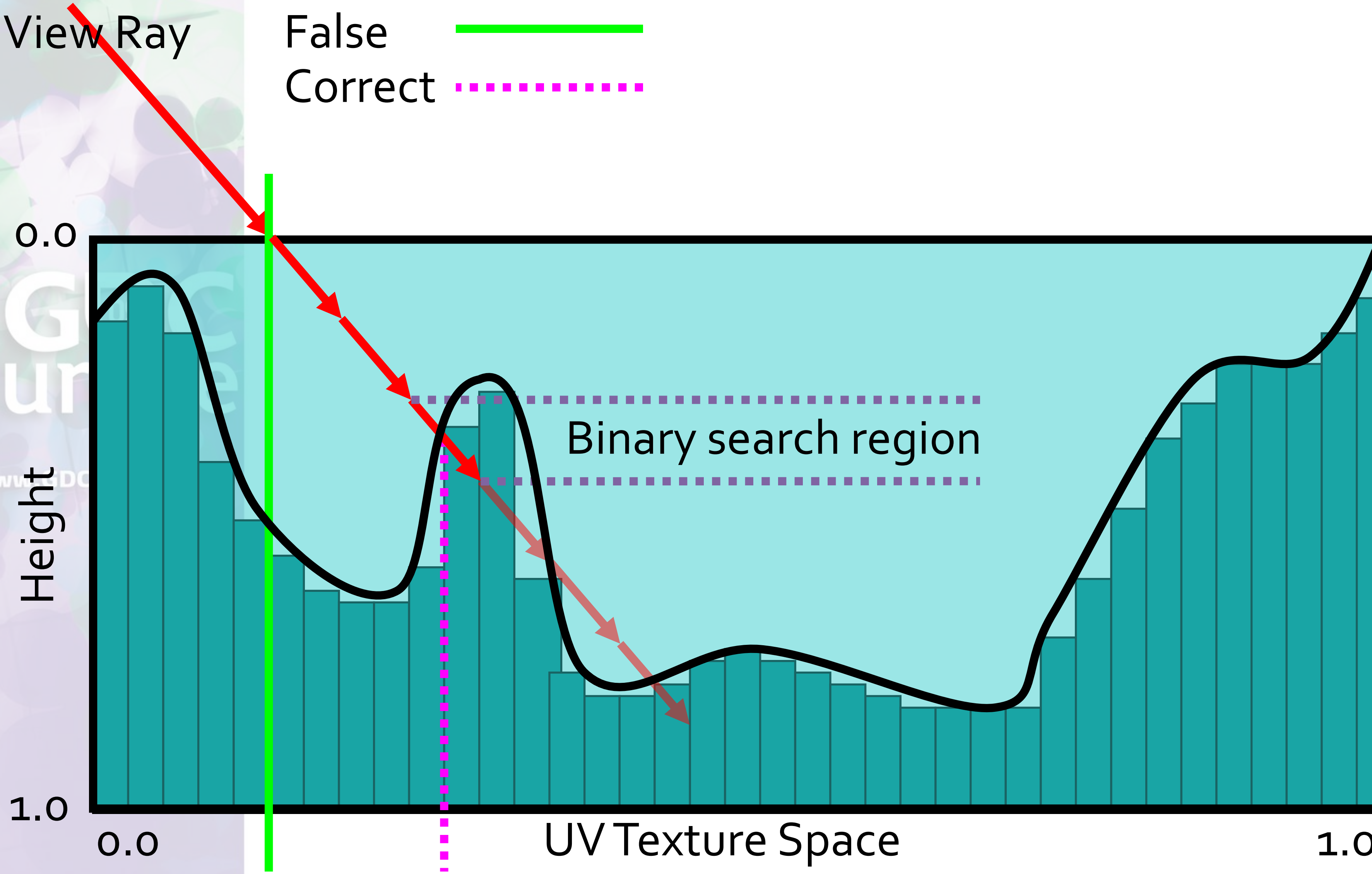
Binary Search

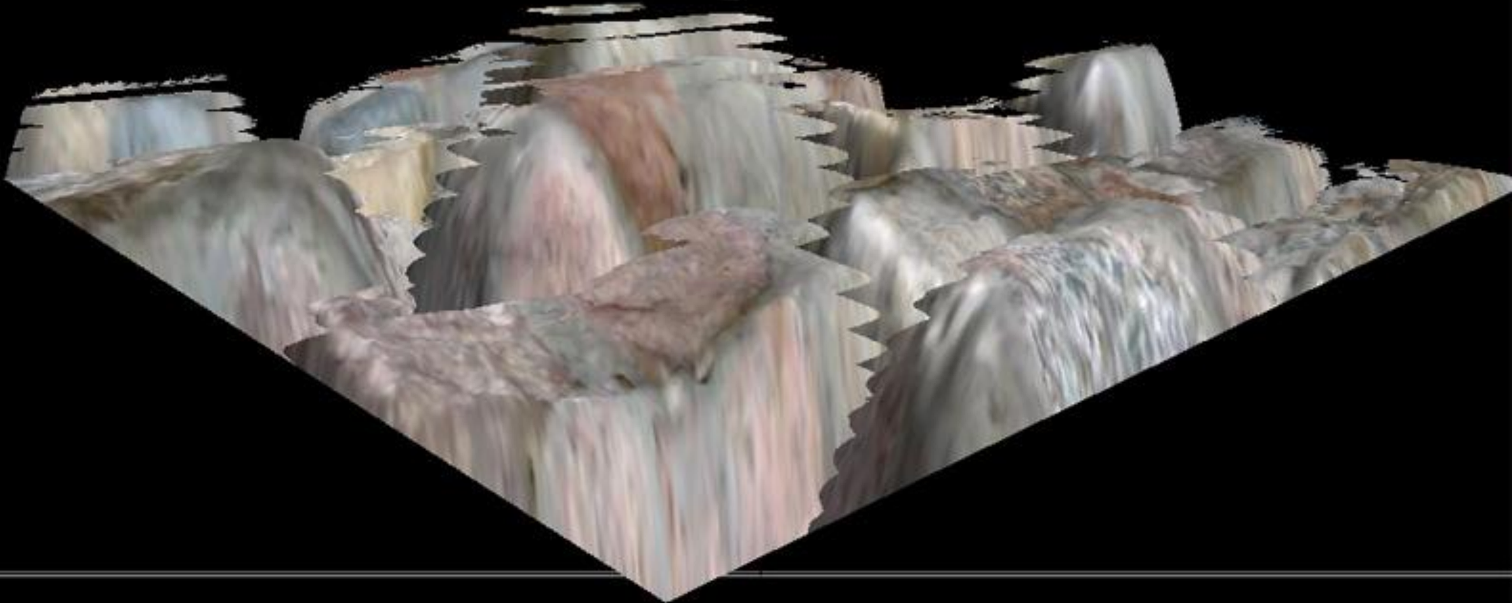
- Static number of iterations
- Performs search along last step vector
- Converges fast
- Utilizes linear filtering

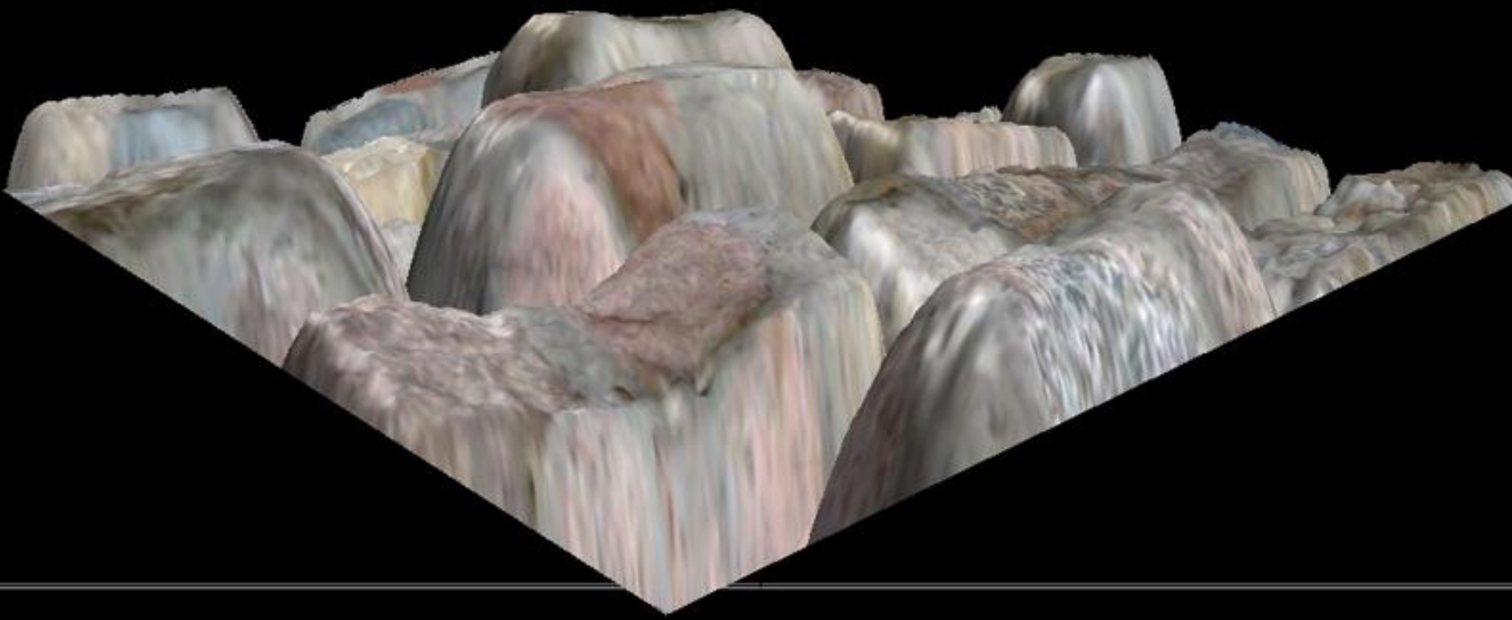
Binary Search

- Drawbacks
  - Utilizes dependant reads
    - Not optimized hardware
  - Slow
  - Adds GPR
  - May find wrong intersection due to linear search fault
    - On its own unusable

Binary search with static step length







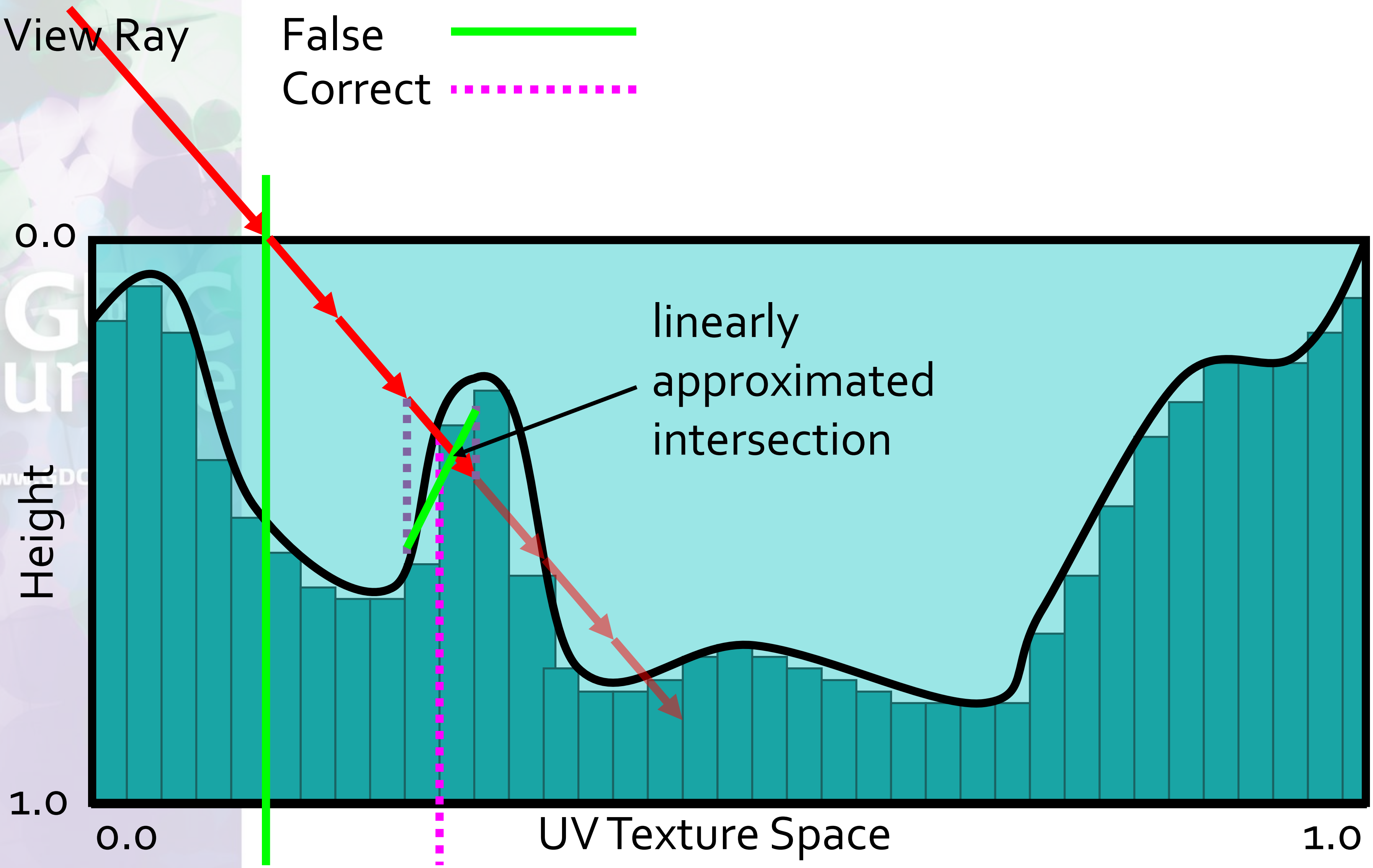
Parallax Occlusion Mapping

- POM (Tatarchuk 06)
  - Substitutes costly binary search by piecewise linear approximation using ALU
  - Adds several performance improvements to linear search
    - Dynamic iteration count
    - LOD system
    - Approximate soft shadows

Parallax Occlusion Mapping

- Pros
  - Faster than relief mapping
- Cons
  - Same as for linear search
  - Inaccurate intersection point resulting in missed features for the cost of less noticeable artifacts

POM


View Ray
False
Correct
0.0
1.0
Height
linearly
approximated
intersection
0.0
UV Texture Space
1.0

Preprocessed method

- Several methods rely on preprocessed data
  - Per-pixel Displacement with Distance Function
    - Using additional 3D textures rising memory footprint to much
    - Impractical
  - Cone Step Mapping
  - Relaxed Cone Step Mapping

Cone Step Mapping

- CSM (Dummer 2006)
  - Based on Cone Maps
    - Associate circular cone to each texel of height field
    - Per-texel cone is the largest cone, not intersecting the height field
  - Performs linear search with step length determined by actual cone radius
    - Leaps empty space
  - Conservative approach
    - Allows accurate intersection computation
  - Requires additional uncompressed 1x8bit texture for cone angles

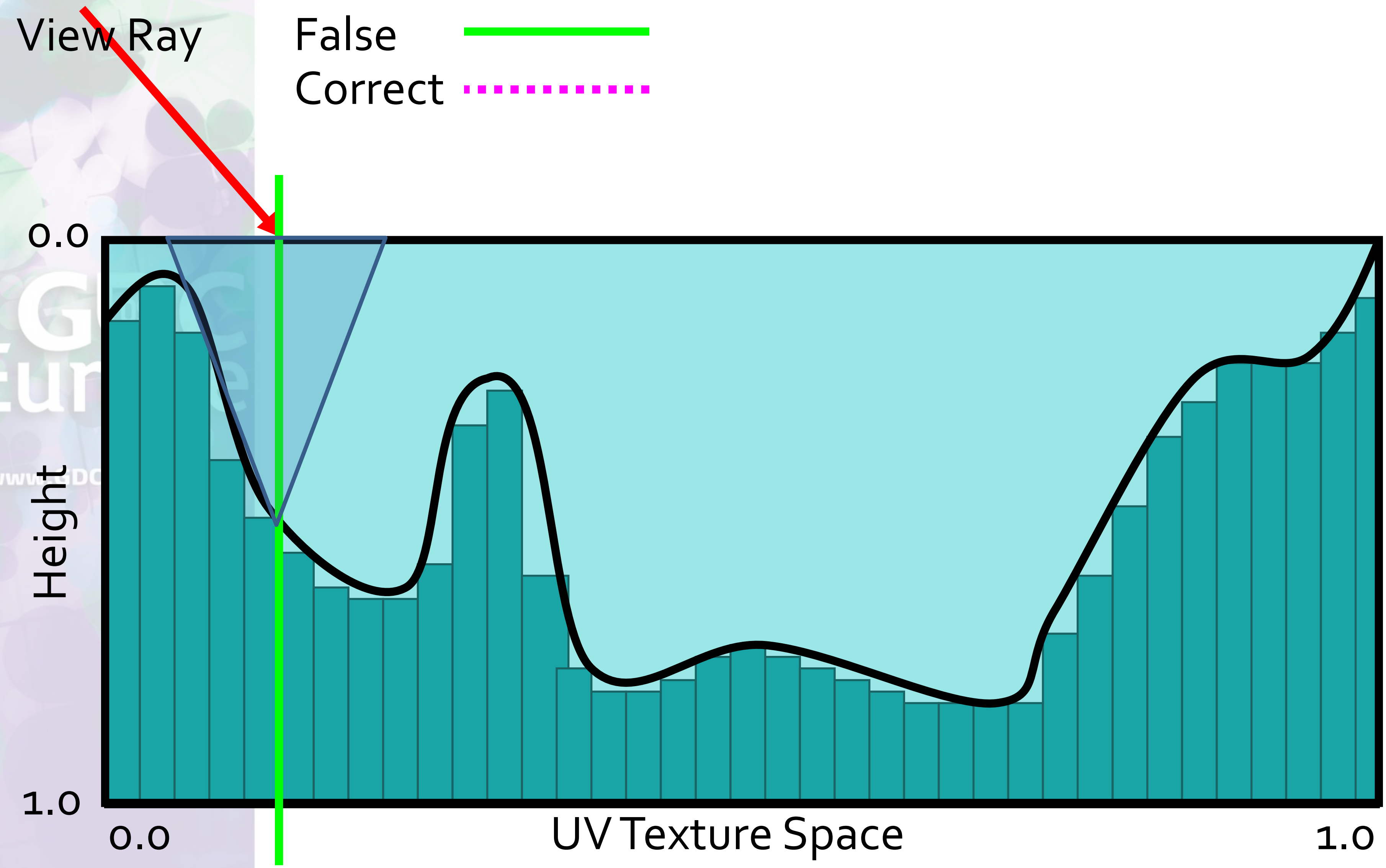
Cone Step Mapping

- Pros
  - Very fast
    - Requires significantly smaller number of iterations than pure linear methods
    - Under-sampling provides distortions artifact, less noticeable than interleaving
  - Accurate
    - There is no possibility to miss a feature

