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# Performance of OpenMP loop transformations for the acoustic wave stencil on GPUs

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## OpenMP and heterogeneous architectures

- The support for heterogeneous architectures was introduced in OpenMP 4.0 and OpenMP 4.5.
- OpenMP 5.1 introduced *unroll* and *tiling* loop transformations. Code offloading for these transformations is supported in Clang 13.
- Despite being around for decades, the availability of these transformations for portability across compilers in OpenMP is relatively new. And we exercise it.

## The application kernel

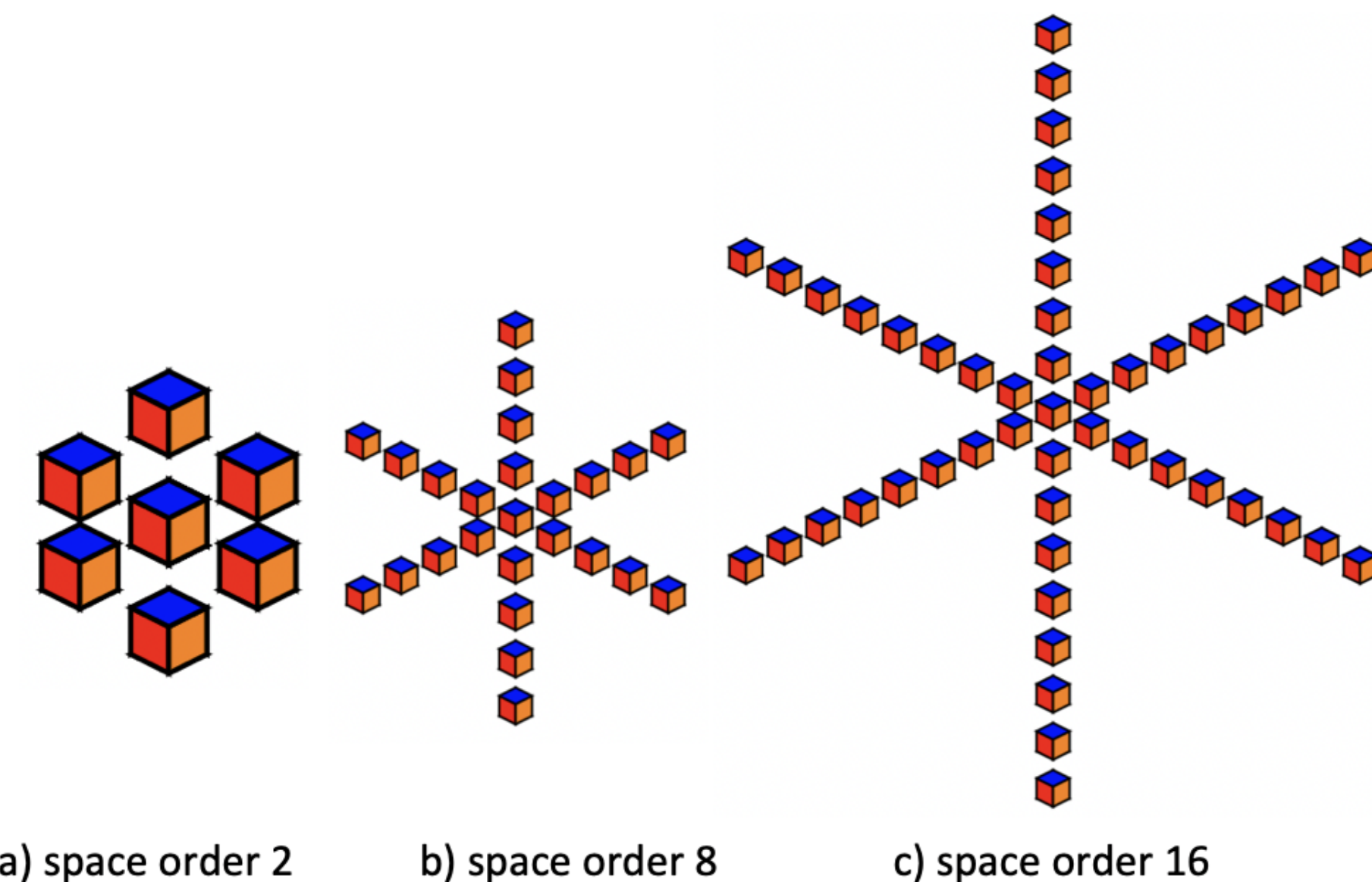
Kernel of seismic applications such as in full-waveform inversion (FWI) and reverse-time migration (RTM), the propagation of acoustic waves can be modeled as follows:

