Real-Time Reflections in **MAFIA III** and Beyond

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Mafia III overview

Open world, 3rd person, action adventure
Story driven, yet not linear
Set in 1968 New Bordeaux
Released October 2016
PS4, Xbox One, Windows, Mac OS

Mafia III is running on custom engine, which is an evolution of engine used in Mafia II.
Agenda

Motivation
Existing solutions
Ray casting on GPU
Reflection rendering
Reflections on rough surfaces
Timings, Results, Conclusion
Future work
Motivation

With PBR, reflections are an essential part of material shading

Having proper reflections is a major step towards photorealism

Not happy with any of the existing solutions
Obvious case – reflection from wet road
Example 1 – without reflections

Doesn’t even look wet without reflections.
Most of the surfaces are quite rough, reflections still play major role.
Example 2 – without reflections
Existing solutions

Screen-space tracing

PROS
- Doesn’t require content authoring
- Good performance
- Low memory cost

CONS
- Only captures what’s on screen
  - Lots of missing information (especially for high roughness)
  - Unstable with movement (camera or dynamic objects)
Existing solutions

Pre-filtered cube-map look-up

**PROS**
- Simple to implement
- Great performance

**CONS**
- Floating reflections
- Problems with transitions between CMs
- Iteration issues (if pre-rendered)
- Missing dynamic objects
- Isotropic

To achieve anisotropy, we would need to pre-filter the CM with multiple kernel configurations that would make it much less practical.
Existing solutions

Combination of SSR + Pre-filtered cube-maps

**PROS**
- Simple to implement
- Good performance

**CONS**
- Partially: Floating reflections
- Partially: Missing dynamic objects
- Isotropic
- Problems with transitions between CMs
- Development iteration issues (if pre-rendered, need to re-render every time scene changes)
- Stability issues (with camera movement)

Bad issues around main character in 3\textsuperscript{rd} person games.
Existing solutions

SSR + Parallax-corrected cube-maps (pre-filtered)

PROS
- Good performance
- No floating reflections
- Better transitions between CMs

CONS
- Only works well for environments with certain shapes
- More content authoring (scene approximation)
- Partially: missing dynamic objects
- Isotropic
- Iteration issues (if pre-rendered)

Multiple variants exist. E.g.:

Kevin Bjorke: sphere approximation
Bartosz Czuba: box approximation
Seb Lagarde: convex approximation
Existing solutions

Cone tracing

**PROS**
- No floating reflections
- Dynamic objects can be included
- Robust
- Doesn’t require authoring

**CONS**
- Requires run-time scene voxelization (difficult to implement)
- Huge memory requirements
- High GPU cost (scene update, tracing)
- Isotropic
Existing solutions summary

None of the existing solutions fulfilled all requirements:

- Stability with camera movement
- Good performance and memory cost
- Working seamlessly in all environments (indoor, city, landscape)
- Reasonable content authoring cost
- Real-time update (scene changes)
Problem breakdown

Problem #1
- General GPU-friendly ray casting
- Find ray intersection with scene
- Achieve mirror reflections (roughness=0)

Problem #2
- Proper BRDF on all materials
- What rays to cast?
- How to process the results
Ray casting on GPU

**Mesh/BVH**
- Branching
- Non-coherent memory accesses
- How to compute shading?

**Voxels**
- Memory heavy
- Non-trivial implementation

**Depth texture**
- GPU-friendly
- Trivial implementation
- Not perfect coverage of the space

Update on mesh/BVH: New API (DX12 DXR) and HW has been announced that is supposed to address some of the issues.
Covering space with 2D projections

Cube-map covers space perfectly from a given POV
- 6 2D views
- Add depth
- Works well if ray start position is close to CM origin
- Efficiency decreases with distance from origin

Tracing height-fields seems to be the right direction for nowadays GPUs.
We like the small implementation cost (we already have 2D rasterization implemented), low memory footprint and good performance.

Cube-map placed in camera covers reflection on vast majority of the pixels on the screen. Has been proven on a prototype.
But can’t render a cube-map every frame! Sparse updates (like 1 side every frame) would result in reflections popping and latency.
Multiple cube-maps

Pick best CM for ray start position
Switch to a different CM when ray enters “shadow region”
Use cube-map array

We’ve got 3 manually placed cube-maps on the right image.
Ray starts tracing the green CM, at some point gets to shadow region, red CM takes over. Ray reaches area without any coverage (implausible result) and blue CM takes over to finally find a hit.

