Interactive Hyper Spectral Image Rendering on GPU

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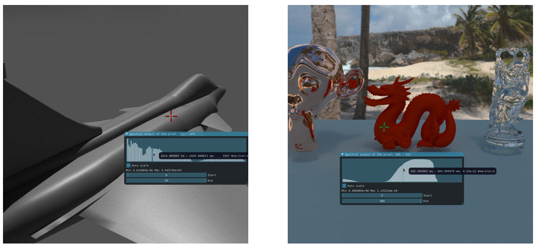
Abstract: In this paper, we describe a framework focused on spectral images rendering. The rendering of a such image leads us to three major issues: the computation time, the footprint of the spectral image, and the memory consumption of the algorithm. The computation time can be drastically reduced by the use of GPUs, however, their memory capacity and bandwidth (compared to their compute power) are limited. When the spectral dimension of the image will raise, the straightforward approach of the Path Tracing will lead us to high memory consumption and latency problems. To overcome these problems, we propose the DPEPT (Deferred Path Evaluation Path Tracing) which consists in decoupling the path evaluation from the path generation. This technique reduces the memory latency and consumption of the Path Tracing. It allows us to use an efficient wavelength samples batches parallelization pattern to optimize the path evaluation step and outperforms the straightforward approach when the spectral resolution of the simulated image increases.

1 INTRODUCTION

Aircraft detection in the IR (Infrared) and Visible bands is an active research field in the aerospace community. Dimensioning the sensors for this purpose requires the spectral radiance of a scene at their input, that can be expensive and difficult to obtain by airborne measurement campaigns. A fast and accurate simulation (fig. 1) of these data is thus needed.



(a) 100 channels in the SWIR range.

(b) 400 channels in the Visible range.

Figure 1: The spectral output of a pixel (red point on both images) and its displayable color can be visualized at the same time.

In the IR range, local illumination methods (e.g. (Whitted, 1979)) are used to simulate the light transport in most cases for former aircraft generation or supersonic flight where IR signature is overwhelmed by the radiation of hot parts. Nevertheless these methods have proved to be insufficient since the new generation of aircrafts relies on their shape (e.g. curved nozzle) to hide their hot parts to improve their stealth characteristic. Hereafter, the inter reflexions have to be taken into account. For the aircraft IR signature simulation, the aerospace community has begun to use global illumination methods (e.g. (Coiro, 2012)). The typical scene is an aircraft surrounded by an environment map which contains the radiation of the sky and the ground. The scene can also contain the volume of the atmosphere and the plume (aircraft exhaust combustion gases).

The spectral output of this simulation can be stored in channels of a spectral image. A channel is not a wavelength but the integration of the spectral radiance over a spectral interval. The spectral resolution of this image has to be very high for the following reasons:

- The evolution of technology leads us to explore new concepts of sensors from 380 to 20,000 nm, at high resolution (a few nm of accuracy in visible, and larger in IR).
- The gases of the atmosphere (fig. 2) and the aircraft's plume can have very spiky absorption and emission spectrum.

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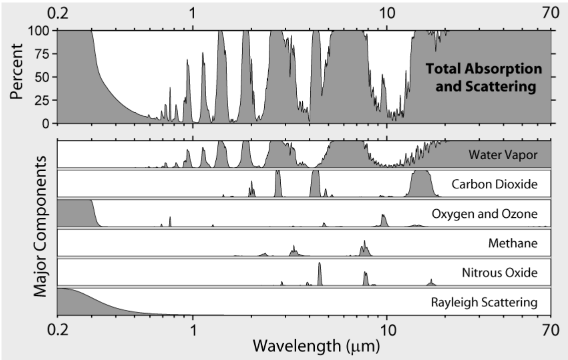

Figure 2: The absorption spectrum of the atmosphere (Rohde, 2007).

The rendering of a such spectral image will lead us to three major issues:

- The computation time: Each channel must be processed.
- The footprint of the spectral image: 4 bytes per channel per pixel.
- The memory consumption of the algorithm: For instance, the Path Tracing (Kajiya, 1986) needs to consume 8 bytes at least (to accumulate the spectral radiance and the path throughput) per wavelength sample per path.

The computation time can be drastically reduced by the use of GPUs, but their memory capacity and bandwidth are limited. The straightforward approach of the Path Tracing would be to evaluate at each bounce the path extension for each wavelength sample.

To be efficient, a path has to be reused by at least one wavelength sample per channel. When the number of channels will raise, the wavelength sample states won't be able to fit into the registers or the local memory. Therefore, they would have to be stored in the global memory which would imply to high memory consumption and latency problems.