$$\frac{1}{v_p^2} \frac{\partial^2 p(\mathbf{x}, \mathbf{y}, \mathbf{z}, t)}{\partial t^2} - \nabla^2 p(\mathbf{x}, \mathbf{y}, \mathbf{z}, t) = f(\mathbf{x}, \mathbf{y}, \mathbf{z}, t) \quad (1)$$

where  $v_p$  is the velocity,  $p(\mathbf{x}, \mathbf{y}, \mathbf{z}, t)$  is the pressure field, and  $f(\mathbf{x}, \mathbf{y}, \mathbf{z}, t)$  is the source. This PDE is solved by finite differences on a 3D grid spaced by distances  $\Delta x$ ,  $\Delta y$ , and  $\Delta z$ . By using second-order central differences, we get the following discretized equation (for 2nd-spatial order), where  $\Delta t$  is the time increment:

$$p_{i,j,k}^{(n+1)} = 2p_{i,j,k}^{(n)} - p_{i,j,k}^{(n-1)} + 2\Delta t^2 \cdot v^2 \left( \frac{p_{i+1,j,k}^{(n)} - 2p_{i,j,k}^{(n)} + p_{i-1,j,k}^{(n)}}{\Delta x^2} + \frac{p_{i,j+1,k}^{(n)} - 2p_{i,j,k}^{(n)} + p_{i,j-1,k}^{(n)}}{\Delta y^2} + \frac{p_{i,j,k+1}^{(n)} - 2p_{i,j,k}^{(n)} + p_{i,j,k-1}^{(n)}}{\Delta z^2} \right) \quad (2)$$

A major performance issue with stencils is their high demand for memory access.



a) space order 2 b) space order 8 c) space order 16  
Figure 1: Shapes of 3D stencils used in the experiments.

## Setup of Experiments

- Experiments on three GPU architectures (see Table 1)
- Discretized 2nd time order, space orders of 2, 8, and 16;
- Grid sizes:  $256^3$ ,  $512^3$ , and  $1024^3$  points with 400, 800, and 1600 time steps;
- Float precision FP32, and FP64;
- Four strategies: collapse, unroll, tile, tile+unroll. For tiling, best block shapes were obtained via auto-tuning.

Table 1: GPUs architecture specifications.

	RTX 2080 Super	V100	A100
GPU Architecture	Turing	Volta	Ampere
SMs	48	80	108
CUDA cores / GPU	3072	5120	6912
Peak FP64 TFLOPS	0.35	7.8	9.7
Peak FP32 TFLOPS	11.2	15.7	19.5
Memory Size	8 GB	32 GB	40 GB
Memory Bandwidth	496 GB/s	900 GB/s	1555 GB/s
Shared Memory / SM	64 KB	96 KB	164 KB
L2 Cache Size	4 MB	6 MB	40 MB

```

1 for(int t = 0; t < time_steps; t++) {
2   #pragma omp target teams distribute parallel for \
   collapse(3)
3   #pragma omp tile sizes(BLOCK1, BLOCK2, BLOCK3)
4   for(int i = radius; i < d1 - radius; i++){
5     for(int j = radius; j < d2 - radius; j++){
6       for(int k = radius; k < d3 - radius; k++){
7         ...
8         #pragma omp unroll full
9         for(int ir = 1; ir <= radius; ir++){
10          // stencil point calculation

```

Listing 2: Using tiling and unroll.

Table 2: Tile sizes applied to 2nd spatial order with FP64.