Cube-map array: to be able to run single tracing pass.

The more complex the environment is, the less efficient the CM coverage is. Would be terrible for fractals but works well for typical environment that we live in.
Manually placed CM is always better than the automatic backup probes. It was used on open water areas for example.
Cube-map coverage issues

Manual placement: Need good tools
Dynamic objects: costly update → rely on SSR
Not all pixels are covered
Inconsistent resolution (depends on distance from CM origin)
Thin objects (rails, poles, signs, ...) interrupt rays

Thin objects create aforementioned shadow regions that interrupt ray tracing.
Our cube-map set-up

8 active geometry CMs
1 sky CM
Resolution of each 512 px, full MIP chain
Can’t pre-render CMs offline
  Dynamic time of day and weather
  If you can pre-render, don’t need separate sky CM

CM array slightly larger to be able to prepare new CM.
Cube-map rendering

Pre-compute max view distance offline (for each side)

Only consider objects in the pre-computed CM range for rendering the CM.
Cube-map rendering

Single CHull scene query for all sides
Use geometry shader to output to affected sides
Limited feature set

- Use lower LODs
- Only render static objects (and static lights)
- No post-FX
- No sky (sky is rendered into separate CM, geometry cube-maps contain sky-flag in alpha channel)
- No specular, no reflections, diffuse only (need some approximation for metallic)
- No fog/volumetric effects
- No transparent objects
- No AA

We want to submit as few draw-calls as possible. Many static objects are large (terrain, buildings) and intersect more than 1 cube-map view frustum (end up in more sides). So we collect all objects (for all sides) and then only test, which sides are affected (fill to CB from CPU). Submit just 1 draw-call that outputs the object into multiple sides using geometry shader.

We have learned that Geometry Shaders aren’t the most optimal way of attacking multi-viewport rendering, however is supported on all our platforms and is least intrusive from the shader combinations point of view.

We are rendering simpler LODs – these don’t have many vertices, so in the end this is not an issue and we will stick to this solution.

No specular in CMs: not only it’s an optimization but it also dramatically reduces noise in the result – specular has high intensity and frequency. Having specular baked in CMs isn’t correct either since specular is view dependent – reflection in a mirror has different specular.
Cube-map updating

Sky CM
Update every few frames (clouds, ToD)

Geometry CMs
Update dynamic lighting regularly (round robin)
Cache G-Buffer and static lighting
Render new when better CM has been found

Because of dynamic time of day and moving clouds, we need to update sky CM very often (several times per second). Sun is considered dynamic light.
Active cube-maps selection

Might differ per project
We use 8 closest to the player, with 2 special cases
   At least one outdoor CM
   Penalty in vertical axis to separate floors
Possible improvements
   Use bounding boxes (in/out, distance)
   Use occlusion queries
   Pre-compute best CM set for volumes

Indoors are typically more populated with CMs, so if player is standing in front of indoor location, all 8 closest might be inside. Outdoor would have no CM at all, so we always force at least one outdoor.
Reflection rendering
Algorithm overview

Down-sample G-Buffer, apply NDF
Trace screen, output distance
Trace cube-maps, output distance & index
Resolve to color
Upscale
G-Buffer down-sampling and jittering

Can’t afford tracing at full resolution
  Trace at half resolution

Bilinear down-sample not recommended
  Incorrect depth on edges
  Lost detail in normal & roughness buffers
G-Buffer down-sampling and jittering

Detect depth discontinuities
  If edge is detected, discard “minor samples”
Pick random sample (exploit temporal filter)
Jitter normal (apply NDF)
Output (all at half-res)
  RT0: Depth
  RT1: Jittered normal and roughness
  RT2: Original normal and roughness

Random sample: we actually alternate pixels in 2x2 block
Screen-space tracing

Trace screen-space depth

Output: traveled distance, “finished” flag

Stencil mask for “finished” flag

Traveled distance: Stencil mask (white means finished):
Best cube-map selection – CPU

Generate 8 cube-map index chains
For each starting CM, estimate best 3 consecutive CMs
Based on distance only
Output: 8 4-item CM chains
Encoded to global CB

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This is something to be improved. We currently only find 3 closest CMs to each CM. It doesn’t even take visibility into account.
Best cube-map selection – GPU

Select best starting CM per pixel
  Use stencil (unfinished pixels)
  Start at SSR end position
  Assign score to each of 8 active CMs
  Output CM index with best score