To overcome these problems, we propose the DPEPT (Deferred Path Evaluation Path Tracing) which consists in decoupling the path evaluation from the path generation. At each bounce, the bare minimum information is stored in a path vertex. Once the path is completed, the wavelength sample of each channel is evaluated. Since the path vertices are saved, the channels can be evaluated per batch to reduce the memory consumption. The state of this batch can be stored in the local memory to reduce latency. This method allows us to optimize the path evaluation and outperforms the straightforward approach when the spectral resolution of the simulated image raises. Our approach enables to render efficiently multi, hyper and even ultra (more than 1,000 channels) spectral image.

Our research are beneficial to some Computer Graphics fields such as the predictive rendering and the colorimetric validation. The main contributions of this article are:

- A framework to render a spectral image composed with K number of channels (section 3).
- A suitable path tracing method (DPEPT) to render a high spectral dimension image on GPU (section 5.1).
- An efficient wavelength parallelization pattern of the path evaluation step (section 5.2).

2 PREVIOUS WORKS

2.1 GPU Implementation of the Path Tracing

The Path Tracing (Kajiya, 1986) is the simplest global illumination algorithm. Its implementation on GPU was first studied by (Purcell et al., 2002) which proposed a multi pass approach due to the lack of programmability of the early hardware.

One of the main problems at this time was the various lengths of the path which implied an inefficient workload and code divergence. A few threads process the long paths while other threads are idle. To solve this problem, (Novák et al., 2010) introduced the Regenerative Path Tracing which decouples path from pixel by using the thread persistent technique. If a thread is idle it generates a new path instead of waiting.

To improve the Regenerative Path Tracing, (Antwerpen, 2011) proposed the Streaming Path Tracing which compacts the regenerated threads to increase their coherence for their primary closest intersection tests.

Later, (Laine et al., 2013) highlighted the register pressure problem of the mega kernel approach (one single kernel devoted to the algorithm), especially when complex materials are used. They introduced the Wavefront Path Tracing, which splits the algorithm in different kernels. In order to reduce the register spilling and to improve the coherence, a kernel was dedicated to each material. This implementation showed a performance gain with scene made of complex materials. However, for a scene containing simple materials, the sorting step (to dispatch the workload to each kernel) and the kernel launching overhead neutralized the performance gain.

(Davidovič et al., 2014) made an exhaustive GPU implementation survey of the Path Tracing. They proposed new approaches and benchmarked the different implementations. The Multi Kernel Streaming Path Tracing was the most performance portable implementation.

2.2 Spectral Rendering

To simulate correctly the light transport, Spectral Rendering is mandatory. Within the computer graphics community, Spectral Rendering is used to make colorimetry validation and predictive rendering.

The simplest way to do spectral rendering consists in carrying one wavelength per path. However, this approach proves to be inefficient because a path is often valid for more than one wavelength. (Evans and McCool, 1999) proposed to reuse a path for a cluster of wavelengths sampled by the lights of the scene. To handle the refractions (one ingoing and outgoing direction valid for only one wavelength), the authors proposed three strategies:

- **Degradation:** A wavelength is chosen to continue the path. The other wavelengths are degraded (their propagation are stopped), which increases the variance.
- **Splitting:** The path is split for each wavelength. This strategy is not easy to implement and it is time consuming.
- **Deferral:** A path is generated for one wavelength. If no refraction occured, the path is reused to compute the other wavelengths.

(Radziszewski et al., 2009) improved this technique by introducing a spectral sampling during the path generation. In order to reduce the variance, the authors suggested to use a MIS (Multi Importance Sampling) (Veach and Guibas, 1995) to take into account the different probability density functions of the wavelength carried by a path.

(Wilkie et al., 2014) clarified the use of multiple wavelengths per path and the MIS method. They proposed a simple but optimized approach. The cluster of wavelengths was generated by one wavelength (named “hero wavelength” by the authors) by applying a regular offset in order to cover the visible range.

3 SPECTRAL IMAGE RENDERING FRAMEWORK

3.1 Why Can’t We Use the Previous Spectral Rendering Works?

The goal of the Spectral Rendering methods in the Computer Graphics community is to compute the tristimulus XYZ. This triplet can be seen as three overlapping channels over the Visible range which integrate the same wavelength samples with different sensor response curve (CIE XYZ curves). These methods don’t match our objectives since:

- The spectral output of each channel have to be conserved without the integration of a sensor response curve (e.g. CIE XYZ curves).
- The channels don’t always overlap, therefore they can’t share the wavelength samples. The spectral domain of the light transport equation has also to be discretized.
- The channel intervals are not always adjacent and uniformly sized. Therefore this dismisses the usage of a regular offset method (Wilkie et al., 2014) to generate a path wavelength cluster.

