



# Fast Neural Representations for Direct Volume Rendering

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## Abstract

*Despite the potential of neural scene representations to effectively compress 3D scalar fields at high reconstruction quality, the computational complexity of the training and data reconstruction step using scene representation networks limits their use in practical applications. In this paper, we analyse whether scene representation networks can be modified to reduce these limitations and whether such architectures can also be used for temporal reconstruction tasks. We propose a novel design of scene representation networks using GPU tensor cores to integrate the reconstruction seamlessly into on-chip raytracing kernels, and compare the quality and performance of this network to alternative network- and non-network-based compression schemes. The results indicate competitive quality of our design at high compression rates, and significantly faster decoding times and lower memory consumption during data reconstruction. We investigate how density gradients can be computed using the network and show an extension where density, gradient and curvature are predicted jointly. As an alternative to spatial super-resolution approaches for time-varying fields, we propose a solution that builds upon latent-space interpolation to enable random access reconstruction at arbitrary granularity. We summarize our findings in the form of an assessment of the strengths and limitations of scene representation networks for compression domain volume rendering, and outline future research directions. Source code: <https://github.com/shamanDevel/fv-SRN>*

**Keywords:** volume rendering, neural networks, compression algorithms

**ACM CCS:** • Computing methodologies → Ray tracing; Neural networks

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## 1. Introduction

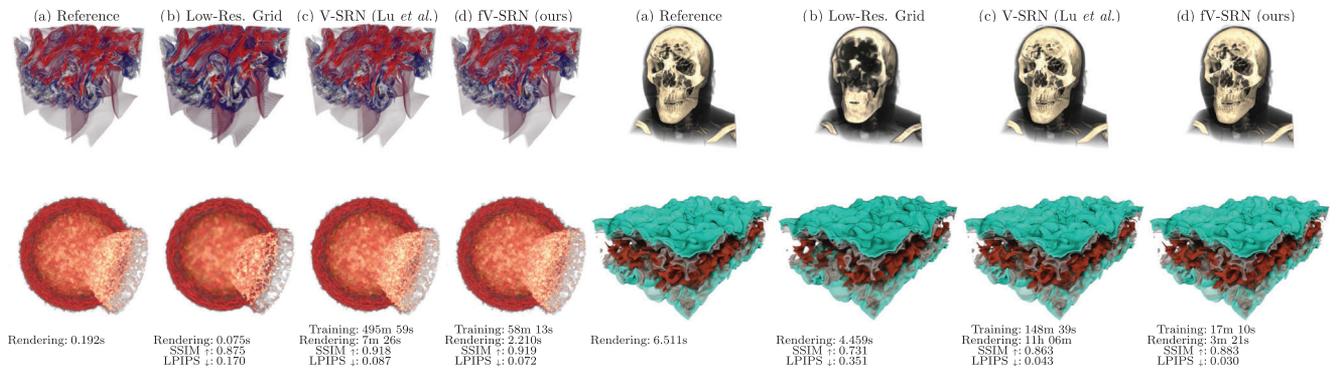
Learning-based lossy compression schemes for 3D scalar fields using neural networks have been proposed recently. While first approaches have leveraged the capabilities of such networks to learn general properties of scientific fields and use this knowledge for spatial and temporal super-resolution [ZHW\*17, HW20, GYH\*20, HW19], Lu *et al.* [LJLB21] have focused on the use of scene representation networks (SRNs) [PFS\*19, SZW19, MST\*20] that overfit to a specific dataset to achieve improved compression rates.

SRNs were introduced as a compact encoding of (coloured) surface models. They replace the initial model representation with a learned function that maps from domain locations to surface points. SRNs are modelled as fully connected networks where the scene is encoded in the weights of the hidden layers. This scene encoding—the so-called latent-space representation—can be trained from images of the initial object via a differentiable ray-marcher, or in object-space using sampled points that are classified as inside or outside the surface. Since SRNs allow for direct access of the encoded model at arbitrary domain points, ray-marching can work on

the compact representation without having to decode the initial object.

Lu *et al.* [LJLB21] introduced *neurcomp*, an SRN where the mapping function has been trained to yield density samples instead of surface points. We subsequently refer to an SRN that predicts density samples as volume representation network (V-SRN). By using a V-SRN, a ray-marcher can sample directly from the compact latent-space representation, and does not require to decode the initial volume beforehand. However, at every sample point along the view-rays, a deep network is called to infer the density sample.

Since SRNs are implemented using generic frameworks like PyTorch or Tensorflow where the basic building block is a network layer, intermediate states of each layer need to be written to global memory to make it available to the next layer. Thus, the evaluation becomes heavily memory-bound when deep networks consisting of multiple layers are used. Due to this reason, direct volume rendering using V-SRN is currently limited to non-interactive applications, with frame rates that are significantly below what can be achieved on the initial data. Furthermore, the size of the networks that are



**Figure 1:** Performance and quality comparison of volume representation networks (SRNs). (a) The original datasets. (b) Low-pass filtered versions, sub-sampled to meet the selected compression rate. (c) *neurcomp* by Lu et al. [LJLB21]. (d) Our proposed fV-SRN. From left to right, top to bottom: Richtmyer–Meshkov (RM), Skull (each of resolution  $256^3$ , 8-bit), Ejecta ( $1024^3$ , 16-bit), Jet ( $512 \times 336 \times 768$ , 32-bit floating-point, courtesy of Lu et al.). The same network configuration was used for all datasets. Compression rates for (b)–(d): 1:32 for RM and Skull, 1:254 for Jet, 1:2048 for Ejecta, including network weights and latent grid. RM, Skull, Ejecta rendered using DVR with a step size of 1 voxel, Jet using Monte-Carlo path tracing with 256 spp to a screen of resolution 1080p. RM and Skull trained using  $256^3$  samples, Jet and Ejecta using  $512^3$  and  $1024^3$  samples, respectively.

used to generate the model representation drastically increases the training times.