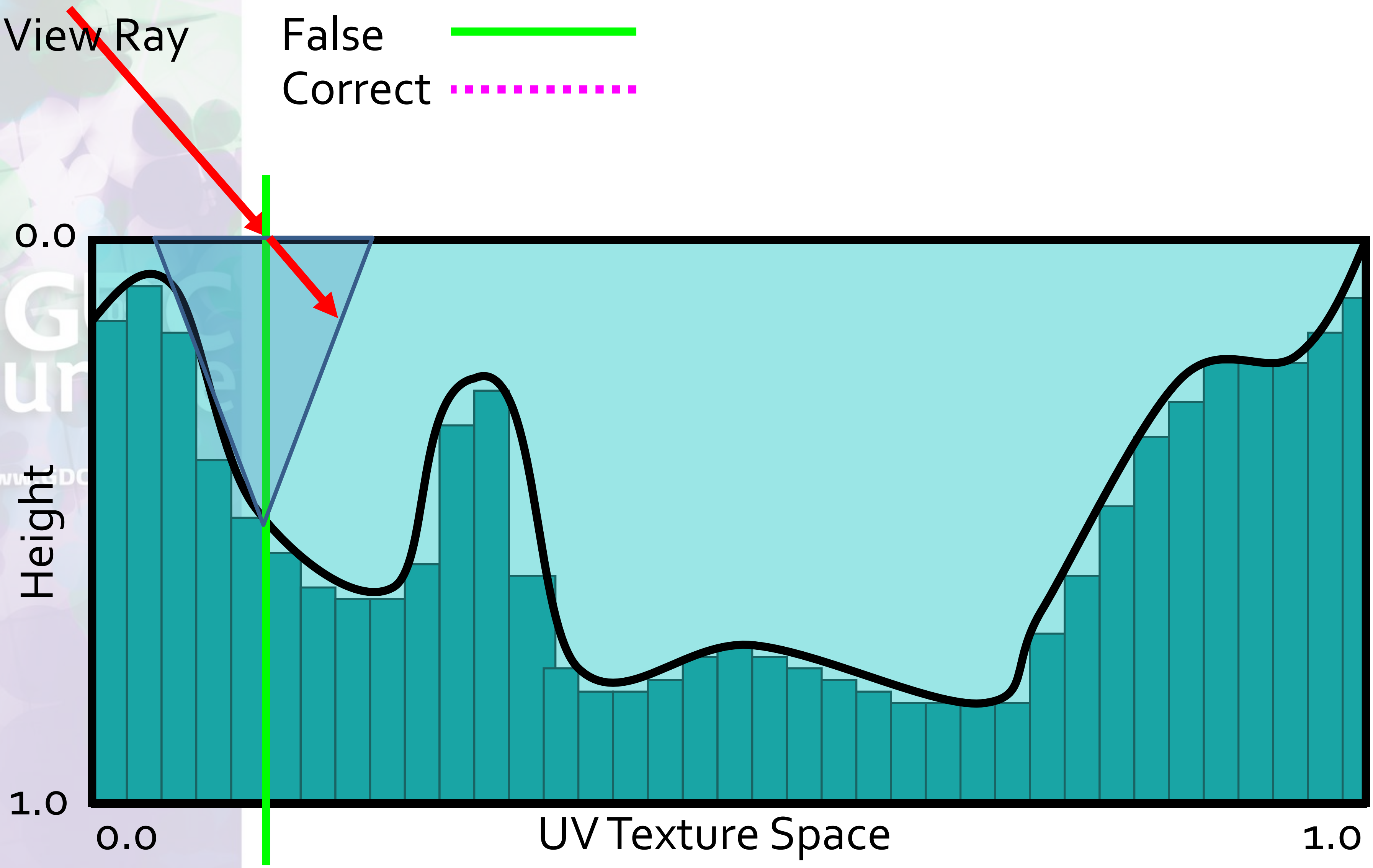
Cone Step Mapping

- Cons
  - May not converge in reasonable number of steps
    - Needs iteration cap
  - Performance highly dependant on height field complexity
  - Horrendous preprocessing time
    - 256^2 - ~2 min
    - 512^2 - ~14 min
    - 1024^2 - ~7.5 h
  - Effectively impractical for interactive artist tweaking or on-the-fly generation

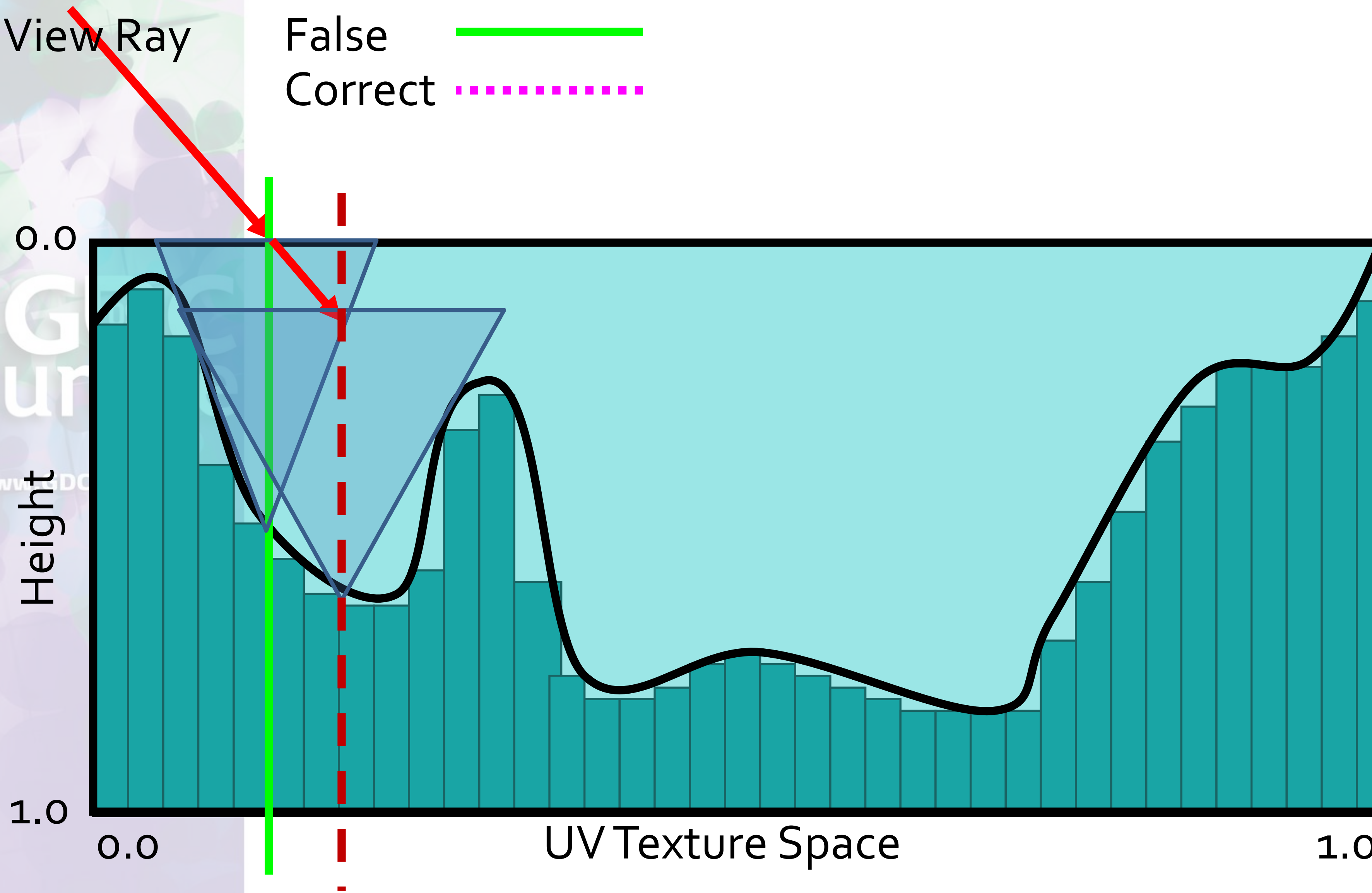
CSM



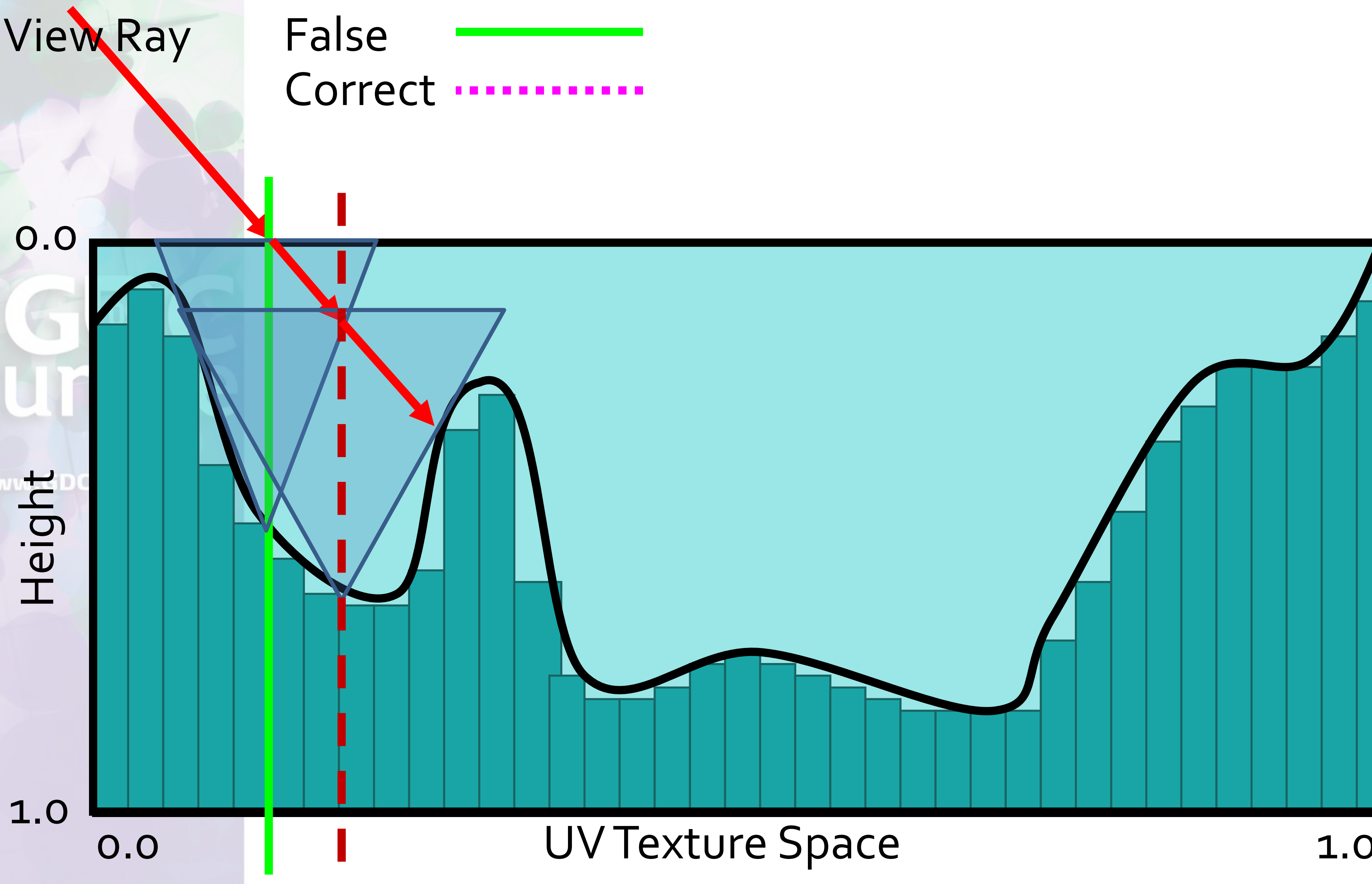
CSM



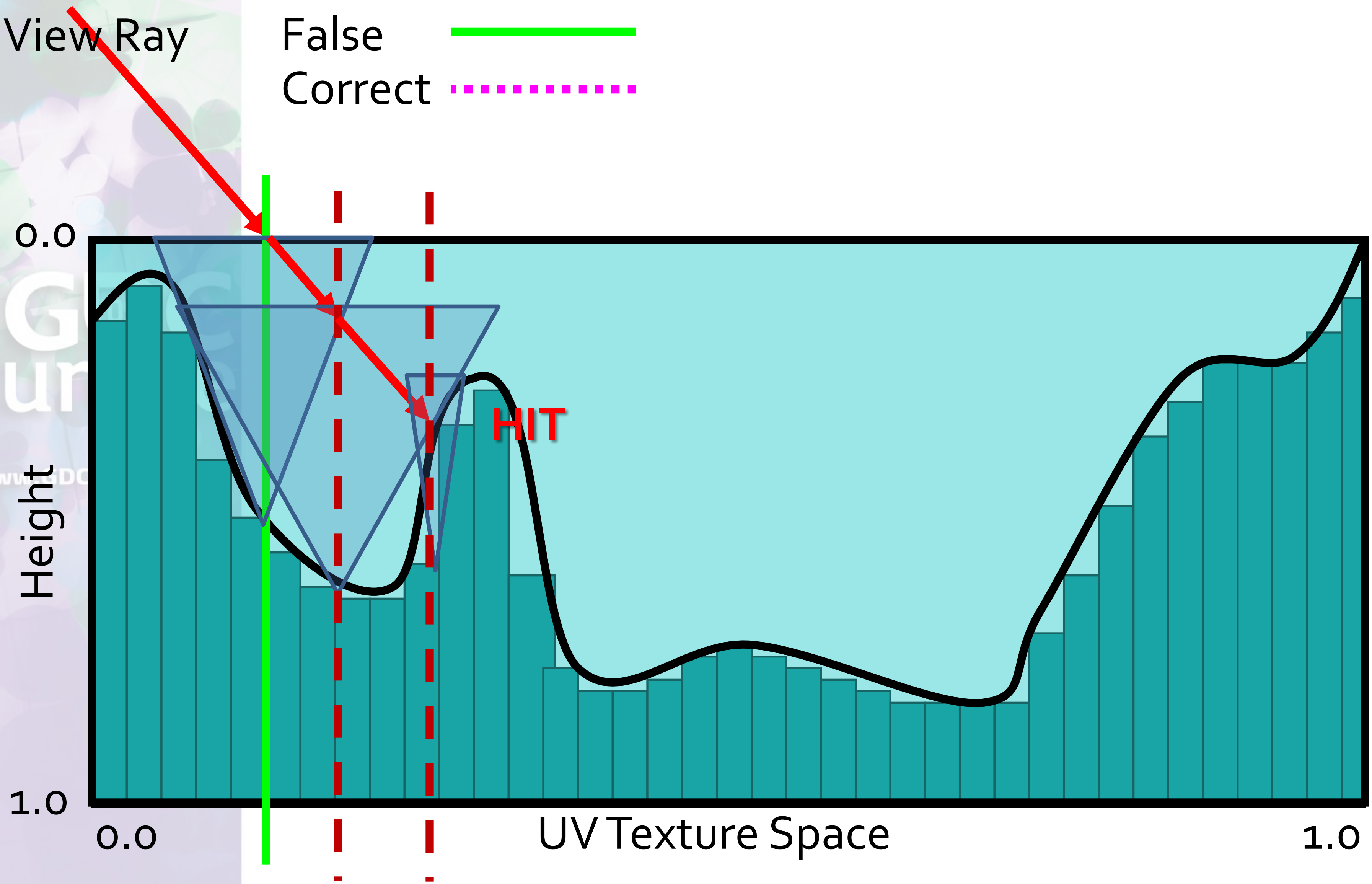
CSM



CSM



CSM

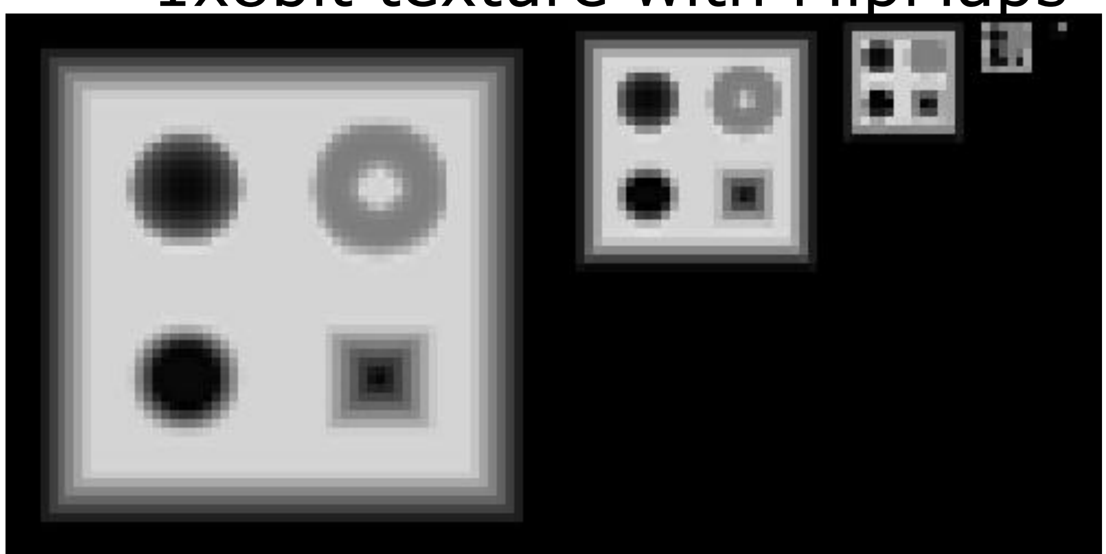

View Ray
False
Correct
0.0
1.0
Height
HIT
0.0
UV Texture Space
1.0

Quadtree Displacement Mapping

- QDM
  - GPU optimized version of classic terrain rendering, hierarchical ray traycing algorithm [Cohen ans Sake 1993]
  - uses mipmap structure resembling a dense quadtree storing minimum depth to the base plane of height field