3.2 The Inputs and Output of the Simulation

The inputs of simulation are spectral data (reflectance, complex index of refraction, ...). They can be stored as a tabulated spectrum, but the bounds retrieval of a query (wavelength sample) to compute the interpolated value requires the use of a binary search. At the moment, we use regular spaced spectrum which gives us a good performance since we can easily retrieve the bounds. The number of sample of each spectrum is entirely dynamic which gives us a good accuracy if needed.

3.3 The Spectral Output Data Structure

The spectral output of the simulation must be stored in a suitable data structure. An efficient and robust data structure for these data is an open problem, further research has to be done. The most straightforward approach is the use of a spectral image composed with K numbers of channels, nevertheless it is memory-wise (3d image) and computation-wise (each channel needs to be processed) inefficient.

As described previously, a channel is not a wavelength but the integration of the spectral radiance over a spectral interval. The spectral radiance is usually weighted by a sensor response curve before the integration. If a large number of sensors have to be evaluated for the same scene, it would be inefficient to recompute the spectral image for each sensor. To reuse the spectral output later, the spectral radiance of the channels are not integrated with a response curve of a sensor. The response curves have to be considered constant in the spectral interval of the simulated channel to be able later to integrate these data correctly. If it's not the case, we need smaller channels to integrate them with a piecewise constant function which corresponds to the response curve in the sensor channel.

3.4 The Light Transport Equation Reformulation

In order to render a spectral image of K number of channels, the spectral domain of the light transport equation has to be discretized. We need to compute a pixel of a such image according to the equation below:

$$P = \begin{bmatrix} \int_{\lambda min_1}^{\lambda max_1} \int_{\omega \in \Omega} f_1(\omega, \lambda)\, \mathrm{d}\omega \mathrm{d}\lambda \\ \vdots \\ \int_{\lambda min_k}^{\lambda max_k} \int_{\omega \in \Omega} f_k(\omega, \lambda)\, \mathrm{d}\omega \mathrm{d}\lambda \end{bmatrix} \quad (1)$$

Where:

P : The spectral pixel.

λmin_k : Lower bound of the channel k.

λmax_k : Upper bound of the channel k.

Ω : Path space.

λ : Wavelength sample.

ω : Path sample.

$f_k(\omega, \lambda)$: Measure function of the channel k.

This approach is however inefficient especially if an image has to be computed with a very large number of channels, since a path can carry multiple wavelengths for the most of material. Therefore, to be efficient, a same path has to carry at least one wavelength sample per channel. Otherwise, more paths would be required to refine the spectral image.

Moreover, the spectral intervals are not necessarily adjacent and their size are not always equal, hence we cannot use the hero wavelength cluster generation of (Wilkie et al., 2014) to avoid the generation cost and the storage of a wavelength sample per channel per path. Instead of that, we generate a unique uniform sample μ between 0 and 1 per path and we use this linear interpolation mapping function between the bounds of each channel to retrieve their wavelength sample:

$$\Lambda_k(\mu) = (1-\mu)\,\lambda min_k + \mu\,\lambda max_k \quad (2)$$

Using the previous statements, we can rewrite the eq. (1):

$$\begin{aligned} P &= \int_{\omega \in \Omega} \begin{bmatrix} \int_{\Lambda_1(0)}^{\Lambda_1(1)} f_1(\omega, \lambda)\, \mathrm{d}\lambda \\ \vdots \\ \int_{\Lambda_k(0)}^{\Lambda_k(1)} f_k(\omega, \lambda)\, \mathrm{d}\lambda \end{bmatrix} \mathrm{d}\omega \\ &= \int_0^1 \int_{\omega \in \Omega} \begin{bmatrix} f_1(\omega, \Lambda_1(\mu))\, \Lambda_1'(\mu) \\ \vdots \\ f_k(\omega, \Lambda_k(\mu))\, \Lambda_k'(\mu) \end{bmatrix} \mathrm{d}\omega \mathrm{d}\mu \end{aligned} \quad (3)$$

This equation can be solved by the Monte-Carlo method:

$$\langle P \rangle \approx \frac{1}{N} \sum_{i=1}^{N} \begin{bmatrix} \frac{f_1(\omega_i, \Lambda_1(\mu_i))\, \Lambda_1'(\mu_i)}{p_1(\omega_i, \mu_i)} \\ \vdots \\ \frac{f_k(\omega_i, \Lambda_k(\mu_i))\, \Lambda_k'(\mu_i)}{p_k(\omega_i, \mu_i)} \end{bmatrix} \quad (4)$$

Where:

N : The number of samples.

$p_k(\omega_i, \mu_i)$: The probability density function of the channel k with the path sample ω_i and the uniform sample μ_i.