Figure 1 demonstrates the aforementioned properties for different datasets and a given memory budget of roughly 3–0.4% of the memory that is required by the original dataset. Given the internal format of the network weights, which is set to 16-bit half-precision floating-point values in the current examples, V-SRN automatically determines the internal network layout so that the memory budget is not exceeded. Compared to the initial datasets in (a), V-SRN in (c) with 18 layers (eight residual blocks) and 128 channels shows high reconstruction fidelity at the given compression rate. Compared to low-pass filtered versions of the original datasets (b), which are re-sampled to a resolution that matches the memory budget, even fine structures are well preserved. However, the rendering times are between a minute to multiple minutes, and training times range from 39 min to multiple hours.

### 1.1. Contribution

In this work, we demonstrate that the efficiency of V-SRN for volume rendering can be significantly improved, both with respect to training and data reconstruction. We achieve this by a novel compact network design called fV-SRN, which effectively utilizes the GPU TensorCores and uses a trained volumetric grid of latent features as additional network inputs. This enables fast training and significantly faster rendering from the compressed representation than prior work.

We compare fV-SRN to *neurcomp* by Lu et al. [LJLB21] as well as non-network-based compression schemes TThresh [BRLP19] and cudaCompress [TRAW12, TBR\*12] regarding compression ratio and reconstruction speed. The results indicate that fV-SRN is significantly faster than *neurcomp* at similar compression rates, achieves similar compression rates than TThresh at significantly lower reconstruction times and significantly outperforms cudaCom-

press in terms of compression ratio at similar decoding speed. Furthermore, since fV-SRN can render directly from the compressed representation, no additional memory is required at rendering time. Building upon the strengths of fV-SRN, we introduce the extension of fV-SRN to predict scalar field values as well as derived quantities like gradients and curvature estimates.

We further demonstrate the use of fV-SRN for temporal super-resolution tasks, to perform smooth, yet structure-preserving interpolation between given volumetric datasets at two consecutive timesteps. This enables to reduce the number of timesteps that need to be stored out of a running simulation. We analyse the possibility of latent-space interpolation to perform this task, and demonstrate that the restriction of available super-resolution schemes like TSR [HW19] and STNet [HZCW21] to obtain interpolations only at a pre-defined discrete set of timesteps can be overcome. Our specific contributions are:

- 1) The design and implementation of a fast variant of V-SRN (fV/SRN) using a volumetric latent grid and running completely on fast on-chip memory.
- 2) An extension of fV-SRN to jointly predict a scalar quantity as well as the gradient and curvature at the given input position.
- 3) A temporal super-resolution fV/SRN using latent-space interpolation as a means for feature-preserving reconstruction of time-sequences at arbitrary temporal resolution.

In an ablation study we shed light on the design decisions and training methodology, and we perform a number of experiments to demonstrate the specific properties of fV/SRN. Its quality and performance are compared to state-of-the-art compression schemes targeting direct volume rendering applications. Our experiments include qualitative and quantitative evaluations, which indicate high compression quality even when small networks are used. fV/SRN can be integrated seamlessly into ray- and path-tracing kernels, improves the rendering performance about two orders of magnitude (between  $150\times$  and  $200\times$ ) on a screen of resolution  $1920 \times 1080$

compared to *neurcomp*, and accelerates the training process by about a factor of  $9\times$  (Figure 1). Due to the use of a low-resolution latent grid, temporal super-resolution between given instances in time can be used even for large time-varying sequences (Section 8).

## 2. Related Work

There is a vast body of literature on compression schemes for volumetric fields and SRNs, and a comprehensive review is beyond the scope of this paper. However, for thorough overviews and discussions of the most recent works in these fields let us refer to the articles by Balsa Rodríguez *et al.* [RGG\*13], Beyer *et al.* [BHP14], Hoang *et al.* [HSB\*21] and Tewari *et al.* [TFT\*20].

**Lossy volume compression schemes.** Our approach, since it attempts to further improve the compressive neural volume representation by Lu *et al.* [LJLB21], falls into the category of lossy compression schemes for volumetric scalar fields. Previous studies in this field have utilized quantization schemes to represent contiguous data blocks by a single index or a sparse combination of learned representative values [SW03, FM07, GIGM12, GG16], or lossy curve fittings like the popular SZ compression algorithm [DC16, ZDL\*20]. Transform coding-based schemes [YL95, Wes95, LCA08] make use, in particular, of the discrete cosine and wavelet transforms. They try to transform the data into a basis in which only few coefficients are relevant while many others can be removed. More recently, Ballester-Ripoll *et al.* [BRLP19] introduce tensor decomposition to achieve extremely high compression rates exceeding 1:1000.

For interactive applications, methods combining transform coding-based schemes and other techniques listed above are often applied brick-wise and embedded into streaming pipelines [TBR\*12, RTW13, DMG20]. They achieve significantly smaller compression ratios as, e.g. TThresh, for the sake of efficient GPU decoding. For example, Marton *et al.* [MAG19] present a rendering pipeline capable of decompressing over 10 Gvoxels/s while reporting a compression ratio of 1:64 (0.5 bits per sample on floating point data). In our work we target the high compression rates achieved by offline schemes like TThresh, while still being able to render images of large volumes from the compressed representation within a second.

Fixed-rate texture compression formats such as ASTC, S3TC and variants [INH99, Fen03, NLP\*12] are implemented directly by the graphics hardware. This means that rendering, including hardware-supported interpolation, is possible directly from the compressed stream. However, the fixed-rate stage allows little or no control over the quality versus compression rate trade-off.

**Deep learning for scientific data compression.** With the success of convolutional neural networks, deep learning methods have started to see applications in visualization tasks. Early works use super-resolution networks to upscale the data if either storing the high-resolution data is too expensive (3D spatial data [ZHW\*17, HW20, GYH\*20], temporal data [HW19], spatiotemporal data [HZCW21]) or the rendering process is too expensive (2D data [WCTW19, WITW20]). Sahoo and Berger [SB21]

extended 3D super-resolution for vector fields by introducing a loss function that penalizes differences in traced streamlines, instead of only point-wise differences. The most recent approach by Lu *et al.* [LJLB21] and Wurster *et al.* [WSG\*21] utilizes SRNs to learn a compact mapping from domain positions to scalar field values.