Quadtree Structure

- Simple construction
  - Mipmapping with min operator instead of average
- Hardware optimized
- Small memory footprint
  - 1x8bit texture with MipMaps



Quadtree Structure

- Quadtree can be generated on-the-fly
  - Negligible performance loss

GF 8800	256^2	512^2	1024^2	2048^2
Quadtree	0.15ms	0.25ms	1.15ms	2.09ms
CSM	< 2min	<14 min	<8h	/

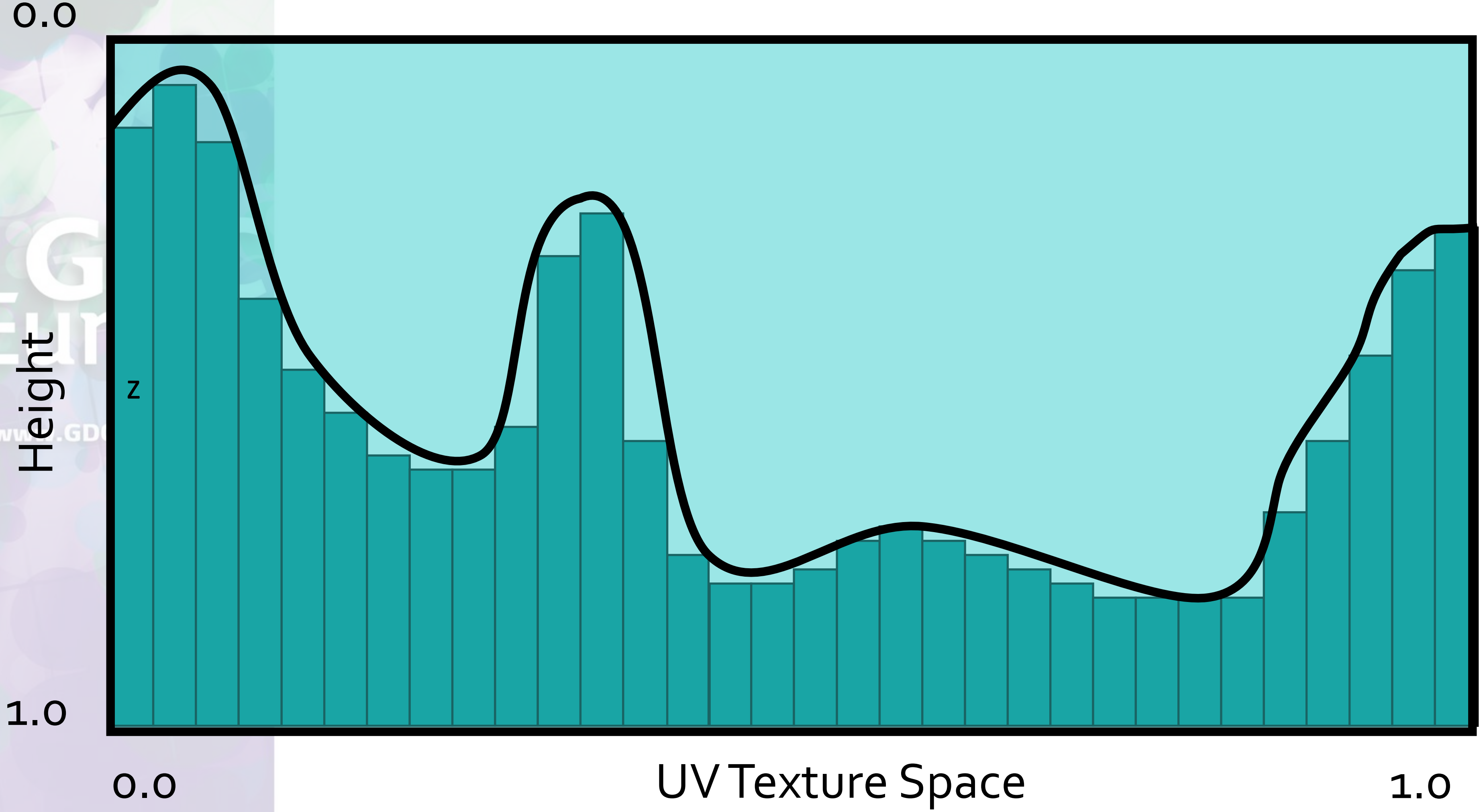
QDM

- Ray tracing
  - Traverse the quadtree
    - From root (max MIP-hierarchy level)
    - To lowest leaf (MIP-hierarchy Level 0)
  - MIP Level 0
    - Accurate intersection
    - Can get inter-texel results using
      - Linear approximation
      - Binary Search
      - Bilinear Patch

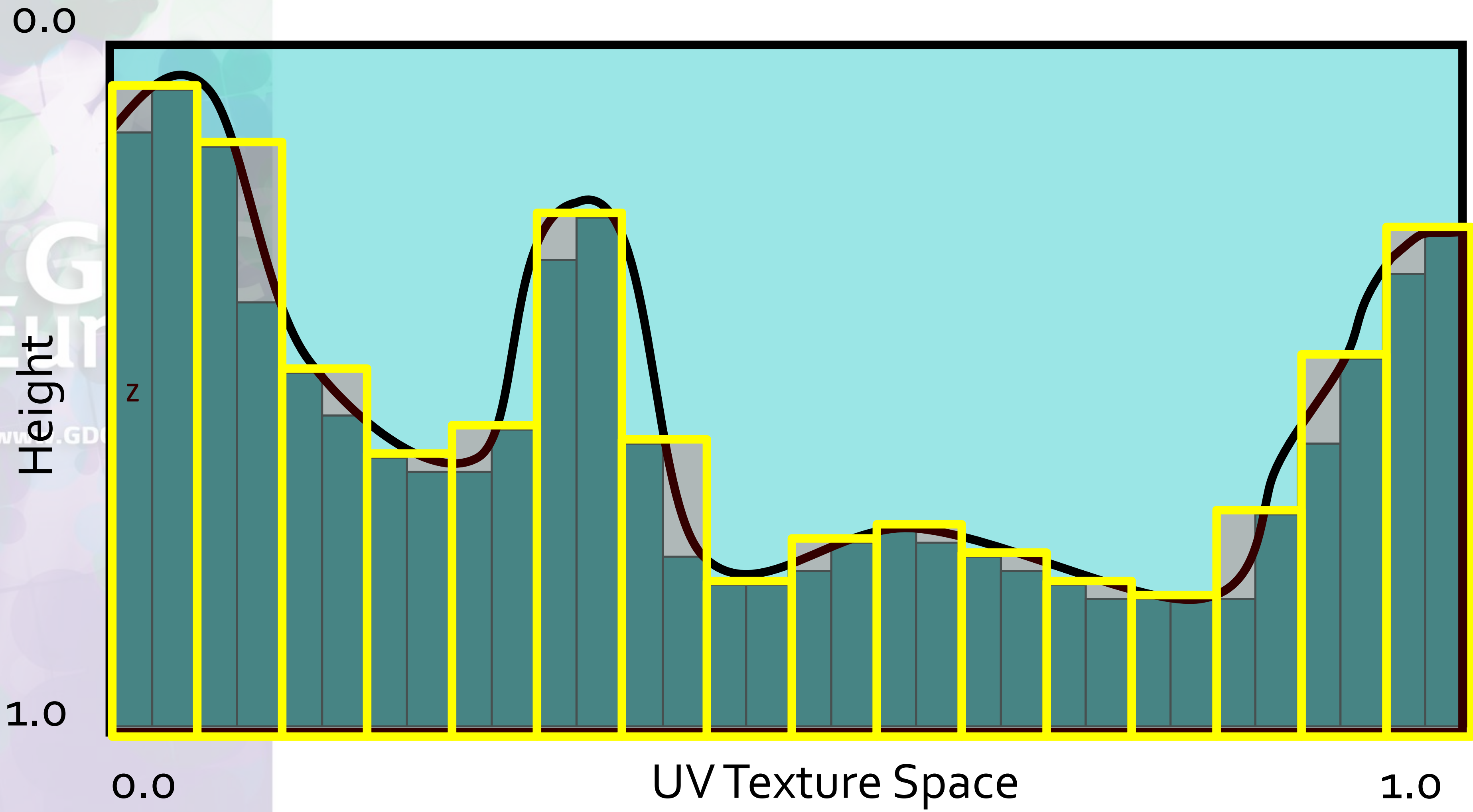
Ray tracing

- While(Hierarchy_Level > 0)
  - Depth =getMaxDepth(Pos,Level)
  - If(Ray_Depth < Depth)
    - Move_Ray_To_Nearest_Intersection
  - Else
    - Descend_One_Hierarchy_Level
- Find_Accurate_Intersection