3.5 The Path Samples Generation

The viability of the spectral sampling methods (Wilkie et al., 2014) for paths carrying a lot of wavelength samples needs to be investigated. Therefore, at the moment, our path decisions (extension or termination) are based by either on the importance sampling of the mean value of the input spectral data (materials and the light) or on an uniform sampling. Since it's not wavelength dependent, the probability density function $p_k(\omega_i, \mu_i)$ can be reduced to:

$$\begin{aligned} p_k(\omega_i, \mu_i) &= p(\mu_i)\, p(\omega_i | \Lambda_k(\mu_i)) \\ &= p(\omega_i) \end{aligned} \quad (5)$$

We can now rewrite the eq. (4) as:

$$\langle P \rangle \approx \frac{1}{N} \sum_{i=1}^{N} \frac{1}{p(\omega_i)} \begin{bmatrix} f_1(\omega_i, \Lambda_1(\mu_i))\, \Lambda_1'(\mu_i) \\ \vdots \\ f_k(\omega_i, \Lambda_k(\mu_i))\, \Lambda_k'(\mu_i) \end{bmatrix} \quad (6)$$

If an ideal refraction is encountered during the propagation (fig. 3), we use the degradation strategy (Evans and McCool, 1999). This strategy chooses randomly one wavelength to continue the propagation and stops the others. In this case, the throughput of the chosen wavelength sample has to be scaled by the number of wavelength samples carried by the path.

(a) 16 spp. (b) 1,024 spp.

Figure 3: Refraction with degradation of paths which carry 64 wavelength samples at different spp (number of sample per pixel).

3.6 Visualization

Since the spectral radiation of a scene at the input of a sensor is refined in a spectral image, a color image (RGB, false color, grayscale...) can be produced at any moment for display purpose if needed. If we change the sensor curve (XYZ, Camera RGB curves...) or the way to convert the spectral data to a color, the simulation don't have to be reseted. This advantage can be useful for predictive rendering and colorimetric validation. However, as stated in the section 3.3, a good amount of channel is needed to be accurate if the sensor response curve is not constant on the spectral interval of the image. Another interesting feature of this kind of rendering is to be able to visualize in real time the output spectrum of a pixel of the image (fig. 1).

4 THE STRAIGHTFORWARD APPROACH OF THE PATH TRACING ON GPU

Our GPU methods are based on the Streaming Path Tracing (Antwerpen, 2011). The Multi Kernel implementation is chosen because the performances are more portable amongst the different GPU Vendors (Davidovič et al., 2014). Moreover, most of the intersection libraries on GPU (Optix Prime (NVIDIA,), Radeon-Rays (AMD,) ...) do not provide an intersection device function which would allow us to integrate it in a Mega Kernel. So we need to split at least some parts of the algorithm to communicate with these libraries.

4.1 Algorithm

The straightforward approach would be to extend and evaluate the path at each bounce. In this case, the states of every wavelength sample of each path have to be kept alive, since the full path is not known and some values (spectral radiance and path throughput) have to be accumulated.

To be efficient, a path has to be reused by at least one wavelength sample per channel. When the number of channels will raise, this approach would lead us to high memory consumption and latency problems, since the states of each wavelength sample have to be updated from the global memory at each bounce.

It should be noted that a Mega Kernel implementation does not solve these problems since the wavelength sample states won't be able to fit into the registers or the local memory. The only possibility is to store them in the global memory.

4.2 The Memory Consumption

The memory consumption of this method is proportional to the number of channels (fig. 4) since we need to store for each thread:

- The path state which weights 32 bytes composed by :
  - The idle state.
  - The current depth.
  - The pixel index.
  - The ray index.
  - The random number generator.
  - The spectral sample μ.
  - The last material PDF (For MIS).
  - The selected channel index in case of refraction.
- For each channel, the wavelength sample state which weights 16 bytes (4 padding bytes):
  - The throughput.
  - The spectral radiance.
  - The direct light contribution (For a Multi Kernel implementation, we need to add it later to the spectral radiance if the shadow ray is not occluded).

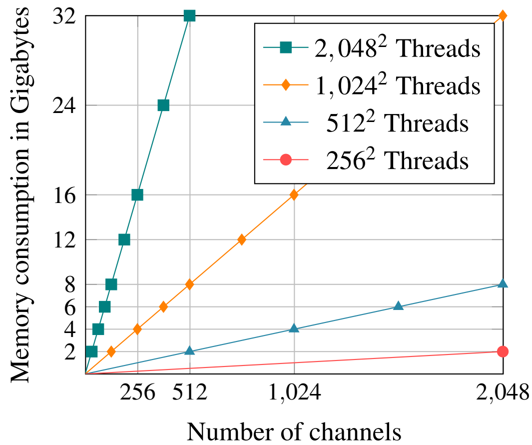

Figure 4: Memory consumption of the Path Tracing for different threads pool sizes.