Berger *et al.* [BLL19] and Gavrilescu [Gav20] avoid the rendering process completely and train a network that directly predicts the rendered image from camera and transfer function (TF) parameters. This results in a compact representation of the data in the network weights from which the image can be directly predicted, but is limited concerning the generalization to new views or TFs if the training data does not provide this specific combination. Super-resolution methods for 3D spatial data or temporal data, on the other hand, are fixed on a regular grid in space (or time) due to the use of convolutional (recurrent) networks. Therefore, they do not allow for free interpolation and require the decompression of a whole block before rendering.

**Scene representation networks.** SRNs address the above issues. By directly mapping a spatiotemporal position to the data value, random access is possible, as opposed to grid-based super-resolution methods. This also allows to freely move the camera during testing.

SRNs were first introduced for representing 3D opaque meshes, either as occupancy grids [MON\*19, MLL\*21] or signed distance field [TLY\*21, DNJ20, LJM21, CLI\*20]. In these methods, the networks were trained in world-space, that is, from pairs of position to data value. This principle was also adopted in the VIS area by Lu *et al.* [LJLB21]. The large network used in this work, however, makes interactive rendering infeasible. For image-space training, that is, training from images through the rendering process, SRNs were first introduced for 3D reconstruction [SZW19], including *NeRF* by Mildenhall *et al.* [MST\*20, TSM\*20]. Further improvements include reduction of aliasing artefacts (Mip-NeRF) [BMT\*21] and incorporation of lighting effects [SDZ\*21]. Performance improvements are achieved by caching evaluated samples (FastNeRF) [GKJ\*21], pre-integration of segments (AutoInt) [LMW21] or depth oracles (DONeRF) [NSP\*21].

Let us remark that in the mentioned scenarios, the networks are trained to predict single surfaces from images, i.e. a computer vision task. This allows for significantly larger step sizes, or the use of sparse latent grids where only regions close to the surface are resolved at high resolution [TLY\*21, YLT\*21]. In the extreme case, a network is completely replaced by a learned sparse voxel representation [YFKT\*21, HSM\*21]. These approaches cannot be transferred to the direct volume rendering scenario addressed in our work, were a surface might not be given or is permanently changed by interactively selecting iso-contours in the volumetric scalar field. Nevertheless, we see potential for future transfer of techniques between both worlds, for example, by integrating the proposed custom TensorCore kernels into computer vision tasks, or extending fV-SRN with aliasing-reducing techniques inspired by Mip-NeRF.

Regarding dynamic scenes, Park *et al.* [PFS\*19] (modelling SDFs) and Chen and Zhang [CZ19] (modelling occupancy grids) introduce a latent vector that allows interpolating between different models. This is the basis for the time interpolation described in

Section 8. Alternatively, Pumarola *et al.* [PCPMMN21] introduce a second network that models affine transformations from a base model.

### 3. Scene Representation Networks

Let  $V$  be a 3D multi-parameter field, i.e. a mapping  $\mathbb{R}^3 \rightarrow \mathbb{R}^D$  that assigns to each point in a given domain a set of  $D$  dependent parameters. In this work, we focus on 3D scalar fields ( $D = 1$ ) and colour fields ( $D = 4$ ), where at each domain point either a scalar density value is given or an RGB $\alpha$  sample has been generated via a TF mapping.

SRNs [MST\*20, TSM\*20] encode and compress the field  $V$  via a neural network comprised of fully connected layers. The network takes a domain position as input and predicts the density or colour at that position, i.e. a mapping  $V_{\odot} : \mathbb{R}^3 \rightarrow \mathbb{R}^D$ . In detail, let  $\mathbf{v}_0 = \mathbf{p} \in \mathbb{R}^3$  be the input position. Then, layer  $i$  of the network is computed as  $\mathbf{v}_{i+1} = a(W_i \mathbf{v}_i + \mathbf{b}_i)$ , where  $W_i$  is the layer weight matrix,  $\mathbf{b}_i$  the bias vector and  $a(\cdot)$  the element-wise activation function. The number of layers is denoted by  $l$ . The output of the last layer  $\mathbf{v}_l \in \mathbb{R}^D$  is the final network output. The intermediate states  $\mathbf{v}_1, \dots, \mathbf{v}_{l-1}$  are of size  $\mathbb{R}^c$  with  $c$  being the number of hidden channels of the network. The matrices  $W_i, \mathbf{b}_i$  are the trainable parameters of the network.

Since the network processes each input position independently of the other inputs, the volumetric field can be decoded at arbitrary positions only where needed, i.e. along the ray during direct volume raycasting. In practice, batches of thousands of positions are processed in parallel. In the spirit of previous SRNs [CZ19, MON\*19, PFS\*19], *neurcomp* by Lu *et al.* [LJLB21] is trained in world-space, using training pairs of position and density  $(\mathbf{x}, \mathbf{v})$ . Let us refer to Section 5 for a study of the most relevant network parameters and the details of the training method.

As shown by Mildenhall *et al.* [TSM\*20] and Tancik *et al.* [TSM\*20], when the SRN is trained only with positional input  $\mathbf{p} = (x, y, z)$  and corresponding density or colour output, the mapping function cannot faithfully represent high-frequency features in the data. To avoid this shortcoming, so-called Fourier features are used to lift 3D positions to a higher-dimensional space before sending the input to the network. In this way, the spread between spatially close positions is increased, and positional variations of the output values are emphasized.

Let  $\mathbf{p} \in \mathbb{R}^3$  and  $m \in \mathbb{N}$ , respectively, be the input positions to the network and the desired number of Fourier features that should be used (see Section 4.1 for a discussion of how to choose  $m$ ). Then, a matrix  $F \in \mathbb{R}^{m,3}$ —the so-called Fourier matrix—is defined. Mildenhall *et al.* [MST\*20] propose to construct the Fourier matrix based on diagonal matrices of powers of two  $\mathcal{K}^3$ , i.e.

$$F_{\text{NeRF}} = 2\pi [2^0 \cdot \mathcal{K}^3, 2^1 \cdot \mathcal{K}^3, \dots, 2^{L-1} \cdot \mathcal{K}^3] \in \mathbb{R}^{3L,3}, \quad (1)$$

where  $m = 3L$ . The matrix is fixed before the training process and not part of the trainable parameters. The inputs to the network are then enriched via vector concatenation as

$$\mathbf{v}_{\text{fourier}} = \mathbf{p} \oplus \sin(F\mathbf{p}) \oplus \cos(F\mathbf{p}), \quad (2)$$

where  $\oplus$  indicates the concatenation operation.