Score per pixel is assigned based on:
- Visibility (is that pixel visible from CM origin?)
- Distance from CM origin
- Ray direction vs. origin → point vector
- CM fade value (when adding/removing CM)
Cube-map tracing

2 passes based on roughness (HQ/LQ)
Start with SSR end point, using best CM
If tracing fails, switch to next CM in chain and continue
If all CMs fail, use fallback
Output traveled distance and CM idx (where hit was found)

Roughness > 0.1: 16 steps, 100 m, scale 1.17 – 1.25, 3 refine iterations

Roughness <= 0.1: 24 steps, 300 m, scale 1.18 – 1.22, 4 refine iterations
Tracing fallback solution in Mafia III

Black reflection
  Mostly OK
  Really bad on very reflective surfaces (water, metals)

Simple lookup of best CM
  Very different results when best CM was changing
  Eliminate popping using temporal filter
Current tracing fallback solution

“Cocoon” cube-map depth MIP

- Use 1 MIP (e.g. MIP#4 – 32x32) to store very smooth approximation of space
- Large blur kernel with MAX filter ignoring sky
- Pushing thin geometry away
- Removing all edges
- Caps windows
- Tracing never fails
- Preserves space but removes details
- Similar idea to parallax corrected cube-maps, automatically generated
Cocoon MIP example

Original depth:  Cocoon depth MIP:
Note how the stairway, columns and flower-pot is pushed to the background but windows are still at their correct location.

Compare to simple look-up, where the windows would be on wrong place.
Generating cocoon MIP

Top-down pass

- Build a MIP chain using MAX filter ignoring sky
- If all (4) pixels are sky, result is sky, otherwise sky pixels are discarded
Generating cocoon MIP

Bottom-up pass

**Lower MIPs (lower than cocoon)**

Replace **sky** pixels with weighted MAX of neighborhood from lower MIP

**Cocoon MIP**

Replace **all** pixels with weighted MAX of neighborhood samples from lower MIP

**Upper MIPs (higher than cocoon)**

Replace **sky** pixels with cocoon MIP sample

Caps windows/sky – also works as an optimization for rays ending up at sky. Instead of burning all steps towards sky, ray hits the sky proxy sooner.

**Weighted MAX:**

```plaintext
float pivotSample = SAMPLE_4D_LOD( srcTex, srcSampler, float4( dir, srcArrayIdx ), srcMip ).r;
float depth= 0;

for each sample
{
    float smp = SAMPLE_4D_LOD( srcTex, srcSampler, float4( vec, srcArrayIdx ), srcMip ).r;
    float weight = pow( dot( vec, dir ), specPow );
    float currVal = pivotSample + ( smp - pivotSample ) * weight;

    depth = max( depth, currVal );
}
```
Cube-map tracing optimizations

Use lower depth MIPs for higher roughness
Pre-compute internal volume (AABB/sphere/convex hull)
Run as async compute shader (lose stencil)
Color resolve passes – inputs

From cube-map renderer
  Geometry color cube-map array
  Sky cube-map

From previous reflection passes (half-res)
  Linear depth
  Jittered normals
  Stencil mask for SSR
  Traveled distance (combined SSR & CM)
  CM idx (for non-SSR finished pixels)

From shading pass
  Diffuse shading buffer (you don’t want specular here)

When tracing is finished (got traveled distance, stencil mask, possibly CM index per pixel), it can be resolved to color using the mentioned inputs.
Color resolve passes

Half-res passes
   Resolve SSR color
   Resolve CM color

Full-res passes
   Upscale half-res resolved buffer, generate low-roughness stencil mask
   Resolve SSR on low-roughness pixels
   Resolve CM on low-roughness pixels
Color resolve shaders

Compute ray end position:
  rayDir = -reflect(viewVector, surfaceJitteredNormal)
  endPos = worldPos + rayDir * traveledDistance
Fetch sky CM
SSR only
  Project end position to screen space
  Fetch diffuse shading buffer (including sky)
CM only
  Fetch cmIdx
  endPos -= cmCenter[cmIdx]
  Fetch color CM[cmIdx]
  color += sky color * (1 – color.a)
Compute fog blend factor
Lerp(color, sky color, fog factor)

A little hack to add fog to reflections (fog is included neither in CM nor is SS diffuse shading buffer): because we have volumetric fog, which is non-trivial to compute for other rays than from camera, we simply fade towards sky color – which in fact is fog integrated over long distance.
Upscale

Inputs:
- Half-res color
- Half-res unjittered normals
- Half-res depth
- Full-res normals
- Full-res depth

Outputs:
- Full-res color (high roughness pixels)
- Stencil mask

Picks 1 sample from half-res color that best matches full-res normal & depth
Reflections on rough surfaces
Check out the edge artifact and missing elongation on the left image.