This is problematic because it limits the number of channels and the size of the pool threads. We saw during our experiments that a size between $1,024^2$ and $2,048^2$ threads is required to reach the peak of performance. A pool of $1,024^2$ threads would quickly limit the number of channels (e.g. 512 channels for around 8.2 GB of memory footprint).

5 DPEPT: DEFERRED PATH EVALUATION PATH TRACING

5.1 Algorithm

The DPEPT consists in two following steps:

1. The building and the saving of the full path.
2. The evaluation of the wavelength samples of the saved paths.

To reduce the memory consumption, the wavelength samples are evaluated per batch by reloading their path (fig. 5). Since registers are scarce and precious resources (and they have to be spared for the path evaluation), the state of a batch are stored in the local memory to reduce latency (algorithm 1).

≋		≋
EvalPath(ω_0, β_0^0) ⋮ EvalPath(ω_0, β_b^0)	…	EvalPath(ω_p, β_0^p) ⋮ EvalPath(ω_p, β_b^p)

Figure 5: One path per work-item parallelization pattern of a work-group for the paths evaluation. ≋ is a work item (thread of the work group). EvalPath(ω_p, β_b^p) is the evaluation of the path sample p for its wavelength sample batch b (algorithm 1).

5.2 Parallelism over Wavelength Samples Batches

Although the DPEPT was better than the straightforward method, the performance was not enough sufficient. To improve the path evaluation step of the DPEPT, a wavelength samples batches parallelization pattern (fig. 6) has been developed.

≋		≋
EvalPath(ω_0, β_0^0) ⋮ EvalPath(ω_p, β_0^p)	…	EvalPath(ω_0, β_b^0) ⋮ EvalPath(ω_p, β_b^p)

Figure 6: Wavelength samples batches per work-item parallelization pattern of a work-group for the paths evaluation. ≋ is a work item (thread of the work group). EvalPath(ω_p, β_b^p) is the evaluation of the path sample p for its wavelength sample batch b (algorithm 1).

Instead of processing a path per work item (fig. 5), the whole work group processes different wavelength samples batch of the same path at the same time. This way, the work group instruction coherence is nearly perfect. And since the work items read exactly the same path, the cache miss decreases and we can benefit from the broadcast feature if it's available.

However, in order to be fully utilized, the workgroup needs to have enough batch. On AMD hardware (16-wide SIMD units), when the number of channels is less than 16, the version 1 (fig. 5) is better than the version 2 (fig. 6).

5.3 The Memory Consumption

The memory consumption of this implementation is dependent on the maximum number of bounces of a path (fig. 7) since we need to store for each thread:

- The path state which weights 32 bytes composed by :
  - The idle state.
  - The current depth.
  - The pixel index.
  - The ray index.
  - The random number generator.
  - The spectral sample μ.
  - The last material PDF (for MIS).
  - The selected channel index in case of refraction.

- A number of vertex which each weights 80 bytes (8 padding bytes) composed by:
  - An integer to store some flags (if a shadow ray was not occluded...).
  - The material ID.
  - The light ID.
  - The direction to the light.
  - The light sample PDF (The cosinus term and the MIS weight are packed in the PDF).
  - The outgoing direction to the light (BSDF space).
  - The ingoing direction (BSDF space).
  - The outgoing direction (BSDF space).
  - The surface self emission MIS weight.
  - The material sample PDF (The cosinus term and the MIS weight are packed in the PDF).

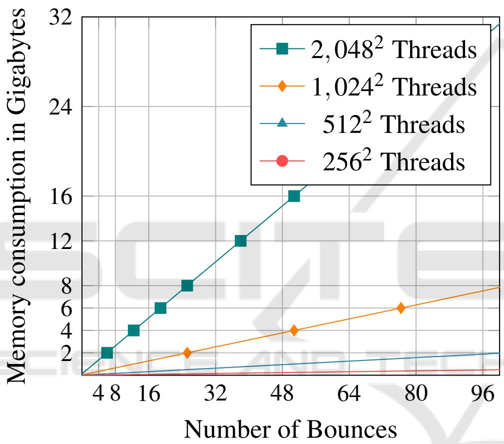

Figure 7: Memory consumption of the DPEPT implementation for different thread pool sizes.

GPUs don't mostly support dynamic allocation on the device side. And when they do, it's strongly advised to not use this feature. Therefore for each thread, a maximum of path vertex has to be preallocated on the host side. Hopefully we do not need as much bounce as channel. Therefore, regardless the number of channels, a pool of $1,024^2$ threads with 32 bounces will consume for around 2.6 GB. Although the size of a path vertex will increase when complex materials (texture, volume...) will be added, there is still plenty of room before reaching the level of memory consumption of the straightforward approach.