Alternatively, Tancik *et al.* [TSM\*20] reported better reconstruction quality when using random Fourier features, where the entries of the matrix  $F$  are sampled from  $\mathcal{N}(0; (2\pi\sigma)^2)$  using the dataset-dependent hyperparameter  $\sigma$ . In our experiments (Section 5.3), however, we could not observe these improvements and, therefore, follow the construction proposed by Mildenhall *et al.* [MST\*20]. In contrast to *neurcomp*, which does not make use of Fourier features, we observed a significant enhancement of the networks' learning skills when incorporating these features.

### 4. Fast Volumetric SRN (fV-SRN)

When using SRNs, the main computational bottleneck is the evaluation of the network to infer a data sample at a given domain location. In frameworks like PyTorch or Tensorflow, the basic building block a network is composed of is a single linear layer. On recent GPUs, when a layer is evaluated, the inputs and weights are loaded from global memory, updated and the results are written back to global memory to make them available to the next layer. In direct volume rendering, if 100 steps along a ray are taken and the SRN consists of seven layers, this amounts to 700 layer invocations and global memory read and write operations. In the following, we show that it is possible to completely avoid loading and storing the intermediate results to global memory by fusing the network into a single CUDA kernel and following certain size constraints. A similar idea has been employed previously for radiance caching in Monte-Carlo path tracing [MRNK21]. Our approach goes beyond this by using a latent grid (Section 4.2), which has been published concurrently by Müller *et al.* [MESK22], and by completely avoiding all global memory access within the network layers and between the samples during raytracing (see Section 4.1). This gives rise to a speedup of up to 16.8 $\times$  of our custom CUDA TensorCore implementation, compared to a native PyTorch [PGM\*19] implementation, for the same V-SRN network architecture, see Section 5.1.

#### 4.1. Custom inference via TensorCores

NVIDIA GPUs expose 64 kB of fast on-chip memory per multiprocessor that is magnitudes faster than global memory (GBs of memory shared across all multiprocessors). These 64 kB are divided into 48-kB freely accessible shared memory and 16 kB of L1-cache. Furthermore, the tensor core (TC) units on modern GPUs provide warp-synchronous operations to speed up matrix–matrix multiplications by a factor of 6 $\times$  [MDCL\*18]. A warp is a group of 32 threads that are executed in lock-step on a single multiprocessor. The core operation of the TC units is—for our purpose—a matrix–matrix multiplication of  $16 \times 16$  matrices of 16-bit half-precision floats  $D = AB + C$ . Each thread holds a part of the input and the output matrices in registers and computes a part of the matrix multiplication. The TC API comes with three main limitations: (a) matrix sizes must be a multiple of 16, (b) inputs and outputs can only be loaded from and stored to shared or global memory, not registers, (c) all 32 threads of the warp must execute the same code.

When evaluating an SRN, each layer computes  $y = Wx + b$ , where  $W$  is the weight matrix,  $x$  the input state vector,  $b$  the bias vector and  $y$  the output state. To use the TC units as described above and regarding constraint (a), however,  $x$  must be a matrix

**Table 1:** Largest possible network configurations for the proposed Tensor-Core implementation of fV-SRN.

Channels	32	48	64	96	128
Layers	22	10	6	3	2

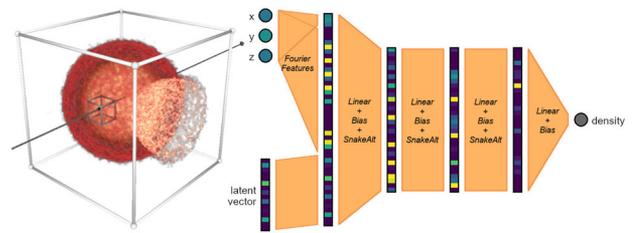
with 16 columns. The first idea is to batch the evaluation so that the 32 threads per warp calculate 16 rays. Then, however, half of the threads are idle in operations like TF evaluation. Therefore, we map one thread to one ray, and block the matrix multiplication  $Y = WX + B$  in the following way (exemplary for 48 channels per layer): The matrix  $W \in \mathbb{R}^{48,48}$  is split into  $3 \times 3$  blocks, and  $X, Y \in \mathbb{R}^{48,32}$  are split into  $3 \times 2$  blocks, each block of shape  $16 \times 16$ . The bias  $B \in \mathbb{R}^{48,32}$  is broadcasted from the bias vector  $b \in \mathbb{R}^{48}$  by setting the column stride to zero. In total, a layer evaluation of 48 channels with 32 rays requires six invocations to the TC units.

Constraint (b) indicates that the weights and biases of the hidden layers, as well as the layer outputs, must fit into shared memory for optimal performance. In contrast, Müller *et al.* [MRNK21] reload the weights from global memory in every layer evaluation per warp. As an example, consider a network with  $l = 4$  layers, each with  $c = 48$  channels. Then the weights and biases require  $4 * 48^2 * 2$  bytes and  $4 * 48 * 2$  bytes, respectively, for a total of  $m_w = 18816$  bytes that have to be stored once. Additionally, each thread stores the 48 layer outputs, leading to  $m_s = 48 * 32 * 2 = 3072$  bytes per warp. Therefore, with the limitation of 48-kB shared memory,  $w = \lfloor (48k - m_w) / m_s \rfloor = 9$  warps can fit into memory. More warps—up to the hardware limit of 32—are advantageous, as they allow to hide pipeline latency by switching between the warps per multiprocessor. Note that the first (last layer) has to be handled separately, as the input (output) dimension differs. This results in the maximal network configurations given in Table 1. The number of Fourier features  $m$  (see Section 3) is chosen as  $m = (c - 4) / 2$ , so that the size of the used input vector  $v$  matches the channel count.