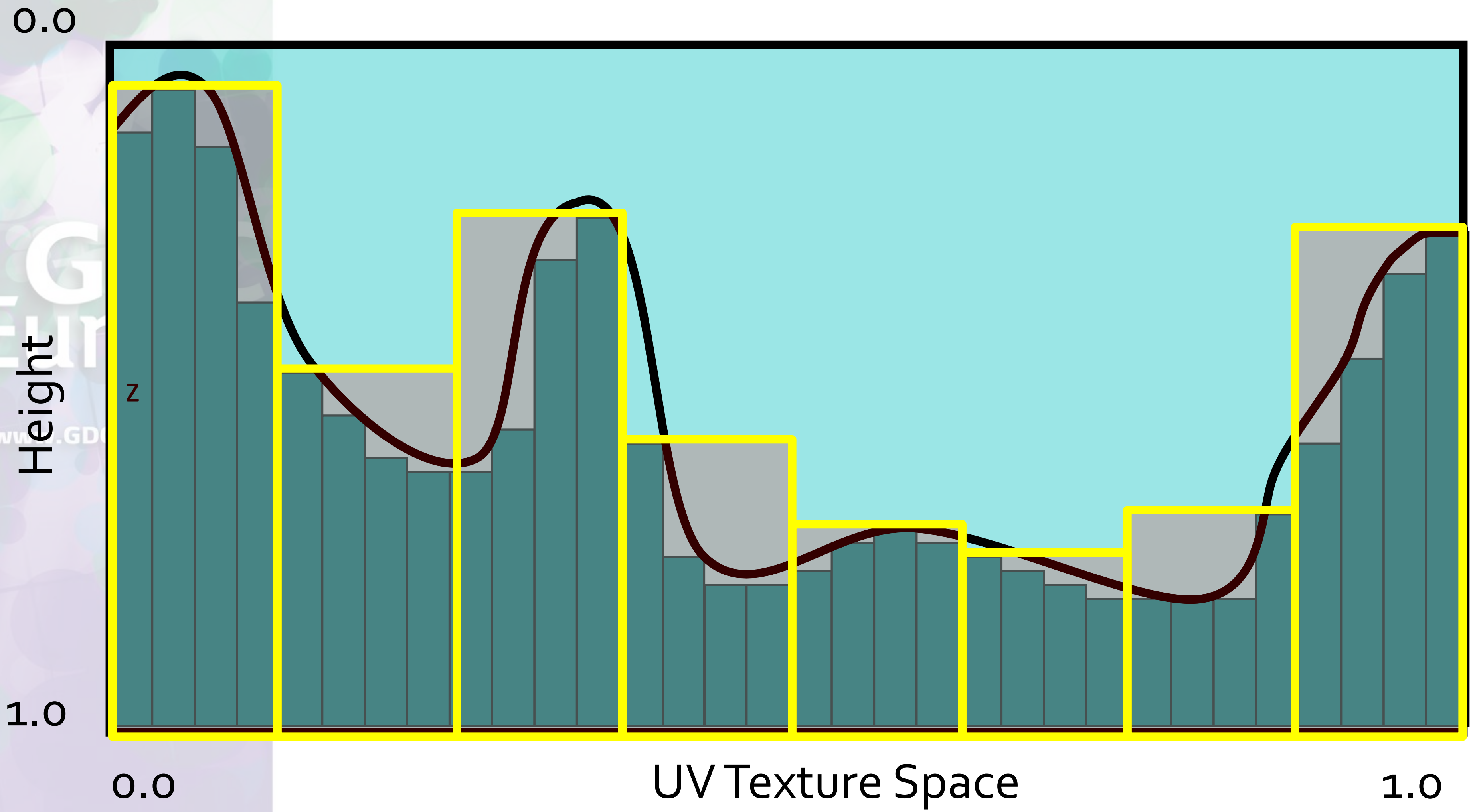
QDM construction



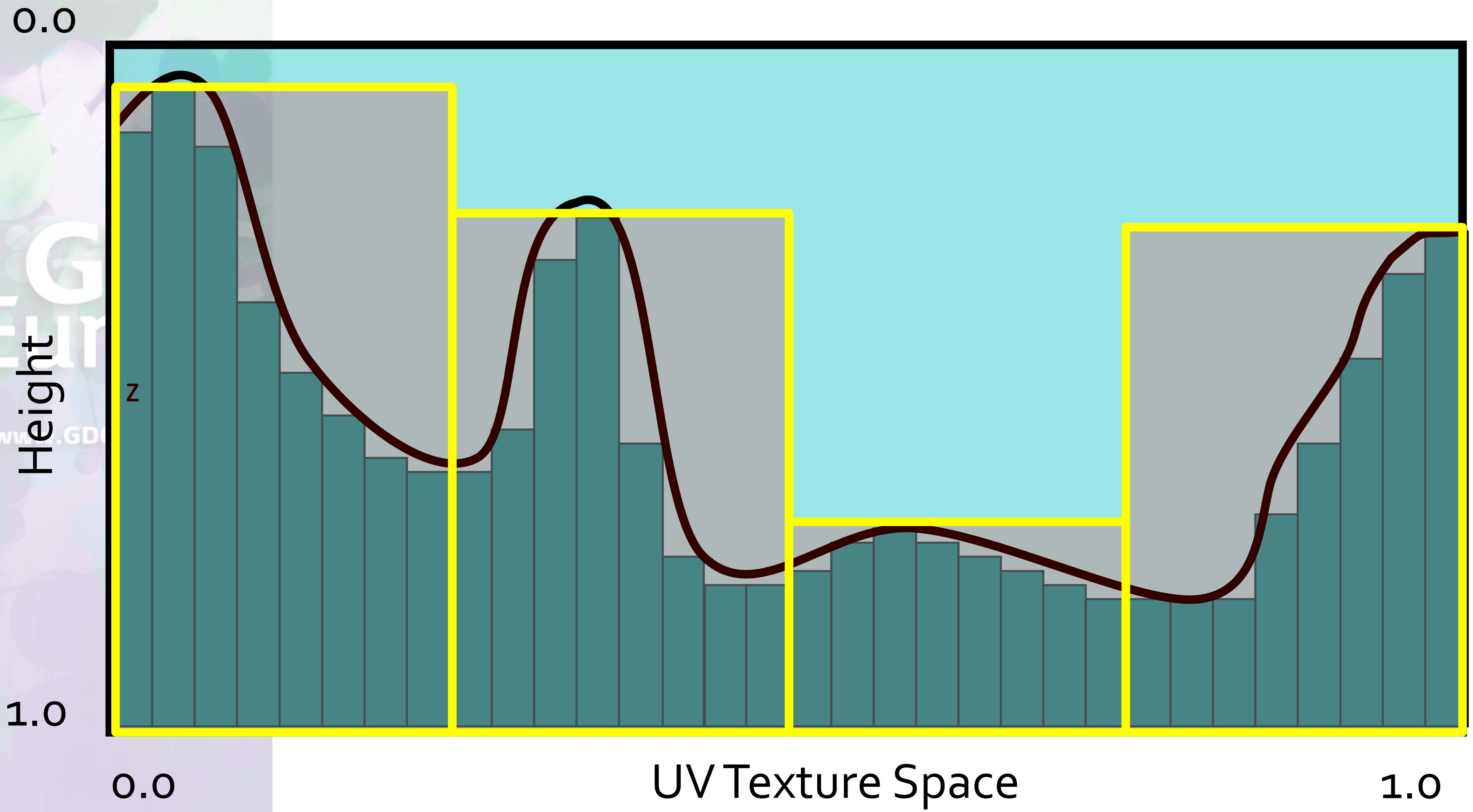
QDM construction



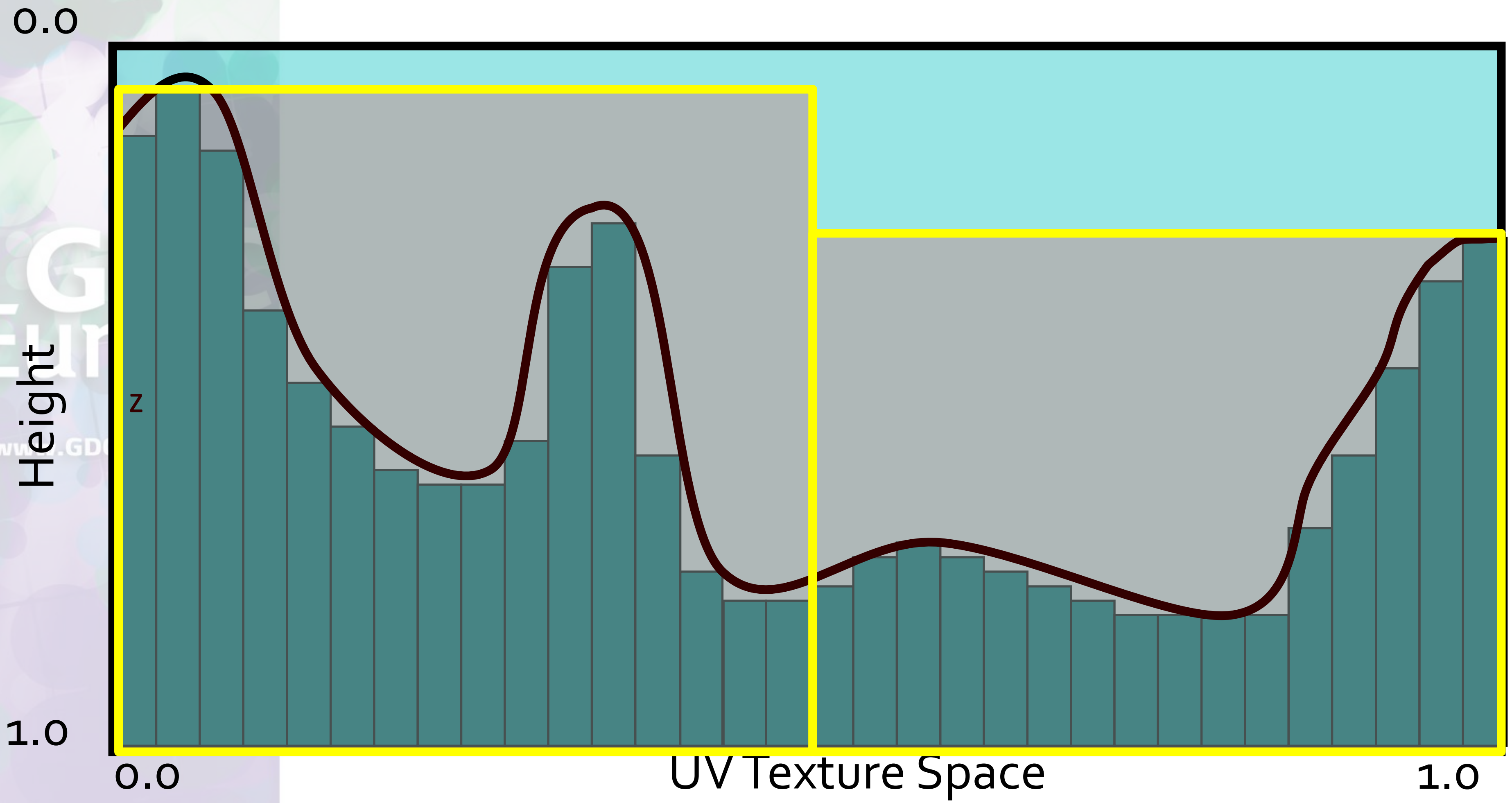
QDM construction



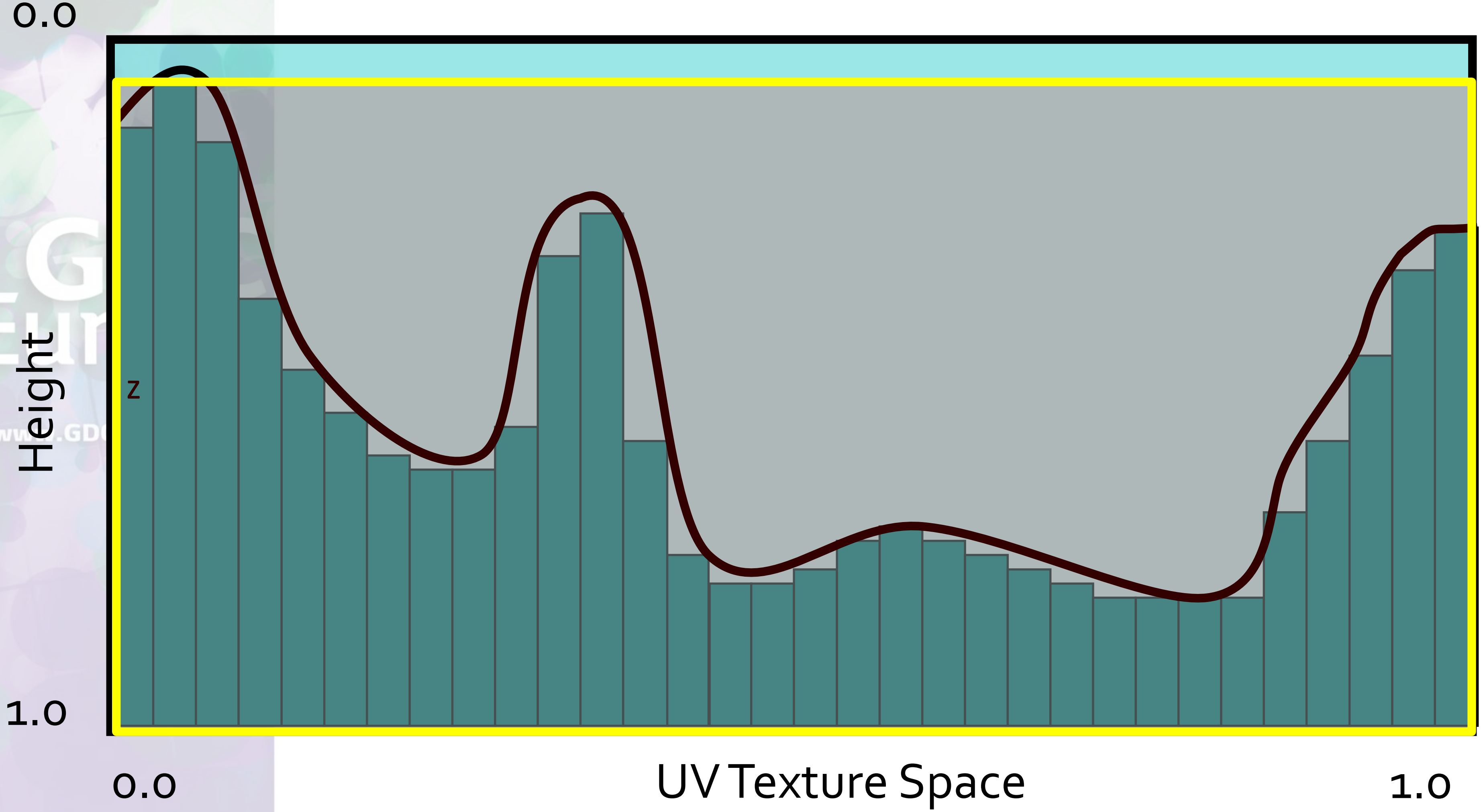
QDM construction



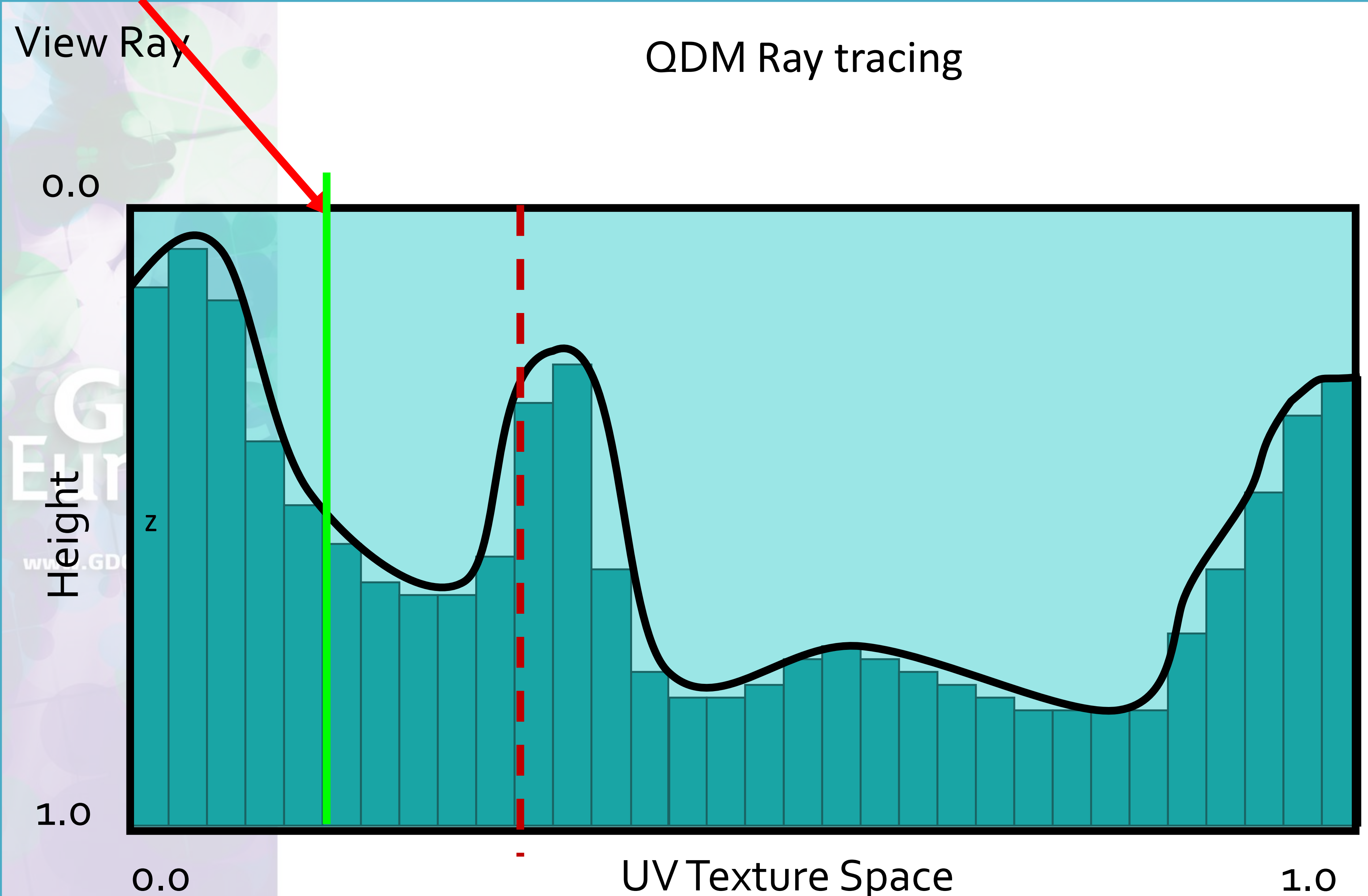
QDM construction



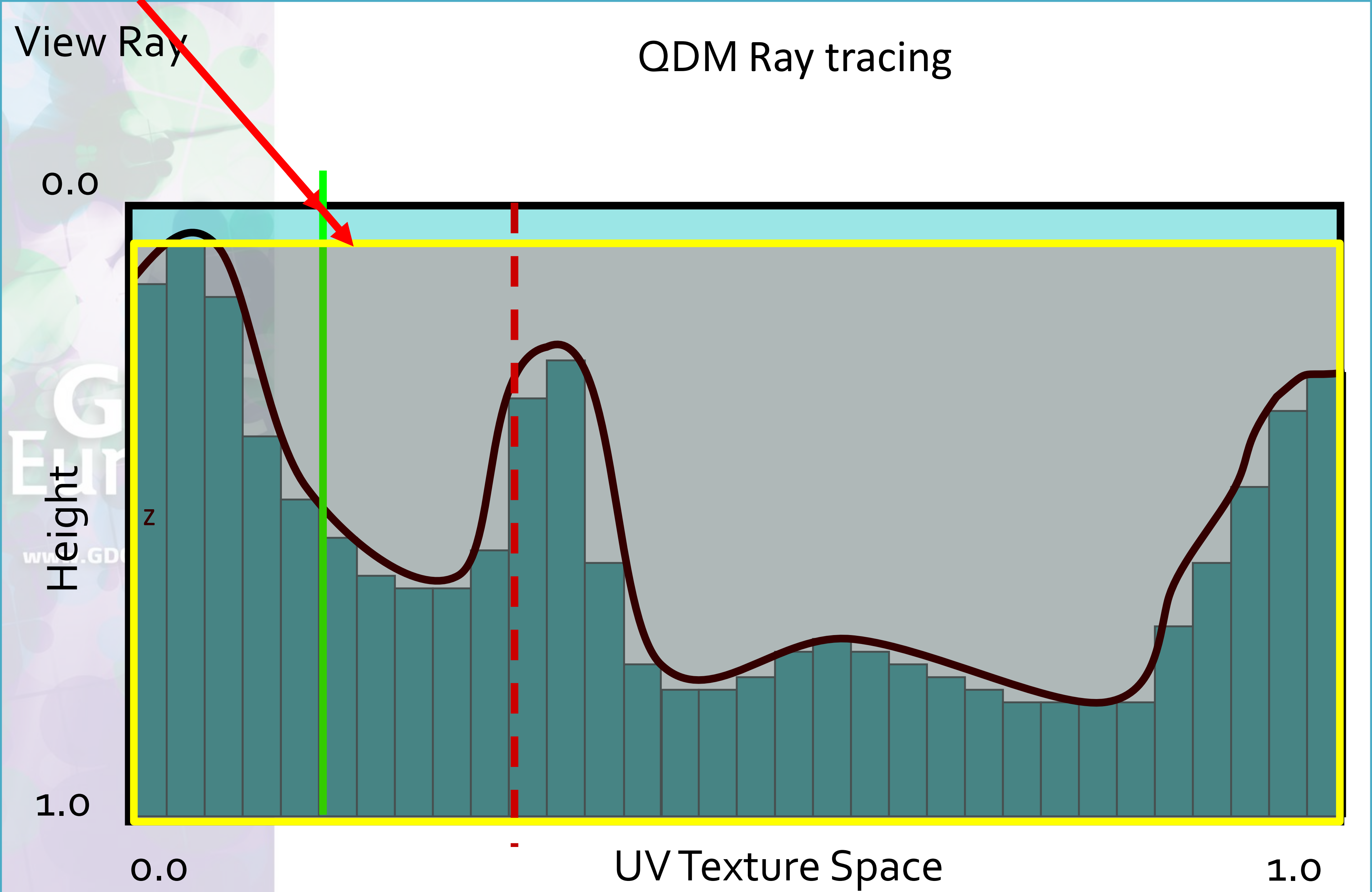
QDM construction



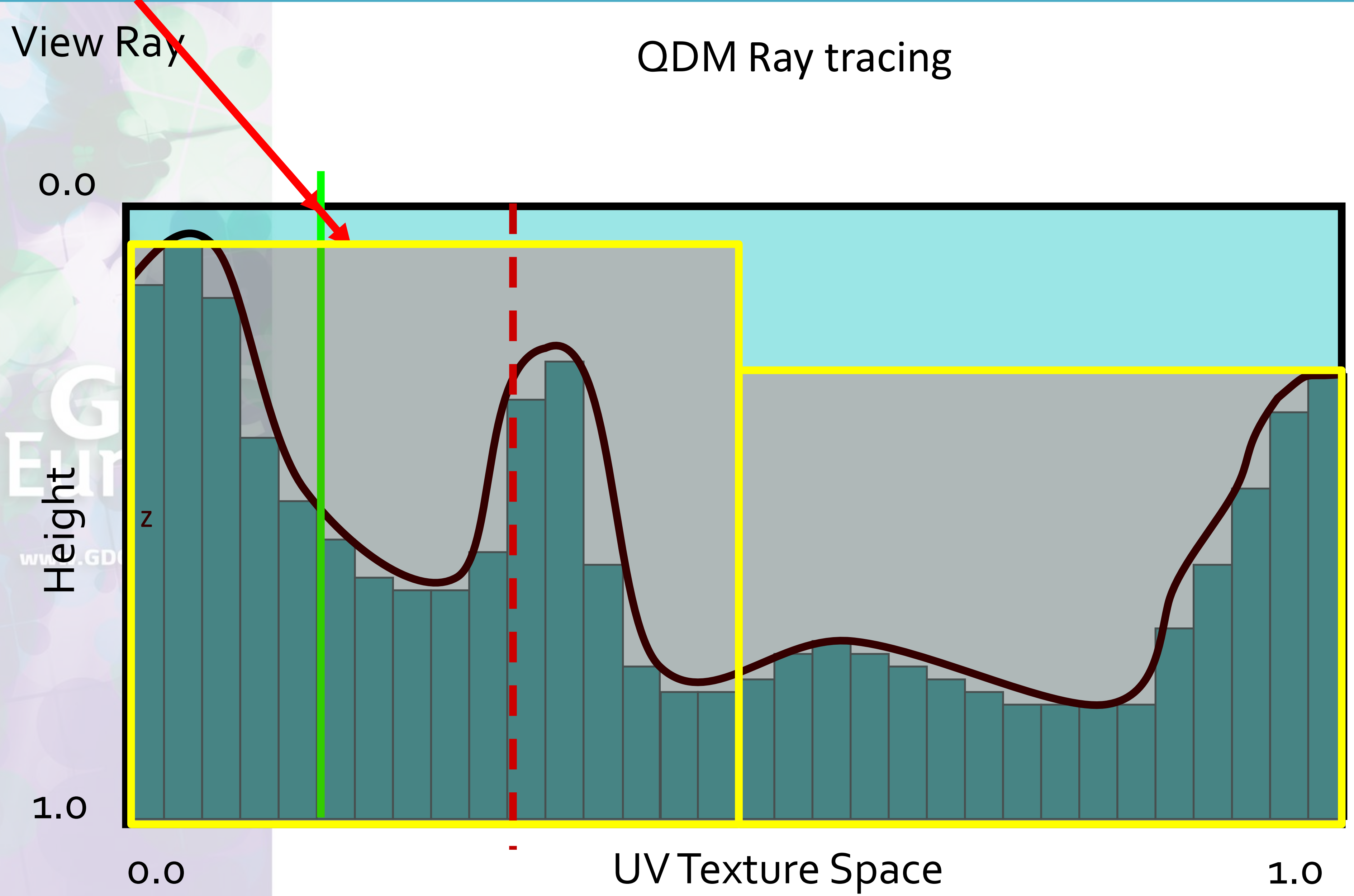
QDM Ray tracing

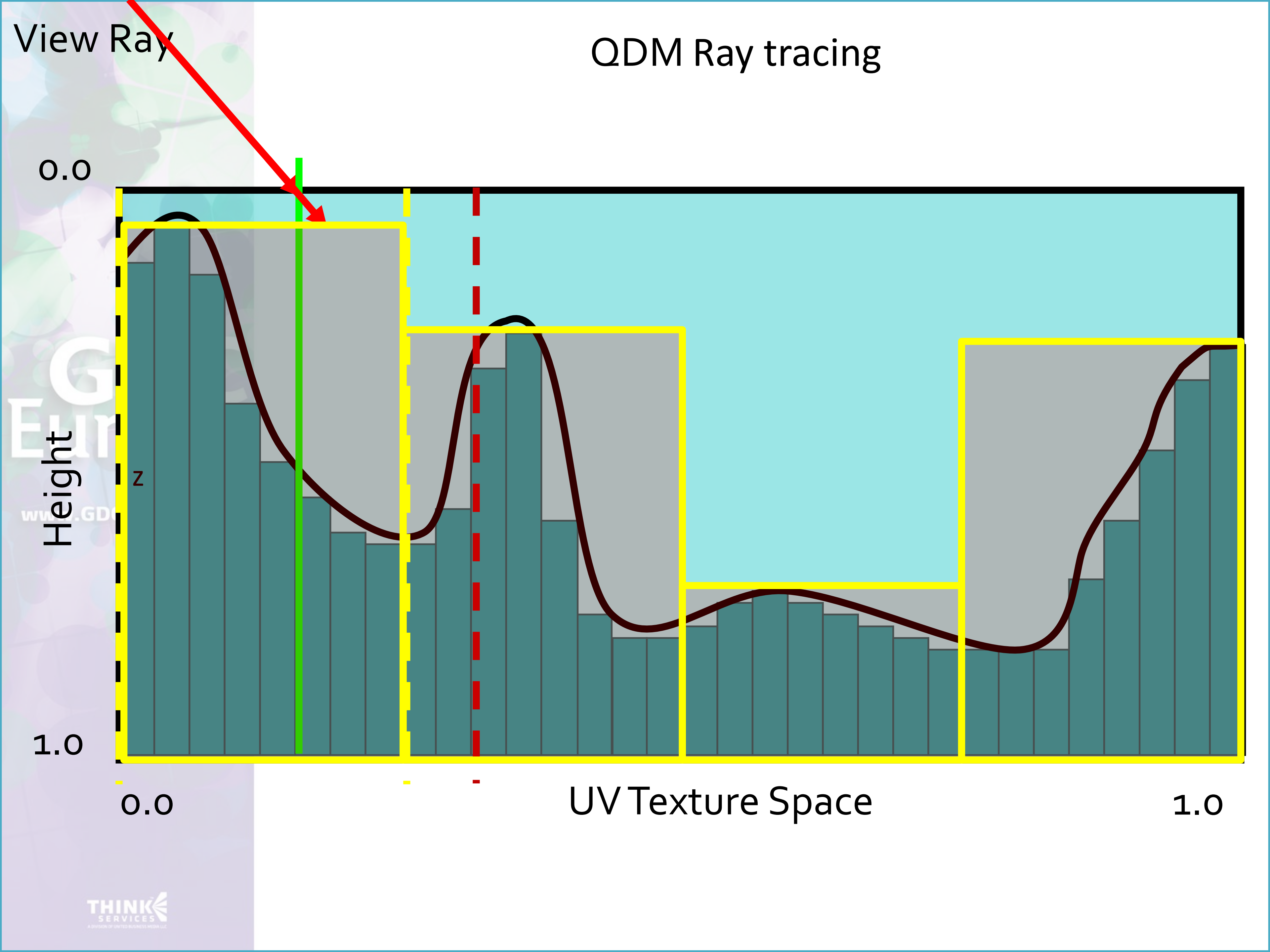


QDM Ray tracing

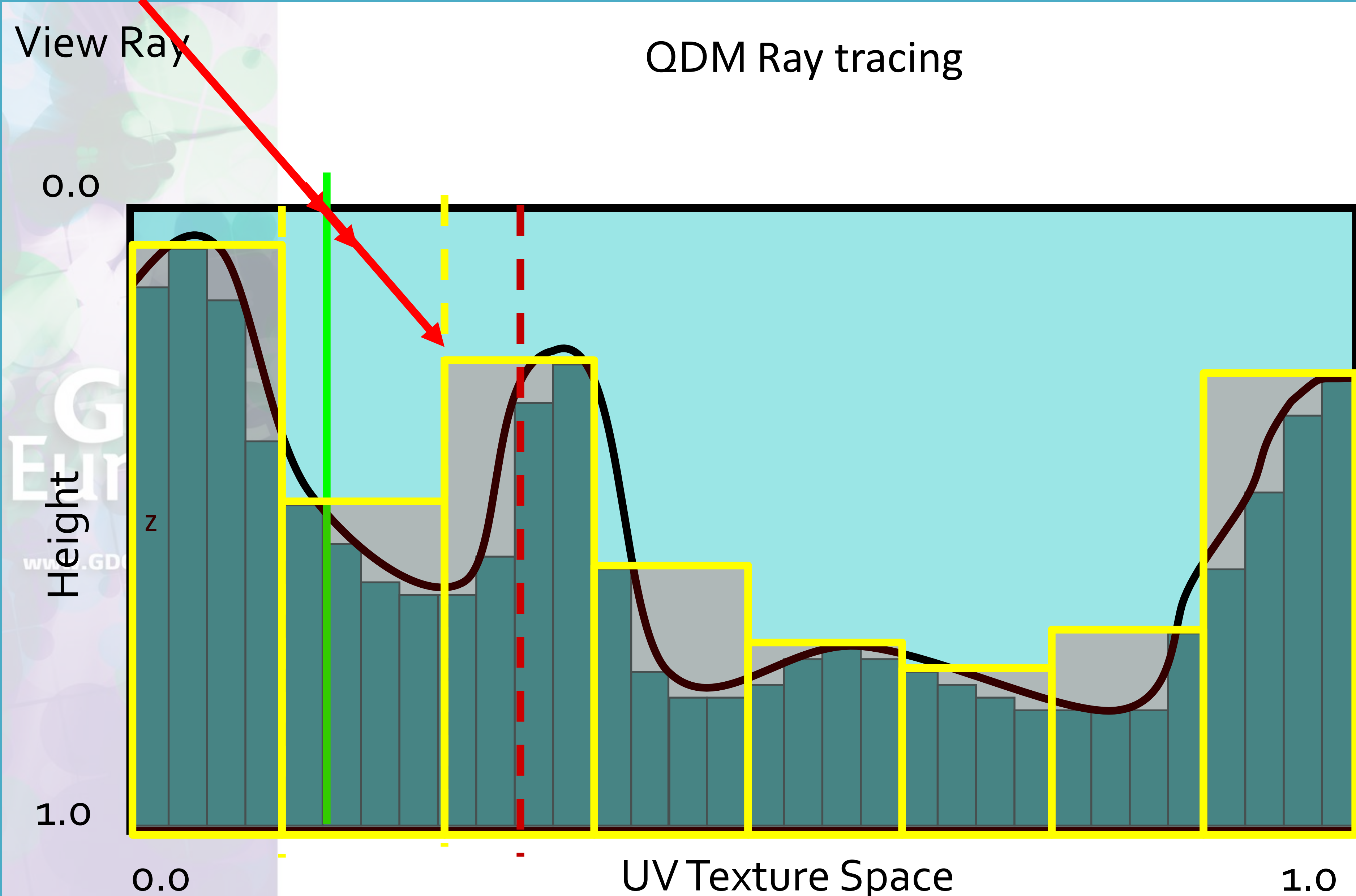


QDM Ray tracing

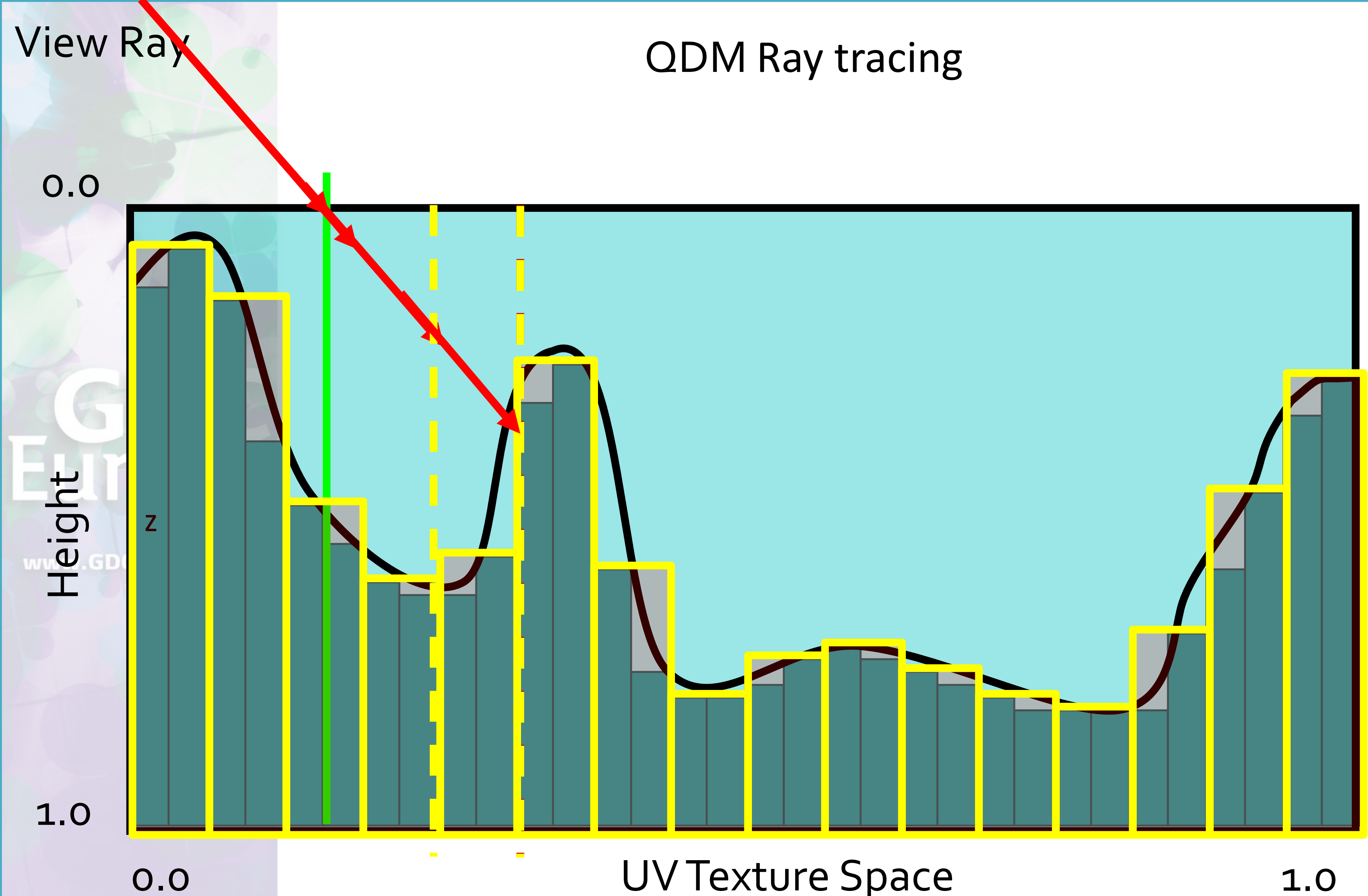



View Ray
QDM Ray tracing
0.0
z
Height
1.0
0.0
UV Texture Space
1.0

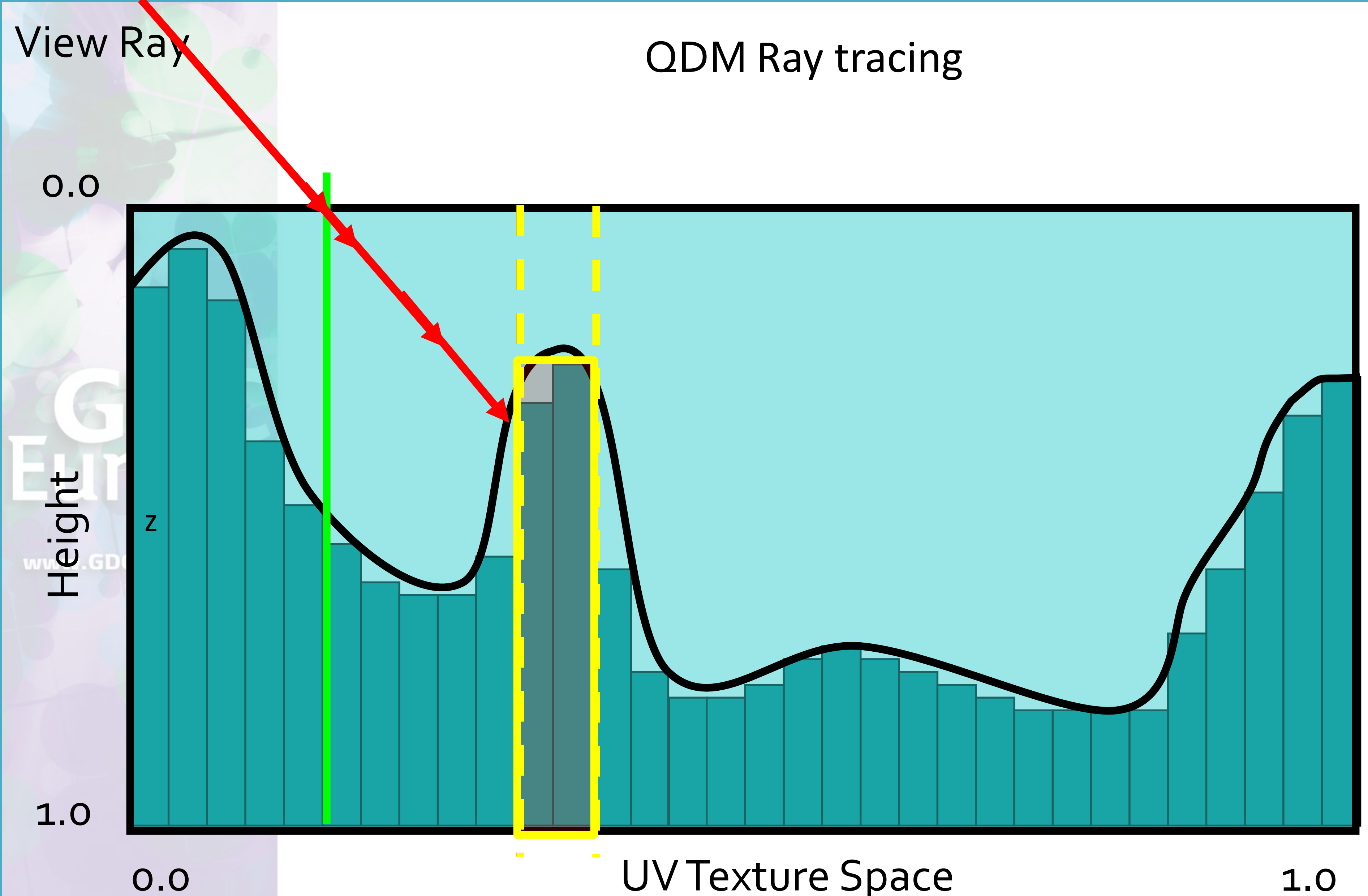
QDM Ray tracing



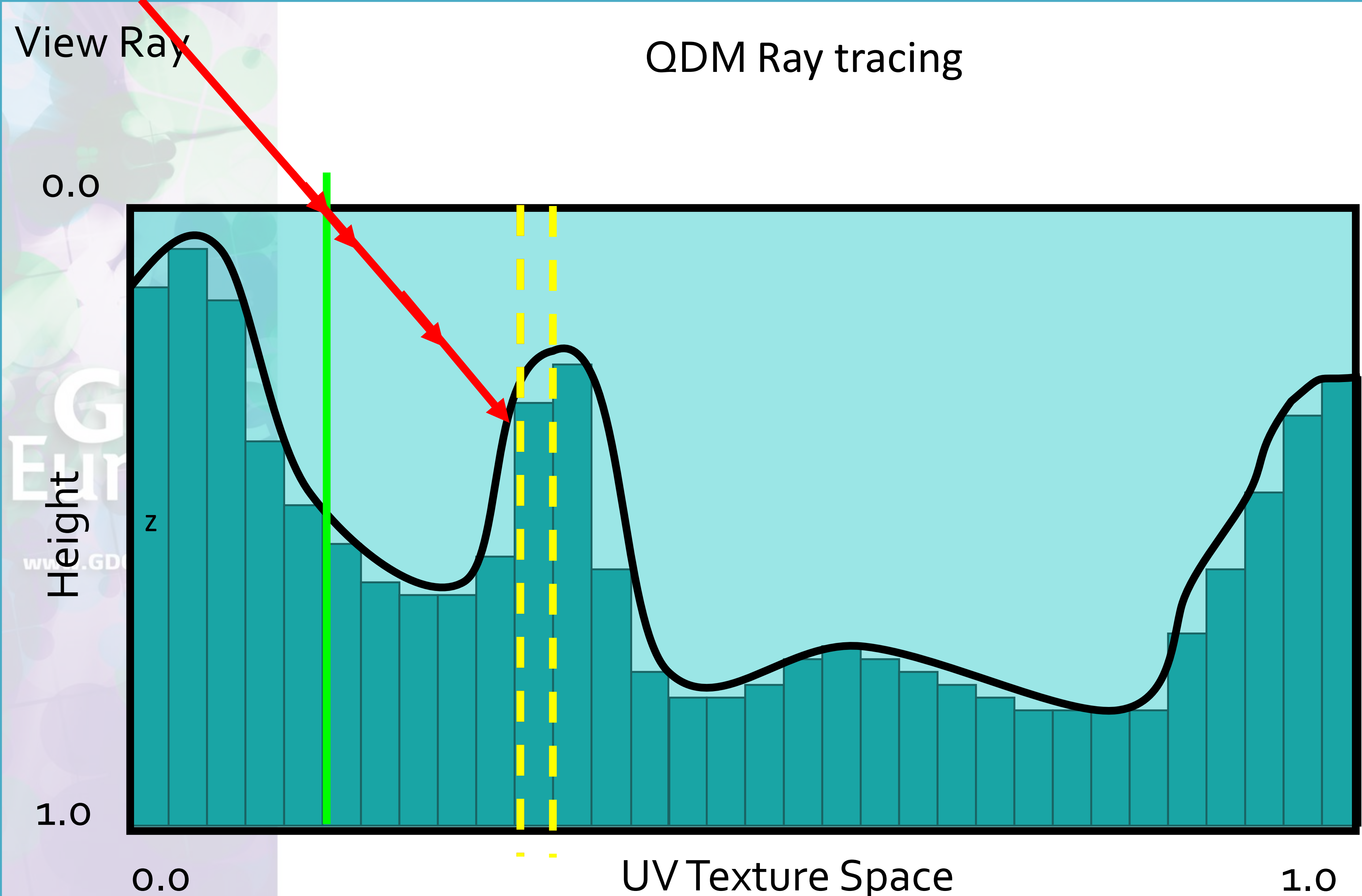
QDM Ray tracing



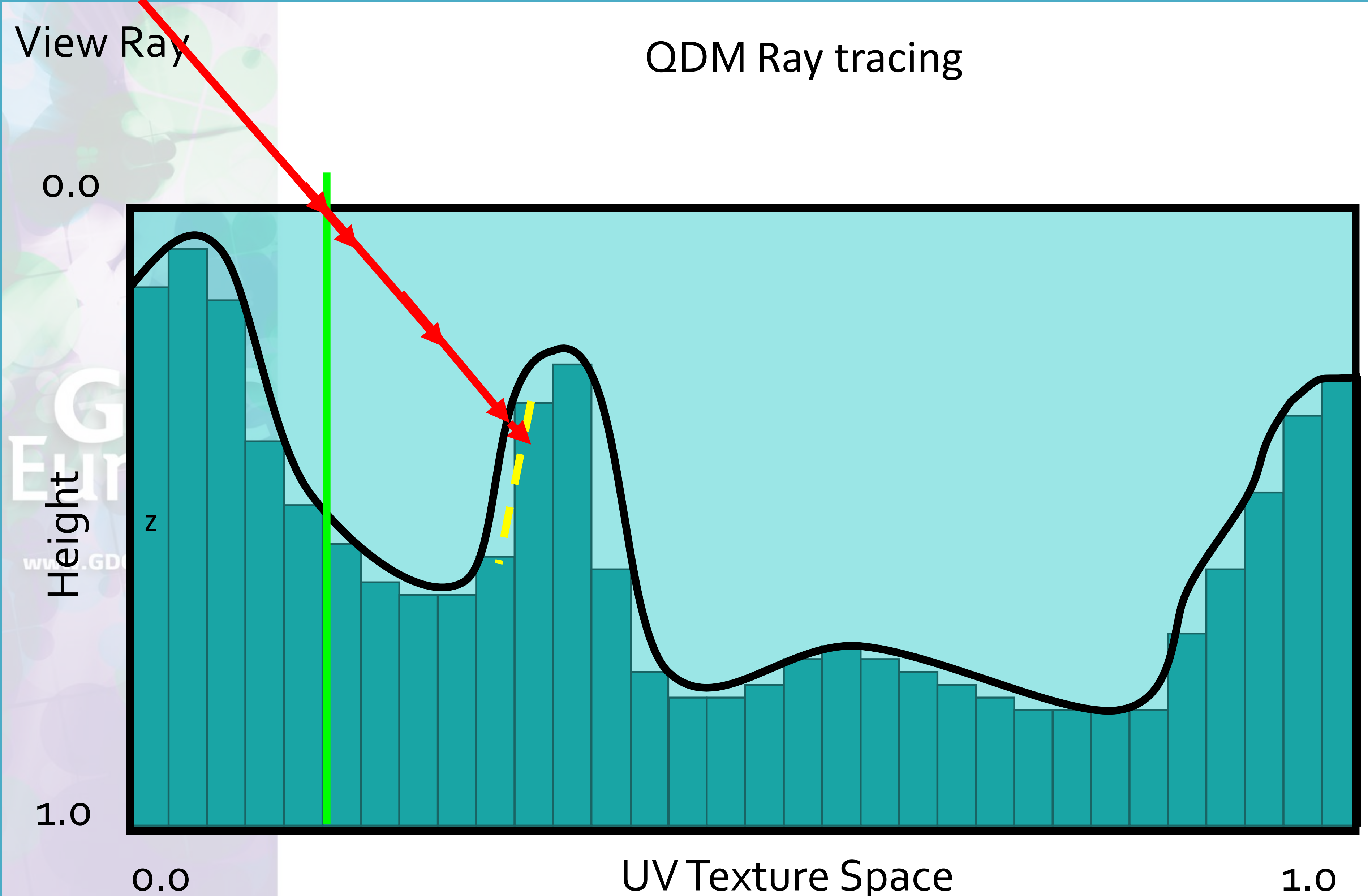
QDM Ray tracing



QDM Ray tracing



QDM Ray tracing



QDM Ray tracing

- Algebraically perform intersection test between Ray, Cell boundary and minimum depth plane
  - Compute the nearest intersection and move the ray
  - In case of cell crossing choose the nearest one
- Ray is traversing through discrete data set
  - We must use integer math for correct ray position calculation
    - SM 4.0 – accurate and fast
    - SM 3.0 – emulation and slower
  - Point Filtering
    - LinearMipMapLinear is possible but may introduce some artifacts
      - Trade samplers for artifacts
      - i.e. when using same texture for normal and depth storage

QDM Ray tracing

- Refinement
  - LEVEL 0 yields POINT discrete results
  - Depending on surface magnification and need for inter-texel accuracy additional refinement method may be used
    - Binary Search
      - Usable for non linear surfaces
    - Linear piecewise approximation
      - Fast
      - Accurate due to approximation between 2 texels only
    - Bilateral Patch
      - most accurate for analytic surfaces
      - Requires additional memory
      - slow

QDM Ray tracing