6 RESULTS

To compare the PT (conventional Path Tracing) and the DPEPT methods, a benchmark (fig. 8) has been made. It consists in measuring the number of paths completed per second (raw performance) and the FPS (interactivity) at different thread pool sizes and number of channels.

The benchmark (fig. 8) has been run on the following scene:

- Cornell box: The maximum depth of this easy indoor scene has been fixed at 5 bounces.
- Conference: The maximum depth of this medium-complex indoor scene has been fixed at 8 bounces.
- Aircraft: An easy outdoor scene which is typically used to dimension aircraft detection sensors. The scene contains a spectral environment light generated by MATISSE (Simoneau et al., 2006). The maximum depth has been fixed at 5 bounces.
- Statues: A medium-complex outdoor scene which contains a refractive object and a spectral environment light converted from a rgb hdr image. The maximum depth has been fixed at 16 bounces.

Except Suzanne (Blender) and the Aircraft (ONERA), the other meshes come from (McGuire, 2017).

For a $1,024^2$ pool of thread with 16 bounces on a Fury X (4GB of VRAM), a full HD image would limit the number of channels to around 220 for the DPEPT and to around 127 for the PT. Therefore, in order to be not limited by the memory consumption of the spectral image, the spatial image resolution was fixed to 512x512.

When the number of channels is under 8, the performance of our method is usually a bit subpar compared to the Path Tracing. However, when the number of channels raises, the Path Tracing is considerably slower than our method.

Due to its lower memory consumption, the DPEPT can render more channels than the straightforward Path Tracing approach which limits the size of the thread pool.

For instance if we render a image with 512 spectral channels, the Path Tracing won't be able to allocate a thread pool size of $1,024^2$ on the Fury X (4GB of VRAM). Our technique can easily reach the size of $1,024^2$ threads and it is thus faster by around 38 times on average (fig. 9).

The results of the benchmark show us that our method allows us to render at interactive frame rate (around 10 FPS) a hyper spectral image (between 100 and 200 channels).