As the network evaluation is directly included in the raytracing kernel, global memory interactions between the renderer and the network can be avoided. The network evaluation terminates automatically when all rays of a warp terminate, e.g. due to opacity-based early-out. As shown in Section 5.1, our TC implementation achieves a speedup of up to  $16.8\times$  against 32-bit PyTorch or  $9.8\times$  against 16-bit PyTorch.

## 4.2. Volumetric latent grid

When using V-SRN with a network configuration that is small enough to enable interactive volume rendering, we observe a significant drop in the networks' prediction skills. The reason lies in the loss of expressive power of the network when relying solely on the few network weights to encode the volume. To circumvent this limitation, we borrow an idea proposed by Takikawa *et al.* [TLY\*21] for representing an implicit surface that is encoded as a signed distance function via an SRN. The proposed architecture employs a sparse voxel octree, which stores latent vectors at the nodes instead of distance values. Each octree node stores a trainable  $F$ -dimensional

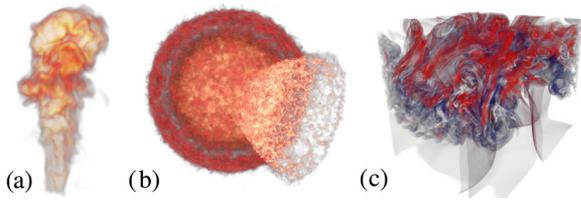
**Figure 2:** Visualization of the proposed fV-SRN architecture: The input position  $x, y, z$  is augmented by the Fourier features and the latent vector sampled from the coarse latent grid on the left. The resulting hidden vector with 48 channels is then passed to an MLP with four layers and 32 hidden channels to predict the scalar density.

vector that is interpolated across space and passed as additional input to the SRN network. Since the SRN learns to predict a single surface, an adaptive voxel octree with a finer resolution near the surface is used. We adopt this approach of a volumetric latent space but use a dense 3D grid instead of a sparse voxel octree. Especially, since in direct volume rendering, it is desirable to change the TF mapping of density values to colours after training, refining adaptively toward a single surface is not suitable.

Let  $G : \mathbb{R}^3 \rightarrow \mathbb{R}^F$  be a regular 3D grid with  $F$  channels, i.e.  $F$  parameters per grid vertex, and a resolution of  $R$  vertices along each axis. In the interior of each cell, the values are tri-linearly interpolated to obtain a continuous field. When evaluating the SRN  $V_{\odot}$  at position  $x$ , the grid is interpolated at  $x$  and the resulting latent vector  $G(x) = z \in \mathbb{R}^F$  is passed as additional input—alongside the Fourier features—to the network. The contents of  $G$  are trained jointly with the network weights and biases.

With this approach, we can keep the network small enough to enable fast inference, up to networks of only two layers à 32 channels, while maintaining the reconstruction quality of V-SRN. For the evaluation of the network and grid configurations, we refer to Section 5.2. We found that the best compromise between speed, quality and compression rate is achieved with a network of four layers à 32 channels and a latent grid of resolution  $R = 32$  and  $F = 16$  features. This configuration is used in Figure 1d and as default in the ablation studies below. The basic network architecture is illustrated in Figure 2. Compared to *neurcomp*, the proposed network leads to a speedup of up to  $9.8\times$  for training and  $165\times$  for rendering. The latent grid is stored in four 3D CUDA textures with four channels each, so that hardware-supported trilinear texture interpolation can be exploited.

By using a latent grid, most of the parameters are stored in the grid instead of the network. For the configuration described above, the grid requires 2 MB of memory (four bytes per voxel and channel), whereas the network consumes only around 7.3 kB of memory. Note that in all specifications of the memory consumption of fV-SRN given in this paper, the memory consumed by the latent grid and the network weights is included. We further avoid storing the latent grid in a float-texture, by using a CUDA feature that enables the use of 8-bit integers per entry that are then linearly mapped to  $[0, 1]$  in hardware. Thus, we compute the minimal and maximal grid value for each channel, and use these values to first map the



**Figure 3:** Datasets used in the ablation study: (a) *ScalarFlow* ( $178^3$ ) [EUT19], (b) *Ejecta* ( $256^3$ ), (c) *RM* ( $256^3$ ).

grid values to  $[0, 1]$  and then uniformly discretize them into 8-bit values. This reduces the memory footprint of the latent grid representation to a quarter of the size, while reducing the rendering times only slightly by roughly 5% due to reduced memory bandwidth. At the same time, the quality of the rendered images is slightly decreased by a factor of up to 2% of the reference SSIM and LPIPS statistics. Visually, however, the discretization does not introduce any perceptual differences, and is used in all of our experiments.

## 5. Ablation Study

To select the network architecture with the best reconstruction quality from the possible configurations within the hardware limitations, we trained different networks on three different datasets (see Figure 3): The *ScalarFlow* dataset [EUT19]—a smoke plume simulation with 500 timesteps, the *Ejecta* dataset—a supernova simulation with 100 timesteps and the *RM* dataset—a Richtmyer–Meshkov simulation with 255 timesteps. All datasets are given on Cartesian voxel grids, and they are internally represented with 8 bits per voxel. All timings are obtained on a system running Windows 10, an Intel Xeon CPU with 3.60 GHz, and an NVIDIA GeForce RTX 2070.