Diagram shows, how two neighbor pixels rays end up in a completely different location in the CM, the results are vastly different. CM is pre-filtered from the point of view of its origin, not from the point of view of reflecting pixel.
On rough surfaces, the kernel is really large – would be very costly for real-time. That’s why MIPs are used, so the blur can’t be depth/normal/roughness aware. Note the big loss of normal map detail but also how it leaks across edges.
Possible approaches

Importance sampling
Noise vs. performance
Need hundreds of samples to get noise-free result

We are shooting 1, 8, 32, 128 rays for every 4 pixels (still tracing at half resolution).
Mafia III approach

Combination of screen-space blur and importance sampling
  50 % SS blur
  50 % importance sampling
  Trade-off between leaking and noise
Large blur kernel (up to 25 % of screen)
  Need to use MIPs
  Can’t be depth-aware

Compute approximate reflection cone angle.
Halve the angle and jitter normal within this cone.
Output the ray traveled distance along with the reflection color.
Build color MIP chain.
For each pixel, estimate the MIP level to be used, based on traveled distance.
Current approach

Mix of all 3 + some tricks
   50 % importance sampling
   50 % using pre-filtered MIPs (both SSR and CM)
   5-sample BRDF-weighted screen-space blur
   Modified sample distribution
   Temporal filter

Math is based on Blinn-Phong (not converted to GGX yet)
Note the leaking and loss of normal map detail.
Current rough reflection approach
Compare several mixtures of importance sampling vs. pre-filtering.
100 % importance sampling is our reference.
Importance sampling vs. pre-filtering – 75:25
- Lost elongation
- Visible Edges
- Less correct – some surfaces look a lot different
Combining importance sampling with pre-filtering

NDF produces vectors with angle $[0, \pi/2)$ from normal

Find angle, where probability drops below threshold (in our case 0.1)

Ignore all vector beyond this angle

Split angle among NDF and pre-filering

Modify NDF to produce vectors $[0, \text{angle}/2)$

Compute cone base radius and MIP level for angle/2

We lose a bit of the tail by ignoring all vectors, where “cos(angle)$^\text{specPow} < 0.1$” but on the other hand that helps reducing the noise quite a bit.
Combining importance sampling with pre-filtering

Example:

\[
\text{roughness} = 0.5 \rightarrow \text{specPow} = 30 \\
\text{angle} = \text{acos}\left(\frac{\text{threshold}}{\text{specPow}}\right) = 0.387
\]

Changing importance sampling vs. pre-filtering ratio:

- More importance sampling \(\rightarrow\) more noise
- More pre-filtering \(\rightarrow\) less anisotropy

Blue graph is target NDF. Red line is threshold (0.1). We ignore regions, where blue is below red. Compute corresponding (cone) angle. Half of the cone is delivered using NDF (green), second half using pre-filtering (yellow).
Pre-filtering cube-maps

We do it at run-time → needs to be fast
Build regular MIP chain
Choose texel scale (in our case 3.5x)
Pre-filter individual MIPs

Simple English: once we know our cone angle, we find cube-map MIP, where cone base radius is texelScale texels (3.5 texels).

Setting texel scale to 1 would cause pre-filtering of only 1 texel -> no pre-filtering at all.

Setting texel scale too high would increase the cost of pre-filtering (you need to add more taps) but also force sampling of higher MIP levels, which will cost additional performance in resolve pass.

When playing with this, cross-check with reference (1000+ taps from upper MIPs or base level).

Found more advanced run-time pre-filtering later – want to have a look at that:

Pre-filtering cube-maps

**MIP pre-filtering (in our case 29 taps):**
\[
\text{numPixels} = 2^{\text{mipIdx}} \times \text{texelScale}
\]
\[
\text{angle} = \arctan\left( \frac{\text{numPixels}}{\text{cmSize}} / 2 \right)
\]
\[
\text{specPow} = \log_{\cos(\text{angle})} \text{threshold}
\]