GPU	Grid size	Best tile sizes		
		Axis 1	Axis 2	Axis 3
RTX 2080	$256^3$	32	1	4
	$512^3$	16	1	4
V100	$256^3$	1	1	4
	$512^3$	8	1	2
A100	$1024^3$	8	1	2
	$256^3$	2	2	4
	$512^3$	2	1	4
	$1024^3$	8	1	4

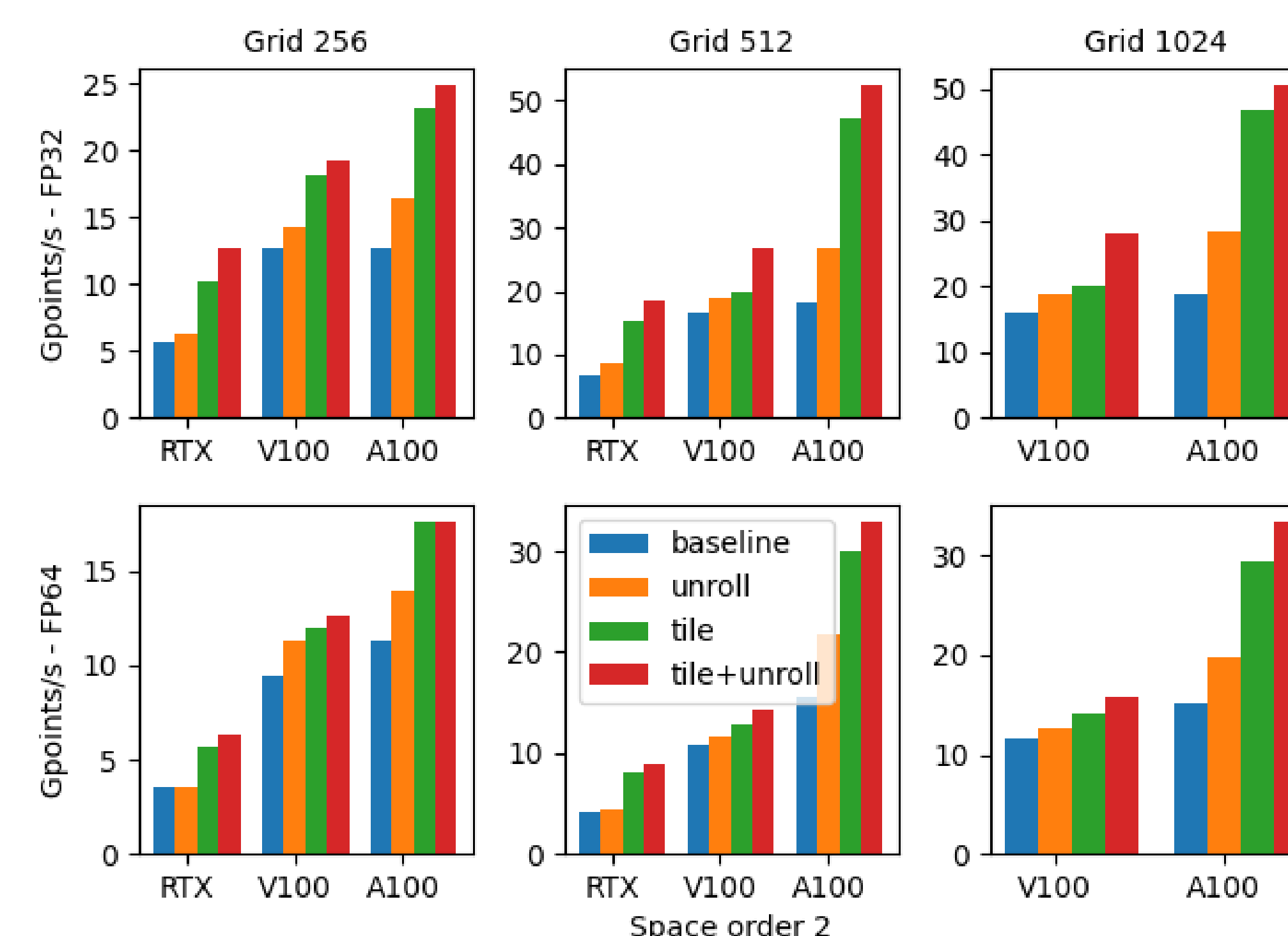


Figure 2: Gpoint/s for space order 2.