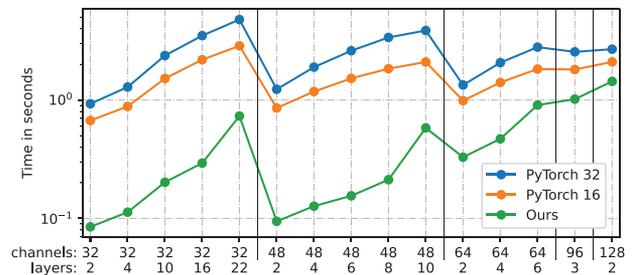
Unless otherwise noted, we analyse the capabilities of fV-SRN using world-space training on position-density encodings. The networks are training on  $256^3$  randomly sampled positions, with a batch size of  $128 \cdot 64^2$  positions over 200 epochs, an  $L_1$  loss function on the predicted outputs and the Adam optimizer with a learning rate of 0.01. We use a modified *Snake* [LHU20] activation function with enhanced overall slope, i.e.

$$\text{SnakeAlt}(x) = 0.5x + \sin^2(x), \quad (3)$$

which results in slight improvements of the reconstruction quality, see supplementary material. After training, the networks are evaluated by rendering 64 images of resolution  $512^2$  from different views of the objects. The quality of the rendered images is measured using the image statistics SSIM [WBSS04] and LPIPS [ZIE\*18] using renderings of the initial volumes as references. For training from rendered images, we refer to Section 5.5 and the supplementary material.

### 5.1. Performance evaluation

First, we compare the performance of the proposed TC implementation to a native PyTorch implementation of the same architecture. Performance measures include the time to access the latent grid and to evaluate fV-SRN with the positional information augmented by



**Figure 4:** Performance analysis of fV-SRN using the latent grid and different layer-channel combinations. A  $256^3$  dataset is rendered to a  $512^2$  viewpoint with a constant stepsize of 1 voxel without gradients and empty-space skipping. Measures are obtained as averages over many views. For thin networks with few channels, fV-SRN outperforms a native PyTorch implementation using 32- or 16-bit floats by up to a factor of  $17\times$ . For wide networks with 96 or 128 channels, computation dominates over memory access, leading to a smaller speedup.

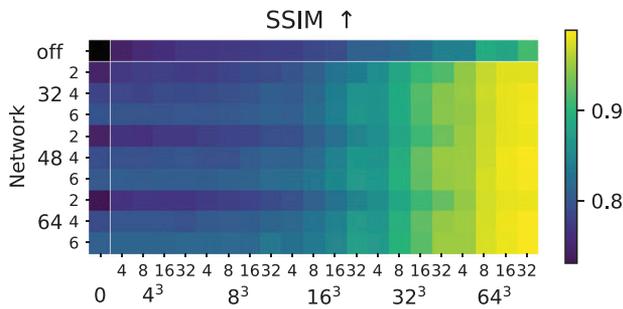
Fourier features. Figure 4 shows the timings for rather lightweight networks as well as the largest possible networks within the TC hardware constraints.

As can be seen, the largest speedup of  $16.8\times$  ( $9.8\times$ ) over a 32-bit (16-bit) PyTorch implementation is achieved for a medium-sized network of six layers and 48 channels. For very small networks of two or four layers with 32 channels, the speedup goes down to  $\approx 11\times$  ( $\approx 8\times$ ). For larger networks, e.g. two layers à 128 channels, the network evaluation becomes computation bound and the reduction of memory access operations as achieved by our solution becomes less significant. However, also in these cases, a speedup of 1.9 (1.5) against 32-bit (16-bit) PyTorch can still be achieved. We notice, however, that fast renderings with 5–10 FPS are only possible with small networks.

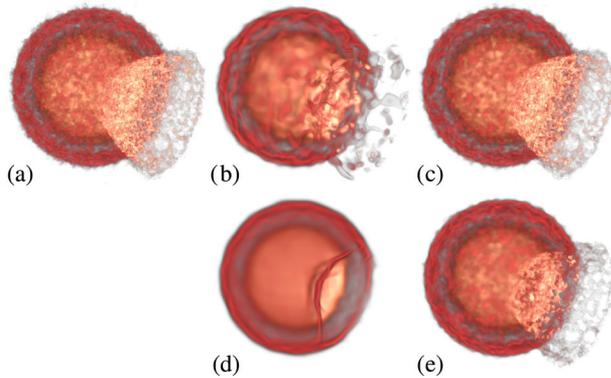
### 5.2. Latent grid

Next, we investigate the effect of the volumetric latent grid on reconstruction quality. For *Ejecta* with many fine-scale details, Figure 5 shows quantitative results for different resolutions of the latent grid and different network configurations. As one can see, the reconstruction quality drastically increases with increasing latent grid resolution. At finer grids, i.e.  $32^3$  and higher, the choice of the network has a rather limited effect on the overall reconstruction quality. The differences between networks of four and six layers are not noticeable. In these cases, a small network of only four layers à 32 hidden channels is sufficient to achieve good reconstruction quality. Only when using small grids—or no latent grid at all—can larger networks improve the overall quality.

To confirm that the quality improvement is not solely due to the volumetric latent grid while the SRN is superfluous, we compare the rendered images to images that were rendered from a low-pass filtered density grid with the same memory consumption as the latent grid (row ‘off’ in Figure 5). For example, for a latent grid of resolution  $32^3$  and 16 features, the original volume is first low-pass filtered and then down-sampled to a grid resolution of  $\sqrt[3]{32^3 \cdot 16} \approx 81$ .



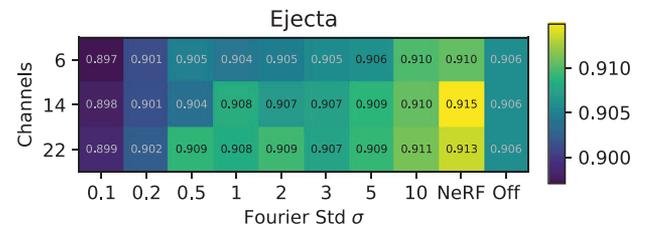
**Figure 5:** Effect of latent grid resolution on reconstruction quality for Ejecta. The x-axis shows the grid resolution ( $4^3, 8^3, \dots, 64^3$ ) and grid feature channels  $F$  (4, 8, 16, 32), or 0 if no grid is used. The y-axis represents the network configuration, the number of hidden channels (32, 48, 64), and the number of layers (2, 4, 6). The special network ‘off’ shows the results without a network, where only a density grid requiring the same memory as the current latent grid  $G$  is used. The LPIPS score and the other datasets show similar behaviour.