- Fixed iteration count
  - Complexity O(log(n))
    - Still may be prohibitive
  - Set maximum iteration count

QDM Ray tracing

- Method degeneration
  - Algorithm can’t go up in hierarchy
    - Typical scenario at feature edge
      - Ray reaches low level and passes by (cell crosses)
      - Further ray advances are at current or lower level – degenerates to linear search
  - Possible solutions
    - Compute the optimal level after cell cross – expensive, doesn’t suit GPU
    - Go one level up after node crossing
      - Simple and fast – works for most cases
  - Solution performance gain can be seen when using high iteration cap

QDM LOD

- LOD scheme
  - Can't use traditional MipMapping
  - Limit stop condition to LOD level computed from current MIP level
    - High performance gain
    - Small feature fidelity loss at grazing angles
      - Mostly unnoticeable
  - Dynamically adjust iteration cap
    - Linear function of angle between geometric normal and viewing vector
  - Fade QDM depth scale (0 = normal mapping only) by linear function of camera space Z

QDM Storage

- QDM is a discrete data set
  - Needs accuracy
    - Uncompressed textures preferable
      - 1x8BIT uncompressed texture
  - With accurate integer math possible to use compressed data
    - DXT5 alpha interpolation – bearable
      - May exhibit small artifacts at feature edges depending on height field profile

QDM

- Pros
  - Accurate under any circumstances
  - Fast and scalable
    - Faster than any online solution for high depth scale and high resolution height fields (>512^2 worth consideration)
  - Negligible additional memory footprint
  - Negligible preprocessing time
  - Trades iteration count for calculation quality
    - High ALU:TEX rate
      - Good for upcoming GPU
      - Not that great for current generation…
  - Other benefits of using quadtree data…

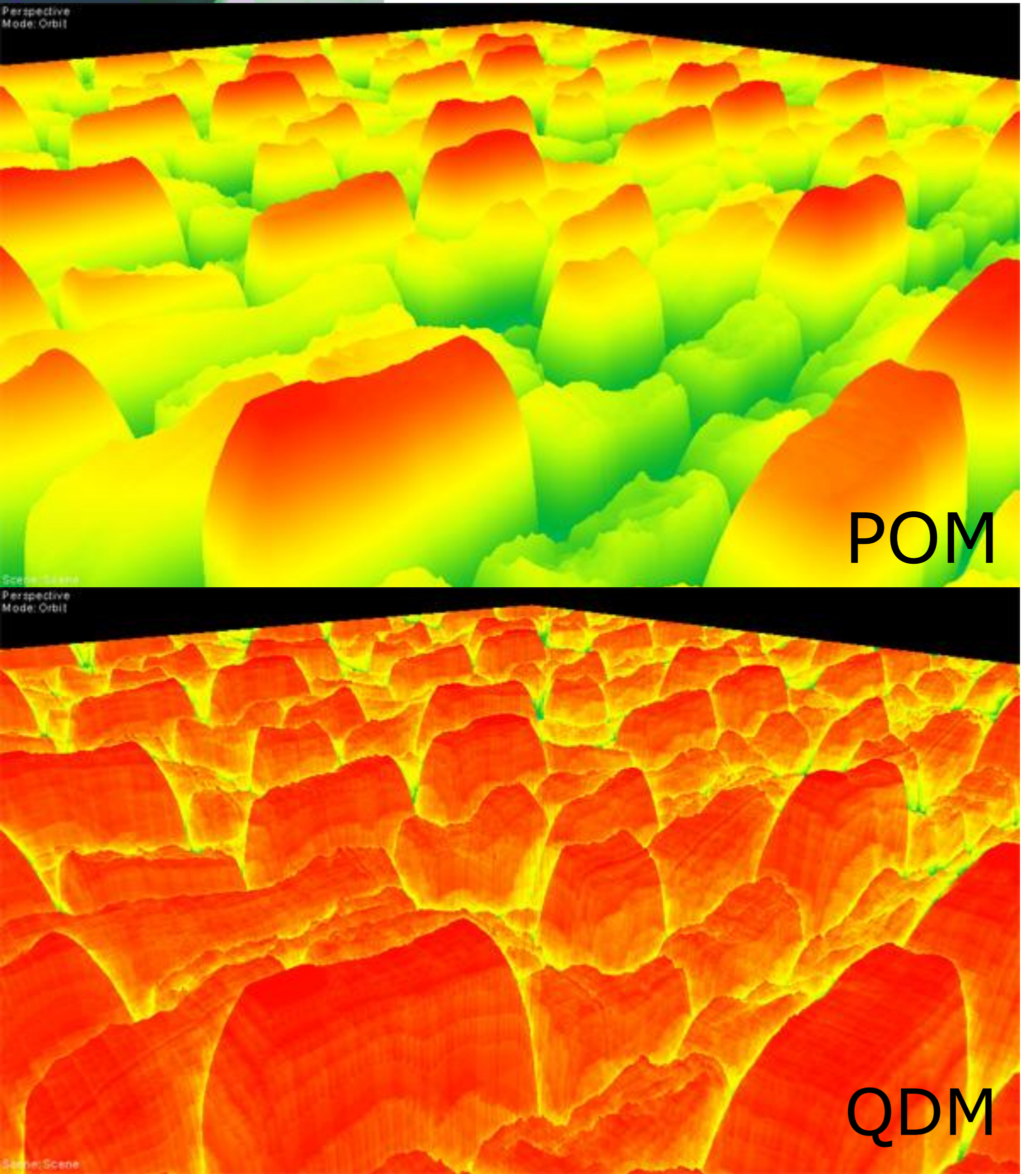
QDM

- Cons
  - Slow per iteration
  - Uses tex2Lod with random access