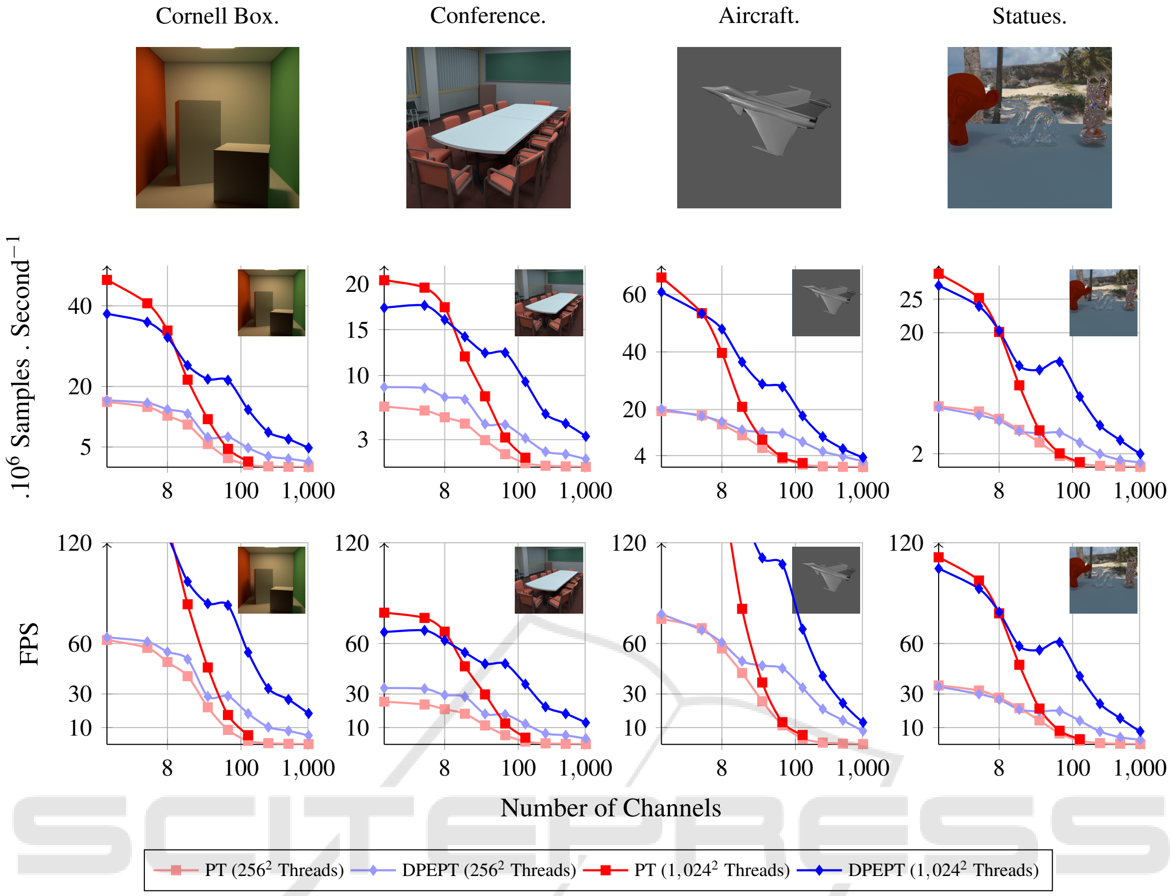

Figure 8: Benchmark with an AMD Fury X (VRAM: 4GB). The scaling of the x-axis is a logarithm base 2.

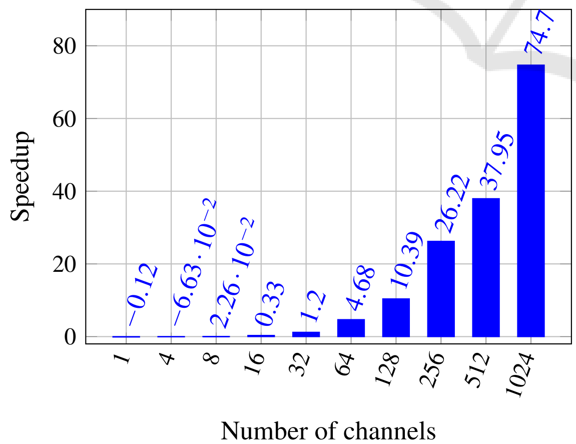

Figure 9: Average DPEPT speedup of the raw performance over the PT for the benchmark (fig. 8).

7 TECHNICAL DETAILS

We use SYCL to implement our rendering engine. SYCL is the new royalty-free Khronos Group standard that allows to code in OpenCL in a single C++ source fashion. It lowers the burden of programmer by managing the data movement transaction between the host and device. Therefore, the programmer can focus on the optimization of his kernels. At the moment there are three implementations of the standard: ComputeCpp (Codeplay,), TriSYCL (Khronos-Group,) and SYCL-GTX (Žužek,). We use the beta of the Community edition of ComputeCpp, since it is the most advanced implementation at the time of this publication.

To compute the ray and shadow ray intersections, we use Radeon-Rays. It is an AMD open source library for ray tracing. Like Optix Prime, we need to provide a ray buffer, and the library returns a hit point buffer. The library can use different back-ends: Vulkan, OpenCL and Embree. We have chosen the OpenCL back-end since we can use it via the interoperability feature of SYCL.

8 CONCLUSION

In this article, we endeavour to simulate efficiently and accurately spectral image (fig. 1). The previous works in spectral rendering don't fulfill the requirements (section 3.1). Therefore, a new framework (section 3) has been described to render a spectral image composed with K number of channels.

The rendering of a such spectral image will lead us to three major issues: the computation time, the footprint of the spectral image, and the memory consumption of the algorithm. The computation time can be drastically reduced by the use of GPUs, however, their memory capacity and bandwidth (compared to their compute power) are limited. When the number of channels will raise, the straightforward method (section 4) will lead us to high memory consumption and latency problems.

To overcome these problems, we propose the DPEPT (section 5.1) which consists in decoupling the path evaluation from the path generation. The memory consumption of this approach is not dependent on the number of channels. Its path evaluation step can be efficiently parallelized (section 5.2). Our method outperforms the straightforward approach when the spectral resolution of the simulated image raises. Our contributions enable to render multi, hyper and even ultra (more than 1,000 channels) spectral image. Interactive frame rate of hyper spectral image rendering can be achieved for easy and medium complex scene.

However we think there are still room to improve the compute time and the convergence of the simulation. More over, the footprint of the spectral image problem is not yet solved, therefore it can limit the simulation if the spectral image is too big to fit in the global memory of a GPU.

9 FUTURE WORK

The possible future work would consist in:

- Improving the compute time. We have made the assumption that it's needed to compute one wavelength sample per channels per path, maybe we can find a better tradeoff between the number of wavelength samples to evaluate per path and the number of path to trace.
- Investigating the feasibility of the spectral MIS (Wilkie et al., 2014) for paths which carry a large number of wavelength samples on GPU. It would improve the convergence of the algorithm when using high wavelength dependent materials.
- Exploring the viability of Out-of-Core methods to refine the spectral image.
- Working on an efficient and compact data structure to refine the spectral output. Right now, the output are stored in a spectral image composed with K number of channel (3d image) which is computational-wise and memory-wise inefficient.
- Studying an efficient multi GPU parallelization pattern for a spectral image rendering.