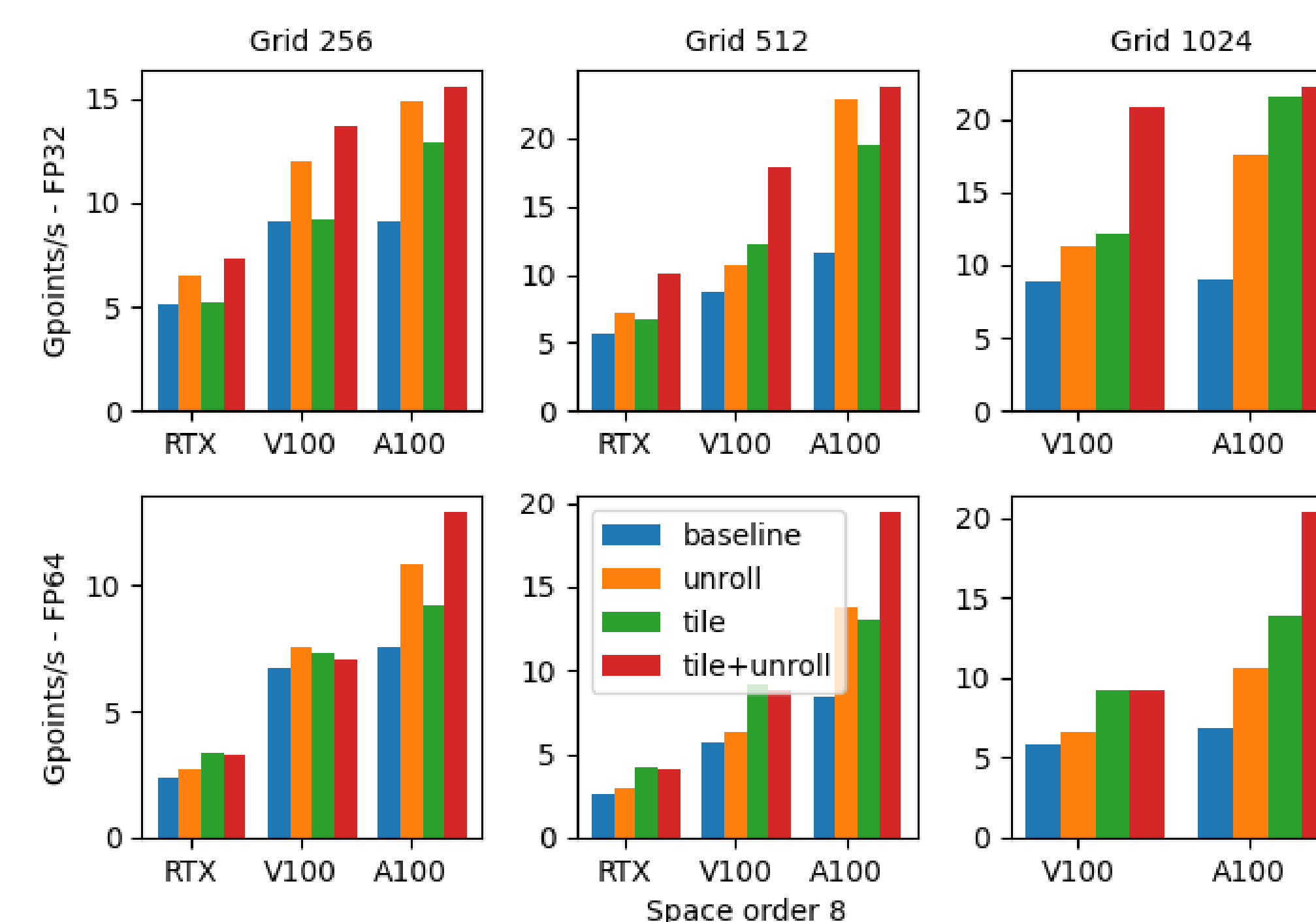


Figure 3: Gpoint/s for space order 8.