    - Incredibly slow on current GPUs
      - High cache miss ratio
      - 30% increase in sampling performance due to 3D texture usage
        - However impractical for memory reasons
  - Not that fast for small depth scale and small resolutions

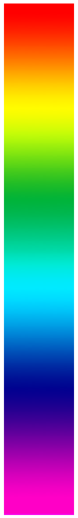
Comparison

- Analytical performance
  - Relief Mapping ~ sqrt(n)
  - CSM <= sqrt(n)
  - QDM ~ log(n)

Comparison



- Convergence (iteration count)



Comparison

- Following comparisons shows accuracy and performance difference between POM and QDM in real game scenario of Two Worlds 2
- CSM and RCSM were thought to be impractical for production due to preprocessing time
  - We assume RCSM being the fastest possible method for height fields < 1024^2
  - RCSM results come from test framework, where it outperformed every other solution by at least 50%
  - Several cases exist where due to height field complexity RCSM is unusable
  - We didn’t test for >1024^2
    - Life is too short ;)

Comparison

- Average Scene Results – full screen effect (Full HD) on GeForce 260 GTX
  - Iteration count set for non artifact rendering
    - Even at grazing angles
  - Various height fields of resolution 512^2 – 1024^2
  - Timing given = technique time – normal mapping time

Depth Scale	POM	QDM
1.0	5ms	5.66ms
1.5	6.66ms	6.7ms
5.0	18.87ms	9ms

POM Depth Scale 1.0

QDM Depth Scale 1.0

POM Depth Scale 1.5

QDM Depth Scale 1.5

POM Depth Scale 5.0

QDM Depth Scale 5.0

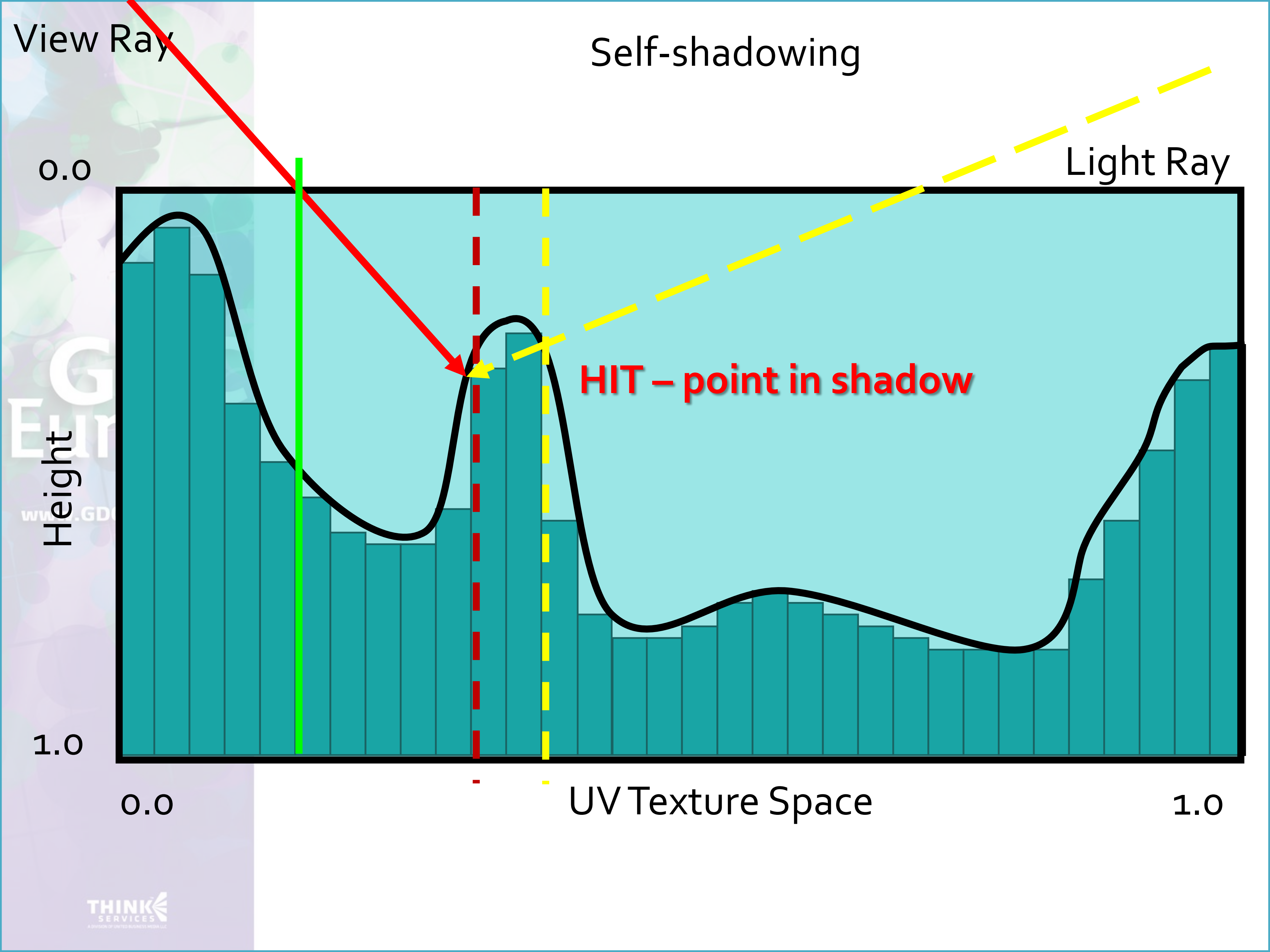
Comparison

- Extreme detail test case
  - one full screen surface at grazing angle
  - 2048^2
  - High depth scale
  - High frequency height field details

POM	QDM
73ms	14ms

Self-shadowing

- Features of the height map can cast shadows onto the surface
- We can test if the displaced point P on the surface is visible from the light source L
  - Ray trace from the point to the light source
  - If intersects with the height field we are in shadow