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REFERENCES

AMD. Radeon-rays. https://github.com/GPUOpen-Libraries AndSDKs/RadeonRays_SDK.

Antwerpen, D. V. (2011). Improving SIMD Efficiency for Parallel Monte Carlo Light Transport on the GPU. *Hpg 2011*, (X):10.

Codeplay. Computecpp. https://www.codeplay.com/ products/computesuite/computecpp.

Coiro, E. (2012). Global Illumination Technique for Aircraft Infrared Signature Calculations. *Journal of Aircraft*, 50(1):103–113.

Davidovič, T., Křivánek, J., Hašan, M., and Slusallek, P. (2014). Progressive Light Transport Simulation on the GPU. *ACM Transactions on Graphics*, 33(3):1–19.

Evans, G. F. and McCool, M. D. (1999). Stratified wavelength clusters for efficient spectral Monte Carlo rendering. In *Proceedings of the 1999 conference on Graphics interface '99*, pages 42–49.

Kajiya, J. T. (1986). The Rendering Equation. *SIGGRAPH Comput. Graph.*, 20(4):143–150.

KhronosGroup. Trisycl. https://github.com/triSYCL/ triSYCL.

Laine, S., Karras, T., and Aila, T. (2013). Megakernels Considered Harmful: Wavefront Path Tracing on GPUs. *mediatech.aalto.fi*, (typically 32).

McGuire, M. (2017). Computer graphics archive. https://casual-effects.com/data.

Novák, J., Havran, V., and Dachsbacher, C. (2010). Path Regeneration for Interactive Path Tracing. *Eurographics 2010*, pages 1–4.

NVIDIA. Optix prime. https://developer.nvidia.com/optix.

Purcell, T. J., Buck, I., Mark, W. R., and Hanrahan, P. (2002). Ray tracing on programmable graphics hardware. *ACM Transactions on Graphics (TOG) - Proceedings of ACM SIGGRAPH 2002*, 21:703–712.

Radziszewski, M., Boryczko, K., and Alda, W. (2009). An improved technique for full spectral rendering. *Journal of WSCG*, 17(1-3):9–16.

Rohde, R. A. (2007). Atmospheric transmission. https://en.wikipedia.org/wiki/File:Atmospheric_Transmission.png.

Simoneau, P., Caillault, K., Fauqueux, S., Huet, T., Krapez, J.-C., Labarre, L., Malherbe, C., and Miesch, C. (2006). Matisse: Version 1.4 and future developments. 6364.

Žužek, P. Sycl-gtx. https://github.com/ProGTX/sycl-gtx.

Veach, E. and Guibas, L. J. (1995). Optimally combining sampling techniques for Monte Carlo rendering. *Proceedings of the 22nd annual conference on Computer graphics and interactive techniques - SIGGRAPH '95*, pages 419–428.

Whitted, T. (1979). An improved illumination model for shaded display. *ACM SIGGRAPH Computer Graphics*, 13(2):14.

Wilkie, A., Nawaz, S., Droske, M., Weidlich, A., and Hanika, J. (2014). Hero Wavelength Spectral Sampling. *Computer Graphics Forum*, 33(4):123–131.

APPENDIX

Algorithm 1: Evaluation of the path ω for the wavelength batch β.

Local Memory:

L : Spectral radiances of the batch β.

τ : Path throughputs of the batch β.

Global Memory:

V : Saved Paths vertices.

I : Spectral Image.

Function:

At the vertex v for the wavelength λ:

$Env(v,\lambda)$: Environment light contribution.

$NEE(v,\lambda)$: Direct light contribution.

$Le(v,\lambda)$: Self emission of the surface.

$\mathcal{T}(v,\lambda)$: Path throughput.

```
Function EvalPath(ω, β):
    // Initialize the batch
    foreach λ ∈ β do
        L[λ] = 0
        τ[λ] = 1
    end

    // Evaluation of the batch
    foreach v ∈ V[ω] do
        if v is a miss vertex then
            // Environment light
            foreach λ ∈ β do
                L[λ] += τ[λ] * Env(v,λ)
            end
        else
            foreach λ ∈ β do
                // Next event estimation
                L[λ] += τ[λ] * NEE(v,λ)
                // Surface self emission
                L[λ] += τ[λ] * Le(v,λ)
                // Update the throughput
                τ[λ] *= T(v,λ)
            end
        end
    end

    // Refine the spectral image
    foreach λ ∈ β do
        Refine(I[ω.pixelID], L[λ])
    end
return
```