**Computing MIP level in resolve shader:**
\[
\text{angle} = \text{AngleFromSpecPow}(\text{specPow}) \quad // \text{see previous slides}
\]
\[
\text{radius} = \tan(\text{angle}) \times \text{traveledDist}
\]
\[
\text{cmRadius} = \text{radius} / \text{length(\text{hitPosCM})} / \text{texelScale}
\]
\[
\text{numPixels} = \max(1, \text{cmSize} / 2 \times \text{cmRadius})
\]
\[
\text{mipLevel} = \log_{2}(\text{numPixels})
\]
Modified NDF

Input: 2 random values \( [0, 1) \), uniform distribution
Default Phong distribution:
\[
\theta = \arccos \left( \frac{\text{rnd}}{\text{specPow} + 1} \right) \\
\phi = 2 \pi \times \text{rnd2}
\]
Half-angle:
\[
\text{halfAngle} = 0.5 \times \text{AngleFromSpecPow} (\text{specPow}) \\
\text{minRnd} = \cos (\text{halfAngle})^\text{specPow} + 1 \\
\theta = \arccos (\text{minRnd} + (1 - \text{minRnd}) \times \text{rnd}) \left/ (\text{specPow} + 1) \right)
\]

We don’t care about the PHI angle for now but want to modify THETA, to get only angle/2 instead of angle. We inverse the function, find minimum random value and then scale the input random value to be in range \([\text{minRnd}, 1)\). Don’t clamp the value, it needs to be linear operation to preserve the relative probabilities.
Combined BRDF comparison

Reference \[= \cos(\text{angle})^{\text{specPow}}\]

Result \[= \int_{-h}^{h} \cos(\text{clamp}(x + \text{angle}, -\pi/2, \pi/2))^{\text{specPow}} \times \cos(x)^{\text{halfAngSpecPow}} \, dx\]

“Result” is what you get, if you modify NDF to half angle and sample MIP corresponding to half-angle.

h – half-angle

halfAngSpecPow – specular power corresponding to half-angle

angle = \acos(\text{threshold}^{1/\text{specPow}})

halfAngSpecPow = \log_{\cos(0.5 \times \text{angle})} \text{threshold}

It’s not 100 % the same but it’s pretty close
Modified NDF

Concentrate as much variance as possible to neighborhood

The best pattern we found was a “+” pattern – assign each pixel a value of 0-4
Every pixel has all 5 “classes” around that it can sample in blur pass

Map class ID to ray direction

\[ \varphi = 2 \pi \times (0.2 \times \text{md2} + \text{GetSSJitterPlus}(\text{ssPos}, \text{frameCounter})) \]

Shuffle temporarily

SS pixels: Hemisphere slices:

Pixel class ID from screen-space position and frame ID:

```
Pixel classID(screenPos) // ssPos used ssPos, or ssPos + 4-frameCounter
{
    const int SAMPLES_COUNT = 2;
    const int SAMPLES_Y_OFFSET = 5;
    const int sampleX = (ssPos.x + SAMPLES_Y_OFFSET * ssPos.y + frameCounter) % SAMPLES_COUNT;
    return 1.0 / SAMPLES_COUNT * sampleX;
}
```

2nd modification of NDF is to concentrate color variance to a small neighborhood, to be able to blur that in SS blur pass and remove the noise. The assumption is that rays going in similar direction are more likely to result in similar color and vice versa. Focus direction variance to neighbor pixels. We found that shifting “+” pattern works pretty well for this purpose.

Blue noise might be a good alternative. Will try that later and compare the results.
Neighbor sample reuse

Sample depth and normal of 4 neighbors
  Same pattern as pixel classification
  Use unjittered normals
Compute weighted average
  Center tap: 1
  Depth/roughness discontinuity: 0
  Evaluate BRDF otherwise

If all the pixels have the same roughness and normal (flat, rough surface), you can look at it as multiple (temporal) samples. Just average them (assuming there is no discontinuity).

If roughness is very different, we haven’t found a way, how to combine these samples.

With changing normals, the BRDF using unjittered normal seems to be a good metric.

For very small roughness, we would have to consider also view vector divergence between neighbor pixels. Instead of that (extra cycles), we simply fade this blur out.
Temporal filter

We use up to 15:1 previous frame blend ratio

Reflections view dependent
  Compute view vector divergence (previous vs. current frame)
  Compute divergence threshold based on roughness
    Mirror reflections: zero divergence threshold but no issues with noise!
    Rough reflections: high divergence threshold but not so much view dependency!

Invisible in last frame (or discarded due to divergence)
  Evaluate extra 4 samples in centers of neighbor “+” elements
  Effectively up to 25 samples (5x5)

We use variance clamping for mirror reflections (roughness = 0) and we gradually increase the clamping window with growing roughness. Variance clamping is fully disabled when roughness > 0.1.