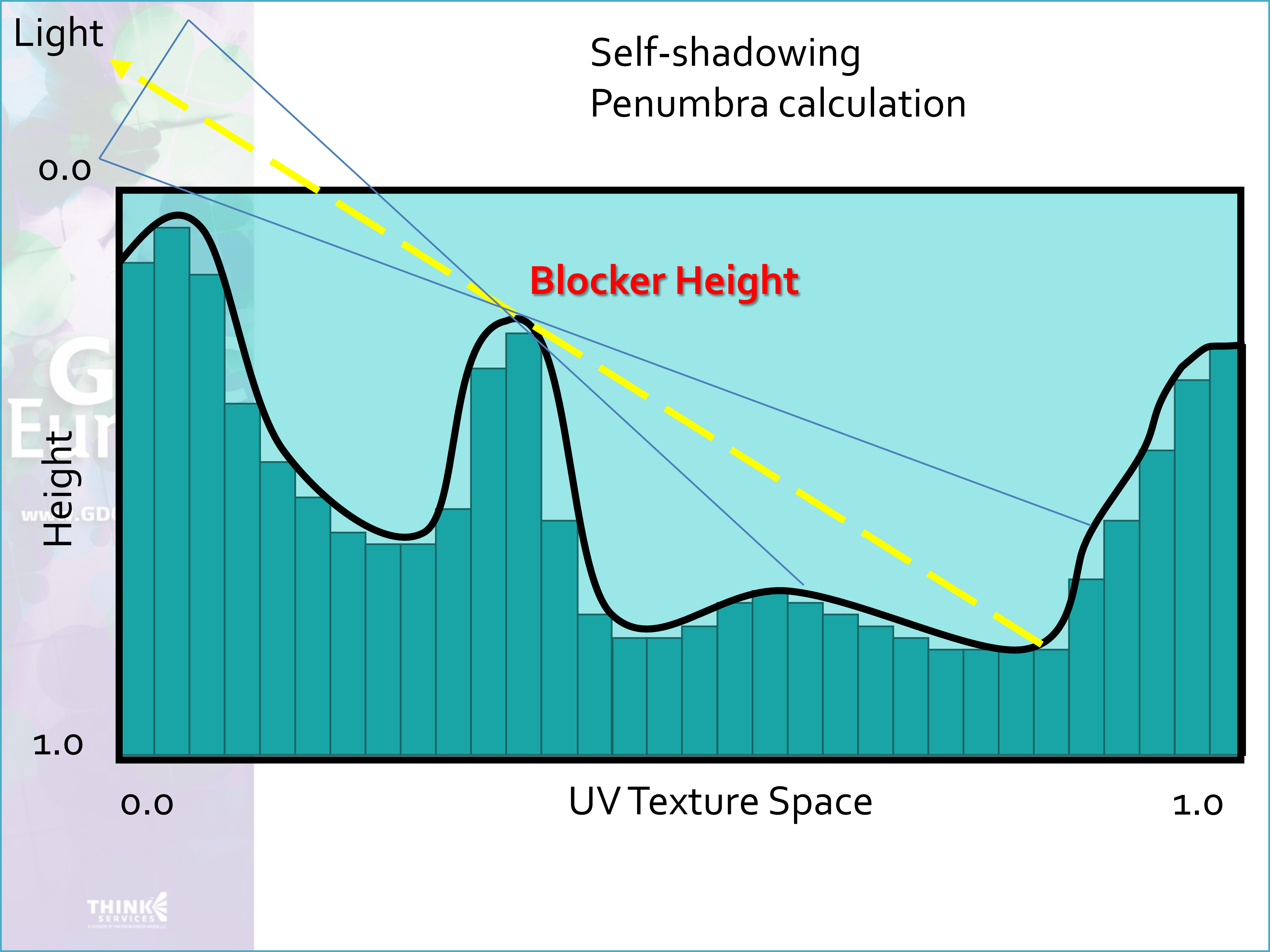

View Ray
Self-shadowing
0.0
Light Ray
HIT – point in shadow
Height
1.0
0.0
UV Texture Space
1.0

Self-shadowing

- Reverse ray tracing is expensive and yields hard shadows
  - N*Ray tracing cost
- We can calculate horizon visibility to obtain self-shadowing (POM 2005)
  - Sample along height field from displaced point in direction of the light source
  - Compute height profile angle by OP(P_height – Pn_height)
    - Pn – n-th sample in L direction
    - OP – operator : min/max , avg…
  - Stop when height profile over light ray

Self-shadowing

- We can obtain soft shadows by filtering sampled values
  - Having blocker height we use linear distance function to approximate penumbra size
- Algorithm complexity O(n)
  - n – number of height field texels along given direction
- For performance reasons we limit sample count
  - Limits shadow effective length
  - Look out for aliasing

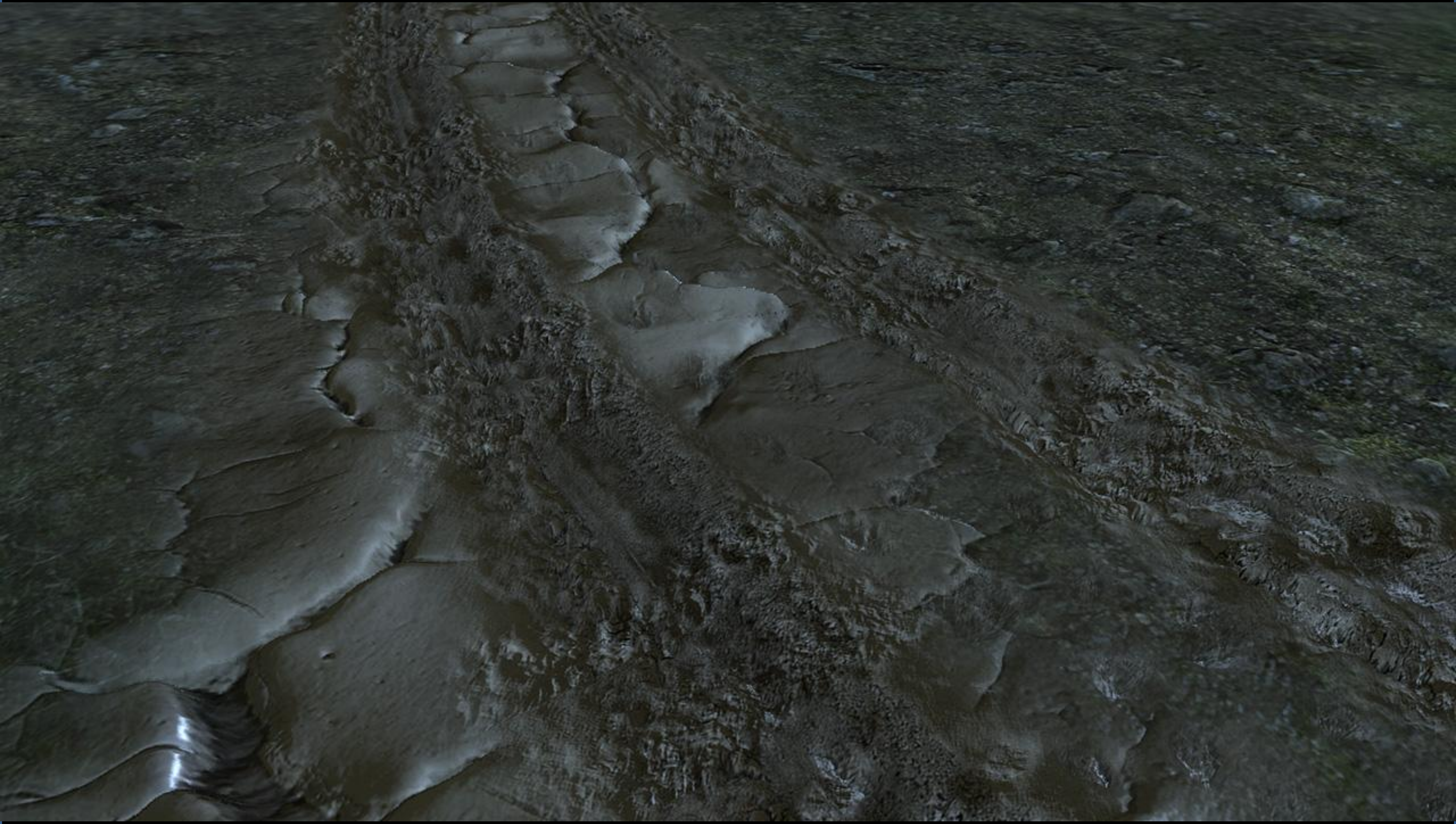

Self-shadowing
Penumbra calculation
Light
0.0
Blocker Height
Height
1.0
0.0
UV Texture Space
1.0

Self-shadowing

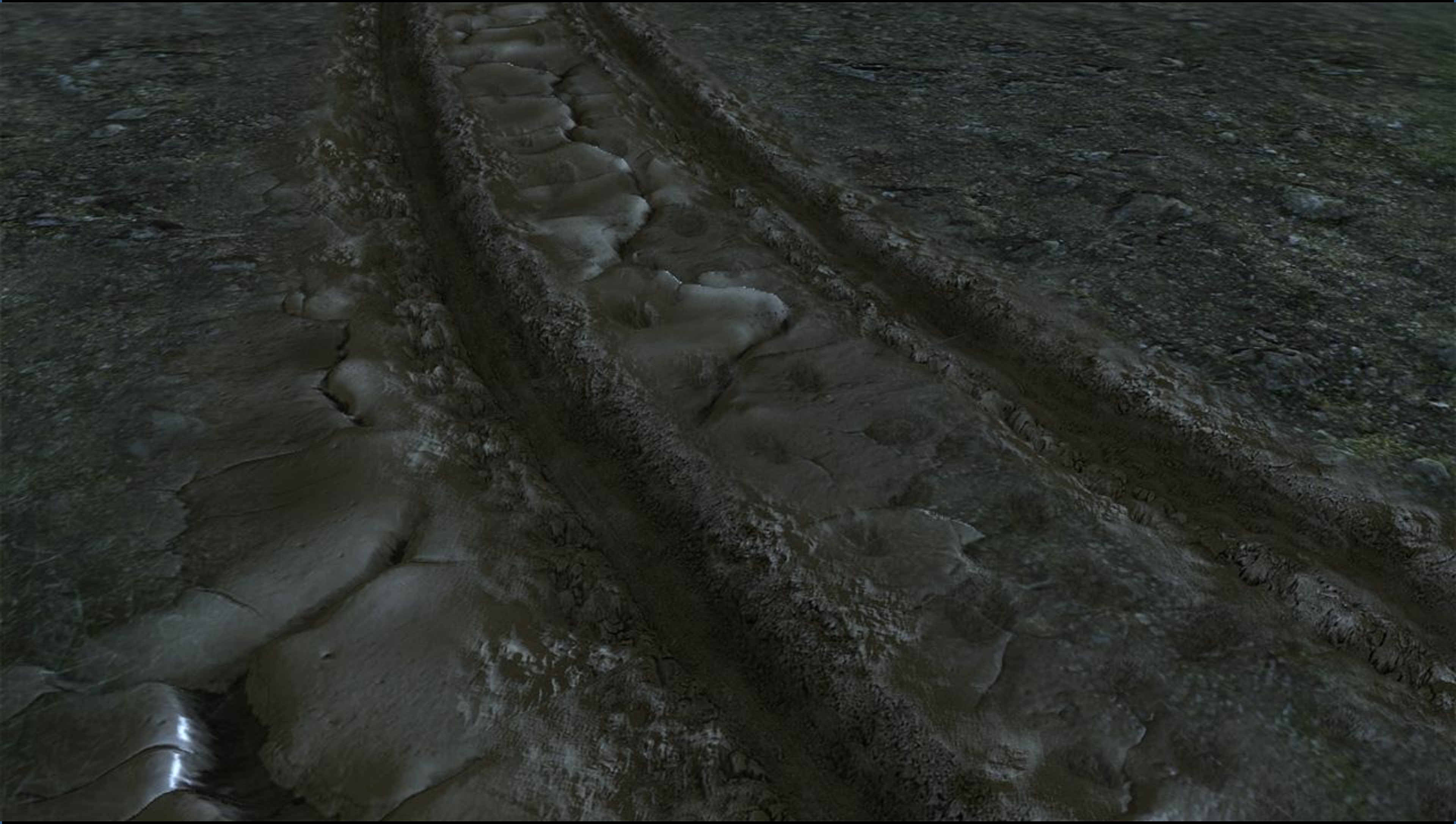
- We can further approximate soft shadows just by horizon visibility query in given light direction

```
float2 lDir = (float2(l.x, -l.y)) * dScale;

float h0 = tex2D(hTexture, P).w;
float h = h0;

h = min(1.0, tex2D(hTexture, P + lDir        ).w);
h = min(  h, tex2D(hTexture, P + 0.750 * lDir).w);
h = min(  h, tex2D(hTexture, P + 0.500 * lDir).w);
h = min(  h, tex2D(hTexture, P + 0.250 * lDir).w);

float shadow = 1.0 - saturate((h0 - h) * selfShadowStrength);
```

SS OFF



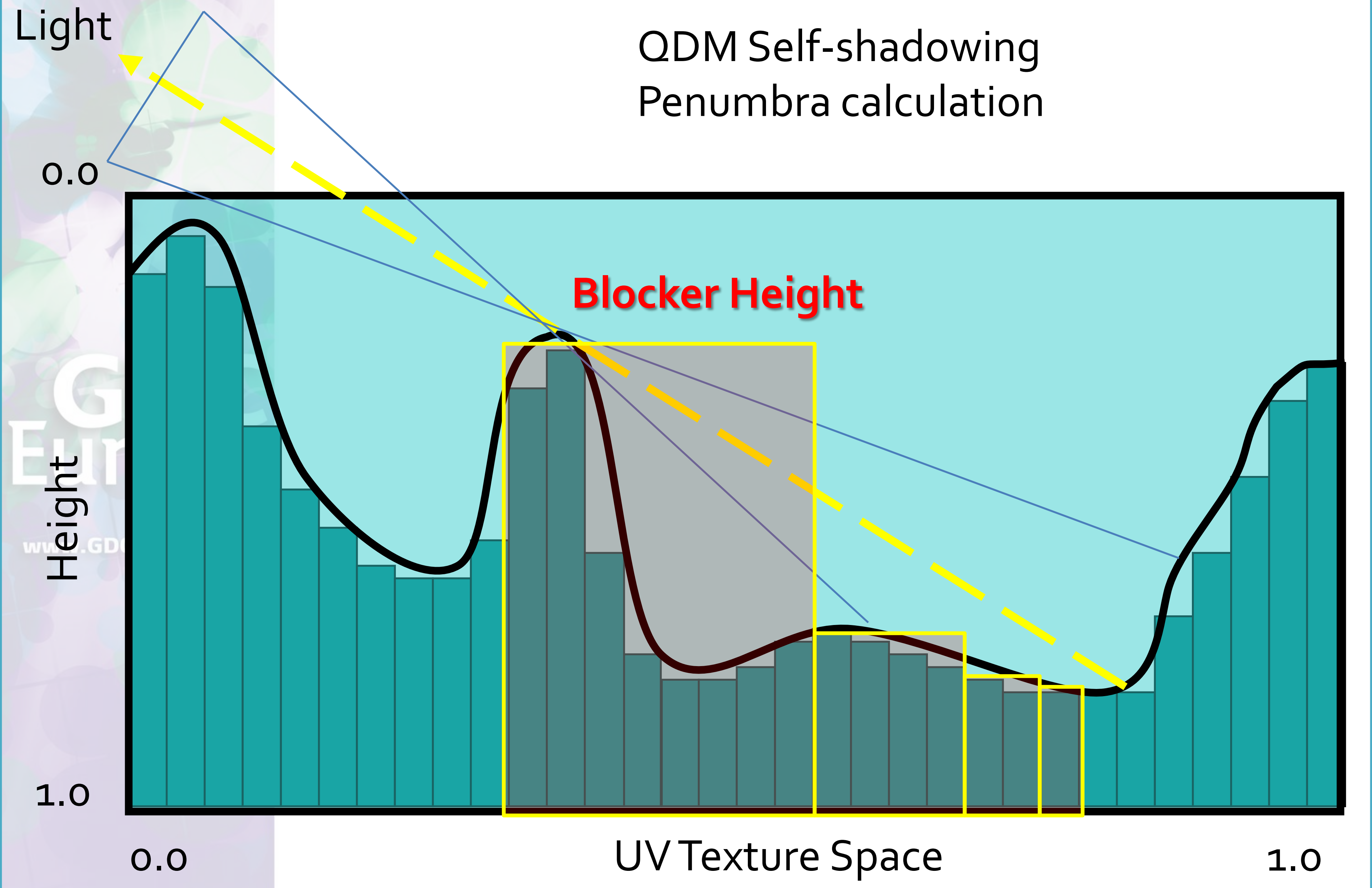
SS ON



QDM Self-shadowing

- Observation for light occlusion computation
  - Small scale details at distance have negligible impact on the total occlusion outcome
- We can approximate further lying profile features using maximum height data from QDM
  - Minimize needed number of queries
- Full profile can be obtained in log(n) steps opposed to (n)
- We compute penumbra shadows by correct distance scaling of shadows

QDM Self-shadowing
Penumbra calculation



QDM Self-shadowing

- Sample code
  - Fast
  - Values tweaked by artist

```
float2 lDir = (float2(l.x, -l.y)) * dScale;

float h0 = tex2Dlod(heightTexture, float4(P,0,0)).w;
float h = h0;

h = min(1.0, w1 * tex2Dlod(heightTexture, float4(P + 1.0  * lDir,0,3.66)).w);
h = min(h, w2 * tex2Dlod(heightTexture, float4(P + 0.8  * lDir,0,3.00)).w);
h = min(h, w3 * tex2Dlod(heightTexture, float4(P + 0.6  * lDir,0,2.33)).w);
h = min(h, w4 * tex2Dlod(heightTexture, float4(P + 0.4  * lDir,0,1.66)).w);
h = min(h, w5 * tex2Dlod(heightTexture, float4(P + 0.2  * lDir,0,1.00)).w);

float shadow = 1.0 - saturate((h0 - h) * selfShadowStrength);

return shadow;
```

QDM Self-shadowing

- Self-shadowing
  - Adds depth
  - Quality
  - Moderate cost
    - Full search only log(n)
    - Depends on shadow length (iteration cap)
    - Independent reads
    - Fast ALU
    - Full screen effect on test scene/machine
      - 0.5ms