**Figure 6:** Effect of latent grid resolution on reconstruction quality. (a) Reference. (b) Latent grid of  $R = 8, F = 8$  with a network of 32 channels, two layers. (c) Latent grid of  $R = 32, F = 16$  with a network of 32 channels, two layers. (d) and (e) Density grid without a network of equivalent memory consumption as (b) and (c).

The width of the low-pass filter is selected according to the subsampling frequency. As one can see from Figure 5, and evidenced by the qualitative assessment in Figure 6, by using a latent grid in combination with the SRN even small-scale structures are maintained. In the low-resolution density grid, many of these structures are lost.

Notably, since the latent grid can be trained very efficiently and takes the burden from the SRN to train a huge number of parameters, the training times of fV-SRN are up to a factor of  $9.8\times$  faster than those of V-SRN with the same total number of parameters, see Figure 1. Especially because SRNs overfit to a certain dataset and training has to be repeated for each new dataset, we believe that this reduction of the training times is mandatory to make SRNs applicable.



**Figure 7:** SSIM values for different types of Fourier features—Tancik et al. with different values for  $\sigma$ , NeRF and disabled features—and different feature sizes  $m$ , evaluated on the Ejecta dataset. The LPIPS score and the other datasets show similar behaviour.

### 5.3. Fourier features

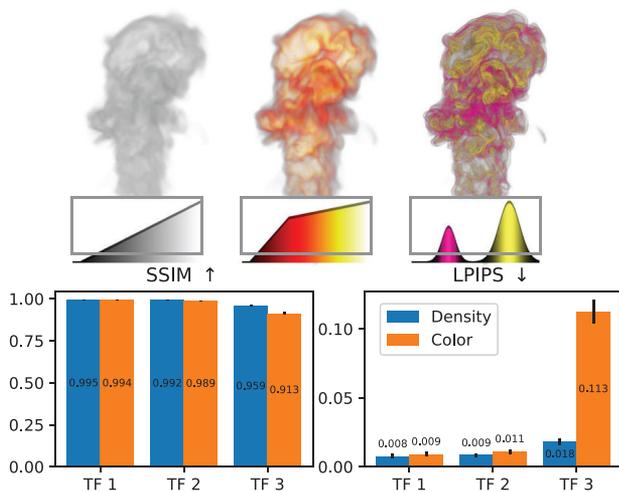
In the following, we shed light on the effects of Fourier features on the overall reconstruction quality of networks that were trained in world-space for density prediction. We compare the construction of Fourier features according to Mildenhall et al. [MST\*20], denoted ‘NeRF’, and Tancik et al. [TSM\*20] with standard deviation  $\sigma$  as hyperparameter. In addition, we evaluate the reconstruction quality when Fourier features are not used. Networks were trained for multiple values of  $\sigma$  and three different numbers of Fourier features. The results can be found in Figure 7. They demonstrate the general improvements due to the use of Fourier features, and furthermore indicate the superiority of ‘NeRF’ over random Fourier feature by Tancik et al. in combination with our network design.

### 5.4. Density versus colour prediction

Next, we shed light on the reconstruction quality for networks that predict densities that are then mapped to colours via a user-defined TF (the approach we have followed so far), and networks that directly predict colours at a certain domain location. In the latter case, the network encodes colours dependent on positions, and the loss function considers the differences between the encoded colours and the colours that are obtained by post-shading at the interpolated input positions.

Density prediction enables to change the TF after a sample has been reconstructed without retraining. When predicting colours, however, the network needs to be re-trained whenever the TF is changed. Hence, this approach seems to be less useful in practice, yet it is interesting to analyse how well a network can adapt its learning skills to those regions emphasized by a TF mapping. Possibly, the network can learn to spend its capacities on those regions that are actually visible after the TF has been applied, which may result in improved reconstruction quality.

Instances of fV-SRN: One that predicts densities and three networks that predict colours that have been generated via three different TFs on ScalarFlow. Reference images for the three TFs are shown in Figure 8, combined with the achieved reconstruction quality. For the first two TFs, there are almost no differences in image quality between density and colour prediction. For the third TF with two narrow peaks, however, colour prediction performs considerably worse, even though the network needs to learn significantly



**Figure 8:** Quality comparison of fV-SNR-based density and colour prediction. The tests were conducted with three different TFs, reference images and transfer functions are shown in the first row.

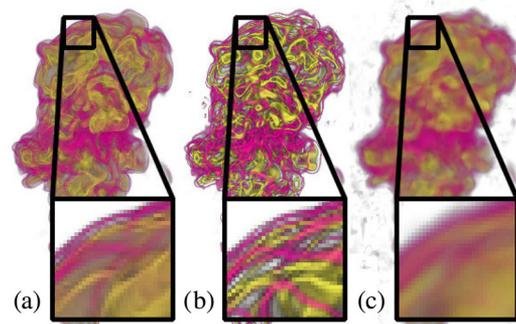
fewer positions at which a non-transparent colour is assigned. We hypothesize that especially narrow peaks in the TF make the prediction difficult. In such cases, the absorption changes rapidly over a short interval, so that the network training on uniformly distributed locations cannot adequately learn these high frequencies.

To force the network to consider more positional samples in regions where the TF mapping generates a colour, we propose the following adaptive re-sampling scheme: After each  $N$ th epoch ( $N = 50$  in our experiments), we evaluate the prediction error over a coarse voxel grid  $E$  of resolution  $128^3$ . Per voxel, eight positions are sampled and evaluated as an approximation of the average prediction error per voxel.  $E$  is then used to sample new training data for the next  $N$  epochs, where the number of sampled positions is made proportional to the values in  $E$ . This allows the training process to focus on regions with high prediction error and samples the volumetric field in more detail in these regions.

By using the proposed adaptive sampling scheme, e.g. the LPIPS score for TF 3 for the colour-predicting network is improved from 0.113 to 0.039. Even though, however, we do not believe that the quality of colour prediction can match the quality of density prediction when rather sharp TFs are used. Thus, and also due to the restriction of colour prediction to a specific TF, we consider this option to be useful only when a colour volume is given initially.