Extra 4 samples: look at it as separable blur. But instead of 2-pass horizontal/vertical, we do “+” and tilted “x” that is sampling the neighbor “+” centers.
Step-by-step recap – tracing

Down-sample G-Buffer depth, normal (add jitter), roughness to half-res buffers
Stencil mask based on roughness (different tracing quality for high/low roughness)
2-pass (high/low roughness) SSR trace outputting traveled distance and FIN flag
Stencil mask for SSR finished pixels
Best CM select
2-pass (high/low roughness) CM trace outputting traveled distance and CM idx
Step-by-step recap – post-tracing

Resolve to color (SSR + CM)
Neighbor sample reuse (screen-space blur)
Temporal filter for high roughness
Depth & normal aware upscale to full res
Resolve low roughness at full res (using half res traveled distance)
Temporal filter for low roughness (with variance clamping)
Timings (1080p @ PS4)

Captured before porting to async CS. Slightly above budget of 3.0 ms.
All the screenshots have been captured using Mafia III assets and the new tech.

Note that the new tech has NOT been shipped in Mafia III.
Conclusion

Stable reflections when camera/dynamic objects move
Reasonable amount of manual work
Little pre-compute (max view distance, inner volume)
Real-time on nowadays gaming hardware
Scalable in terms of:
  - Lighting changes: re-light cube-maps
  - Geometry changes (destruction): re-render affected cube-maps
  - Scene complexity: adjust amount of cube-maps
Future work

Convert to GGX
Temporal re-projection using reflection depth
Improve upscaling pass
Pre-compute optimal starting CM and chain
Investigate automatic probe placement
Investigate better handling of off-screen dynamic objects
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Help with presentation

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Proof review
References

Umenhoffer, Patow, Szirmay-Kalos. 2007. GPU Gems 3 – Chapter 17. Robust Multiple Specular Reflections and Refractions  

Stachowiak. SIGGRAPH2015. Stochastic Screen-Space Reflections  
http://advances.realtimerendering.com/s2015/Stochastic%20Screen-Space%20Reflections.pptx

Robinson, Shirley. 2009. Image-Space Gathering  
http://www.nvidia.com/object/nvidia_research_pub_015.html

Valient. GDC2014. Taking Killzone Shadow Fall Image Quality into the Next Generation  

Lagarde. SIGGRAPH2012. Parallax Corrected Cube-Maps  


Czuba. 2011. Box Projected Cube Environment Mapping  
https://blenderartists.org/forum/archive/index.php/t-209688.html

Manson, Sloan. 2016. Fast Filtering of Reflection Probes  

.....questions?

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Bonus slides
Cube-map tracing pseudo-code

```plaintext
stepScale = Rand( stepScaleMin, stepScaleMax )
currStep = ComputeInitialStep( maxRayLength, stepScale )
bestCMIdx = FetchBestCMIdx
currCMIdx = bestCMIdx
usedCMs = 0
currPos = cmCenter[currCMIdx] // currPos is always in CM space
for each step:
  currPos += currStep
  cmDepth = FetchCMDepth( bilinear, currPos )
  cmDepthPoint = FetchCMDepth( point, currPos )
  cmDepth = clamp( cmDepth, cmDepthPoint - threshold, cmDepthPoint + threshold )
  cmDist = length( currPos ) // Note: sqrt can be avoided
  if cmDist > AddBias( cmDepth )
    if ComputeMassDepth( currPos, currStep ) + cmDepth > cmDist
      // Hit has been found
      numRefineSteps++
      if numRefineSteps >= maxRefineSteps
        success = true
        break
    else
      currPos = currStep
      currStep *= 0.5
  else
    // Entered shadow region → need to switch CM
    usedCMs++
    if usedCMs >= maxTracedCMs
      // Tracing failed, need fallback
      success = false
      break
    else
      currPos += cmCenter[currCMIdx]
      currCMIdx = cmOrder[bestCMIdx][usedCMs]
      currPos -= cmCenter[currCMIdx]
      currStep *= stepScale
  if success
    Secant refine
  else
    Use fallback solution

Output:
RT0: length( currPos + cmCenter[currCMIdx] – rayStartPos )
RT1: currCMIdx
```

CM depth texture contains distance from CM origin instead of linear depth

- Simpler math
- Eliminate pre-filtering issues on CM edges