QDM SS OFF

QDM SS ON

Ambient Occlusion

- AO
  - Represents total light visibility for point being lit
  - Adds depth
  - Can be computed and approximated similarly to self shadowing
    - We perform several horizon occlusion queries in different directions
  - Need to calculate only when height field changes
  - Especially useful for large scale terrain scenarios (i.e. darkening objects laying in a valley)

Ambient Occlusion

- Horizon queries
  - For each pixel perform horizon queries in const n equally spaced directions and average results
    - Fast
      - n*cost of horizon profile querying
    - May need many directions
      - 4-12 shall work fine
  - Can use jittering
    - For each pixel rotate directions by random
    - Can get away with 4 directions
      - Uses dependant reads
      - Still better results than more directions
- Generally expensive
  - Use at content generation
  - If dynamic use time amortization

Surface Blending

- Used mainly in terrain rendering
- Commonly by alpha blend
  - $V = w * V1 + (1-w) * V2$
- Blend weights typically encoded at vertex color
  - Weights being interpolated
- More accurate and flexible encoding blends in textures
  - Problematic
  - Large memory footprint

Surface Blending

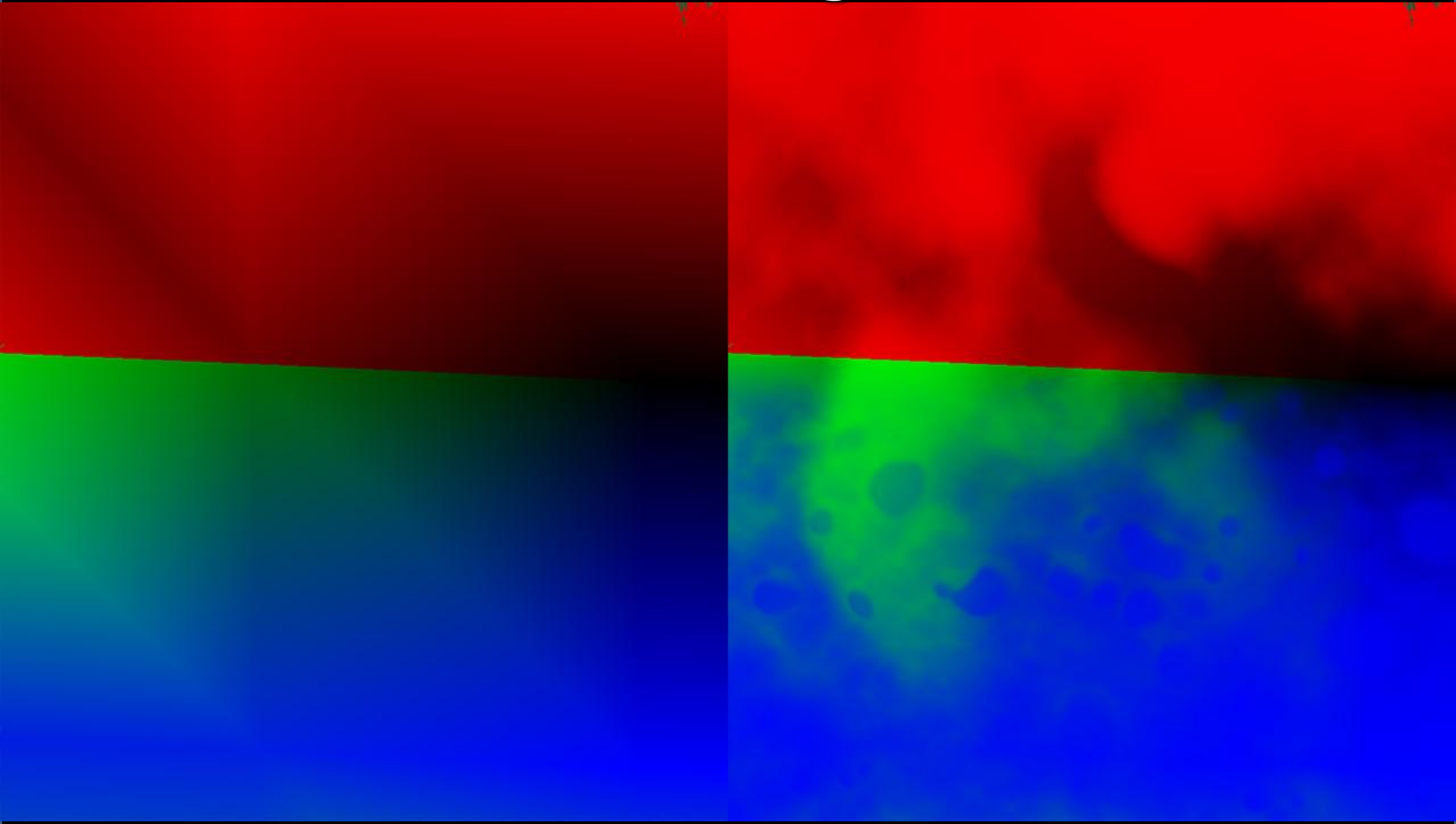
- Alpha blending is not a good operator for surface blending
  - Surface exhibit more variety in blends than simple gradients from per-vertex interpolation
  - In real life surfaces don't blend
    - What we see is actually the highest material (or material being on top)
    - Rocks and sand – at blend we should see rocks tops

Height Blending

- Height blending
  - Novel approach using height information as additional blend coefficient

```
f1 = tex2Dlod(gTerraTex0Sampler, float4(TEXUV.xy, 0, Mip)).rgba;
FinalH.a  = 1.0 - f1.a;
f2 = tex2Dlod(gTerraTex1Sampler, float4(TEXUV.xy, 0, Mip)).rgba;
FinalH.b  = 1.0 - f2.a;
f3 = tex2Dlod(gTerraTex2Sampler, float4(TEXUV.xy, 0, Mip)).rgba;
FinalH.g  = 1.0 - f3.a;
f4 = tex2Dlod(gTerraTex3Sampler, float4(TEXUV.xy, 0, Mip)).rgba;
FinalH.r  = 1.0 - f4.a;

FinalH*= IN.AlphaBlends;

float Blend  = dot(FinalH, 1.0) + e;
FinalH/= Blend;

FinalTex = FinalH.a * f1 + FinalH.b * f2 + FinalH.g * f3 + FinalH.r * f4;
```

Blend Weights



Final Blend Color

Height Blending

- HB
  - Adds variety
  - Cost is minimal
    - Opposed to discussed methods
  - Prefers the highest surface
    - Intersection search phase therefore needs to find highest point only

Displacement with HB

- Displacement mapping
- May use any intersection search technique
- Need to reconstruct surface profile from blend weights and individual height fields
  - Commonly alpha blend used for surface reconstruction
    - H = alphaBlend(h1,h2,h3,h4,W_Vec)

Displacement with HB

- Displacement mapping with HB
  - Using HB operator seems more natural for surface reconstruction
  - New blend operator
    - HB = max(h1,h2,h3,h4)
  - Optimal in terms of convergence
    - HB >= alphaBlend
      - Ray will hit HB surface faster

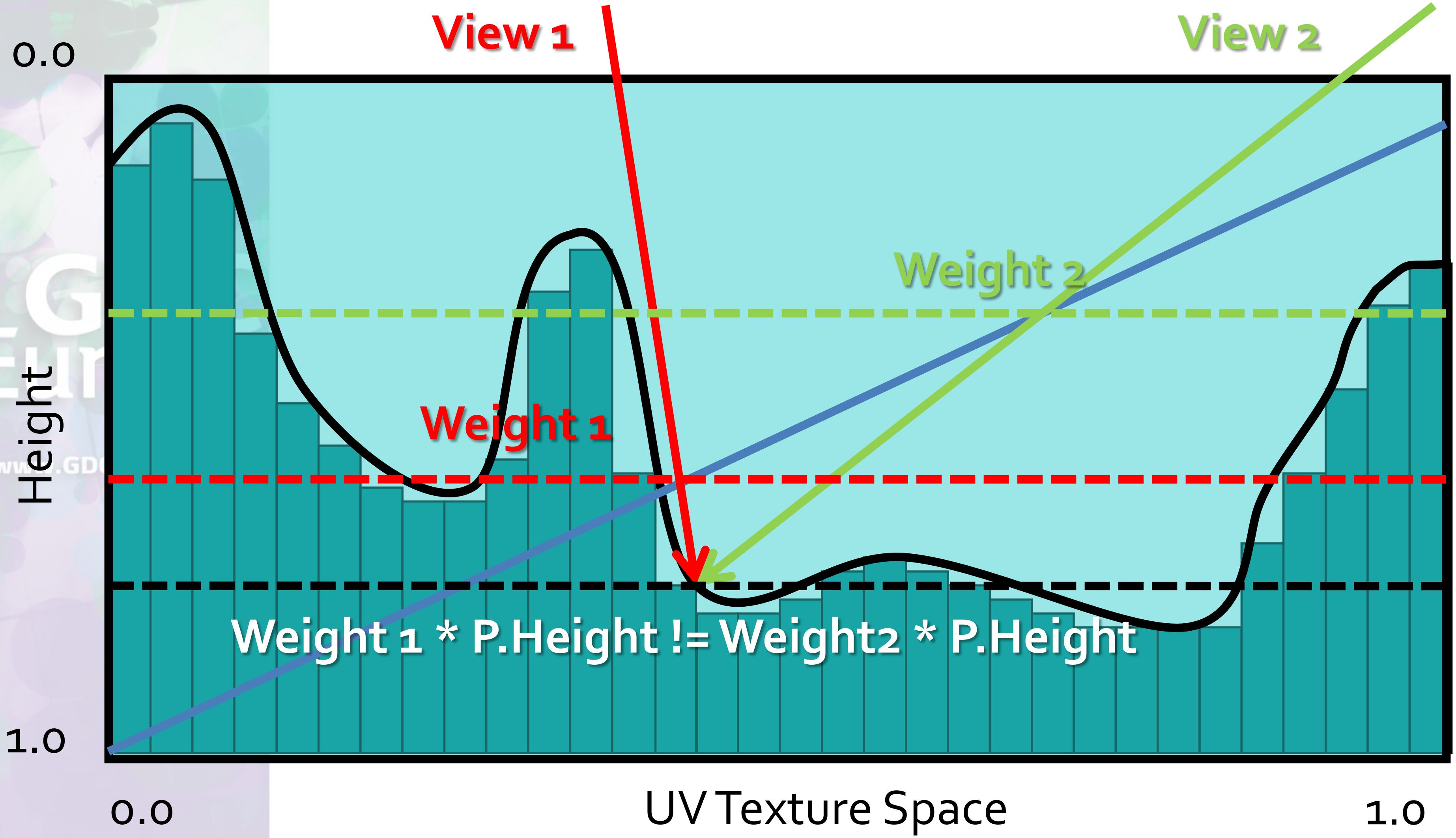
Displacement with HB

- While searching intersection using any online algorithm simply substitute actual h sample by result of blend equation
- Can cut search region by max blend weight
- Using per-vertex blend weights produces view dependant depth floating artifacts
  - Negligible with small depth scale and depth scale minimization at blend zones
- For correct results use per-pixel blend weights
  - Can compute small texture from vertex blend weights

Displacement with HB

- While searching intersection using any online algorithm simply substitute actual h sample by result of blend equation
- Using per-vertex blend weights produces view dependant depth floating artifacts
  - Can not reconstruct correct surface height as blend weights are constant taken from view vector position
  - Negligible with small depth scale and depth scale minimization at blend zones
- For correct results use per-pixel blend weights
  - Can compute small texture from vertex blend weights
  - Additional sample
  - Must use for high depth scale and accuracy

Vertex Blend Artifact



Displacement with HB

- Preprocessed data relying on distance (Distance Function, CSM) cannot be used with blend weights without pre-computation
- Preprocessed data relying on depth can be used with modified weight structures

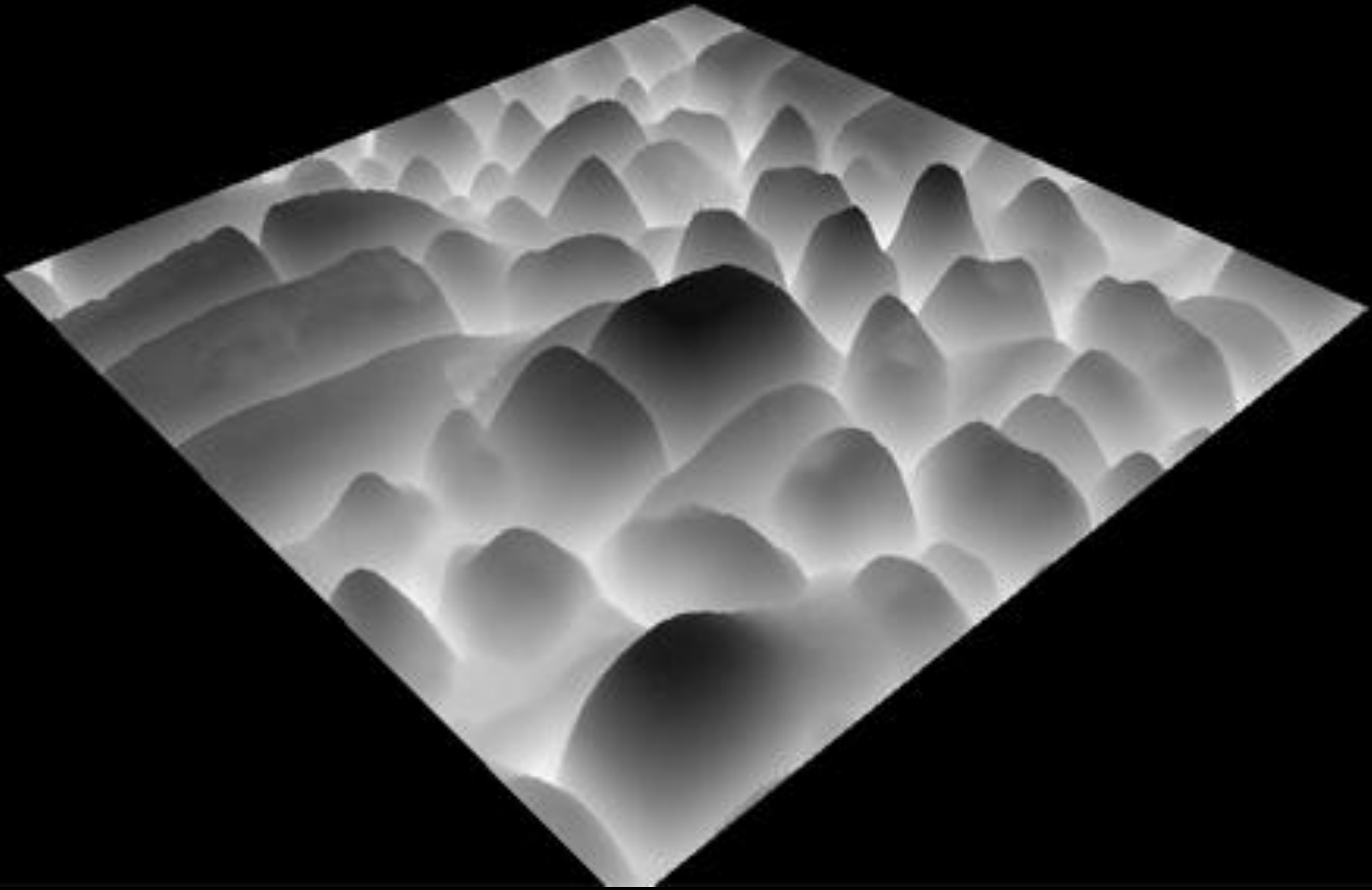
QDM with HB

- QDM is based on depth data
- Observation
  - $\max(x_1,\dots,x_n) * \max(w_1,\dots,w_n) >= \max[(x_1,\dots,x_n) * (w_1,\dots,w_n)]$
- QDM1 * QDM2 = Conservative QDM
  - CQDM at Level 0 represents exact surface blend with HB operator
- This is possible only with non-aggregate operators (min,max)
  - NOT! AVG, Weight AVG – Alpha Blend

QDM with HB

- QDMHB
  - Effectively we can use QDM with all its benefits while blending surfaces for artifact free rendering
  - Cons
    - On-the-fly / pre-computed Blend QDM
      - Blend Texture from vertex
      - QDM from blend texture
    - Conservative approach
      - Slower convergence
      - More iterations may be needed dependant on field complexity
      - In practice <10% more iterations than needed

QDMHB



Surface blend comparison

- In game scenario on test machine
  - Timing given = technique time – normal mapping time
  - Per-Vertex Blend with 4 surfaces

Relief Mapping	POM	POM with HB
3ms	2.5ms	1.25ms

Relief Mapping

POM Alpha Blend

POM Height Blend

Conclusion

- Valid solution for every scenario
  - Know what you need
  - Compose you solution from given building blocks
    - POM, QDM, Self Shadowing, AO, Height Blend – Per-Vertex/Pixel
    - As needed…

Conclusion

- On limited hardware
  - Optimize as much as you can
    - Terrain - fast low iteration POM with Per-Vertex HB, computed only for textures that really benefit
    - Special Features – QDM with Soft Shadows
    - General Objects – use low iteration POM, Soft Shadows at artist preference, check whether QDM is optimal for >1024^2

Conclusion

- On limited hardware
  - Trade ALU for bandwidth and memory
    - Generate specular textures on the fly
      - From difusse
      - By artist set per texture coefficients for functions input
        - Pow
        - Scale
        - Invert
  - Our terrain solution as seen on screens utilize only one DXT5 texture while using Shirmay-Kallos lighting equation

Conclusion

- Look out for future GPUs
  - Proposed high ALU methods will be even more beneficial for new architecture
  - Ray tracing vs. tessellation ?
    - Will see…
- Happy surfacing!

Acknowledgements

- Reality Pump
  - especially Mariusz Szaflik – RP lead programmer for continuous help in graphic struggles

Additional Info

- Additional information will be available in upcoming technical article, go to
- www.drobot.org – for details
- hello@drobot.org