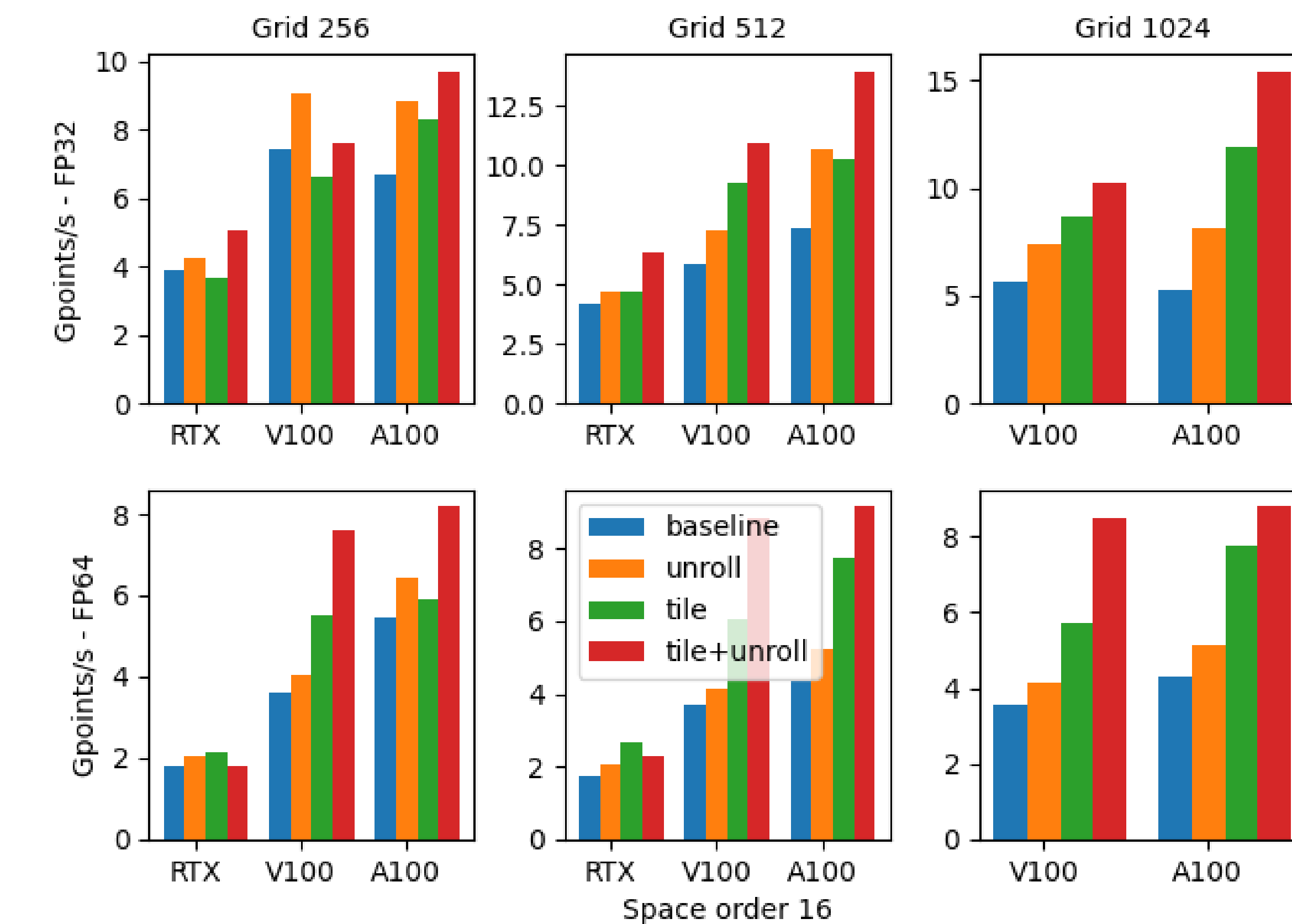


Figure 4: Gpoint/s for space order 16.

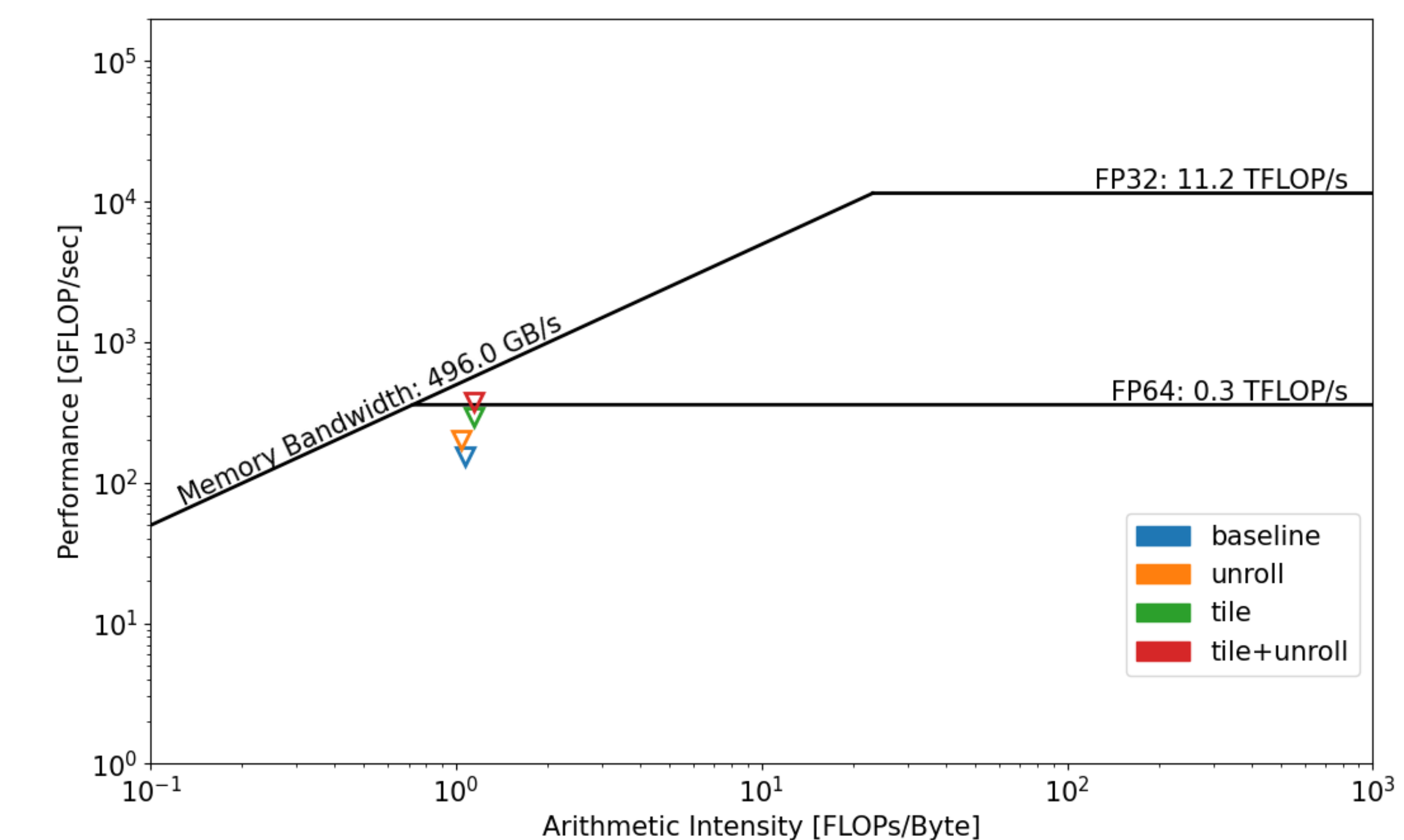


Figure 5: Roofline plot for FP32, 2nd space order on RTX 2080 Super.

## Main Findings

- As a general remark, both loop transformations, unroll and tiling can yield significant improvements to the performance of the kernel evaluated on all GPUs evaluated.
- Performance gains ranged from 1.13x to 2.93x. In most scenarios, the best performance was achieved by combining unroll and tiling.
- The performance of tiling is highly sensitive to the choice of block size.

```

1 for(int t = 0; t < time_steps; t++) {
2   #pragma omp target teams distribute parallel for \
   collapse(3)
3   for(int i = radius; i < d1 - radius; i++){
4     for(int j = radius; j < d2 - radius; j++){
5       for(int k = radius; k < d3 - radius; k++){
6         ...
7         for(int ir = 1; ir <= radius; ir++){
8           // stencil point calculation

```

Listing 1: The baseline strategy for the wave equation on GPUs.