### 5.5. Image-based training

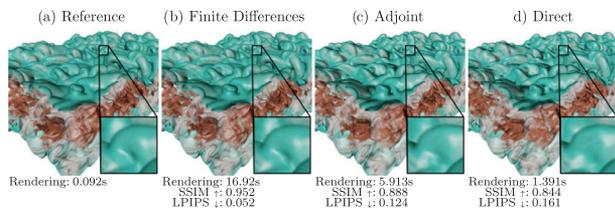
In all of the previous examples, networks were trained on losses involving the differences between the initial and reconstructed data samples. Thus, the network uses its capacities even for data samples which might never contribute to the final images. In the following, we evaluate the feasibility of generating a perceptual adaptive compressed encoding, which is solely based on the resulting image quality.



**Figure 9:** Screen- versus world-space training, using a TF with sharp peaks. (a) Reference rendering with stepsize of 0.1 voxels. (b) Rendering with a stepsize of 4 voxels and reconstruction using fV-SRN trained in world-space. (c) Rendering with a stepsize of 4 voxels and reconstruction using fV-SRN trained in screen-space.

Therefore, we train fV-SRN in screen space using pairs  $(C, I)$  consisting of camera extrinsics  $C$  and reference images  $I$ . The network learns to adapt its internal mapping function so that the reference images are best preserved. In the original work by Sitzmann *et al.* [SZW19] and Mildenhall *et al.* [MST\*20], this strategy has been pursued using an extremely memory intensive approach, which requires to store the intermediate values along the rays of sight for backpropagation. This severely limits the number of rays and steps that can be processed. For example, Mildenhall *et al.* [MST\*20] report that only 128 steps along the ray with an image resolution of  $64^2$  can be used for training. To support arbitrarily many steps along the ray during training, we use the approach proposed by Weiss and Westermann [WW21] for differentiable volume rendering. This approach exploits an analytic inversion of the blending function to ensure a constant memory footprint, regardless of the number of steps per ray that need to be backpropagated. However, when training in screen-space, the network cannot reconstruct a density field from the provided colour images. Weiss and Westermann [WW21] have shown that the non-convexity of the applied TFs make the reconstruction of densities ill-posed. Therefore, the networks used for screen-space training are fixed to a pre-defined TF and directly predict the colour and absorption.

For the details on the training method including different input parametrizations to incorporate the ray direction, used hyperparameters and quantitative results, we refer to the supplementary material. Instead, we focus here on qualitative results. If a dataset with a high frequent TF, e.g. TF 3 in Figure 8, shown in more detail in Figure 9a, is rendered with a large step size of 4 voxels between samples, severe rendering artefacts occur due to undersampling, see Figure 9b. The networks trained in screen-space do not show such artefacts, since they are trained from artefact-free reference images (Figure 9c). On the one hand, however, these networks have difficulties in accurately recovering sharp colour transitions in the images and tend to produce blurry results. On the other hand, even at a rather coarse stepsize of 4 voxels, the overall structure of the rendered field is reconstructed since the network seems to use its capacities on those structures that are seen in the reference images. Due to these observations, we believe that it is worth analysing screen-space training further and to shed light on how to extend the



**Figure 10:** Network-based direct volume rendering including gradient-magnitude-based shading. (a) Gradients are computed via finite differences, i.e. calling the network eight times for gradient estimation. (b) Gradients are computed via the adjoint method, by backpropagation through the volume, (c) fV-SRN is trained to predict scalar values and gradients. Shown is Jet with a compression ratio of 1:985 and Phong shading. fV-SRN without gradient estimation (i.e. no shading) requires 1.373 s.

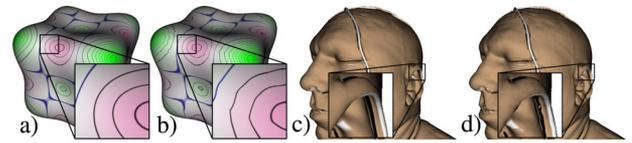
network capacities so that accurate reconstruction becomes possible.

## 6. Gradient Prediction and Higher-Order Derivatives

In the following, we shed light on the use of fV-SRN to learn a mapping that not only predicts a scalar field value at a given position but also the gradient and even higher-order derivatives at that position. The gradient is important in volume rendering to apply gradient-magnitude-based opacity and colour selection via TF mappings [Lev88], and, since the gradient at a certain position is the normal vector of the isosurface passing through this position, to illuminate the point, e.g. via Phong lighting.

In particular, we evaluate different strategies to estimate gradients in network-based scalar field reconstruction: Using finite differences by calling the network multiple times (*FD*), using the adjoint method (*Adjoint*) and training fV-SRN to predict the gradients alongside the density. As we will show, the latter improves the rendering performance by  $\approx 12\times$  over finite differences and  $4 - 5\times$  over the adjoint method, while reducing the quality only slightly, see Figure 10. All three methods are implemented using the proposed TC kernel (Section 4.1).

The common method to compute gradients during volume ray-casting is to use *FD*, more concretely central differences, between trilinearly interpolated scalar values with a step size of 1 voxel size [Lev88]. Compared to computing analytical derivatives of the trilinear interpolant, the use of central differences avoids discontinuities at the voxel borders. Since the use of *FD* (with fV-SRN) introduces a bias if the same method (w/o network) is used as reference, *FD* with fV-SRN leads to the best prediction in general, see Figure 10b. This method, however, introduces a large computation overhead as seven network evaluations are required to compute the density and gradients. Therefore, in previous work, the adjoint method (*Adjoint*) was proposed as an alternative [DNJ20, LJLB21]. *Adjoint* uses backpropagation through the trained reconstruction network to predict the change of the scalar value depending on changes of the position, see Figure 10c.



**Figure 11:** fV-SRN for isosurface rendering with curvature-based TF mapping. (a,b) Gaussian curvature  $\kappa_1\kappa_2$  on an implicit dataset [KWTM03], (c,d) principal curvatures  $\kappa_1$  and  $\kappa_2$  are mapped to colour on an isosurface in a CT scan. (a,c) are the references, (b,d) show the predictions by fV-SRN.

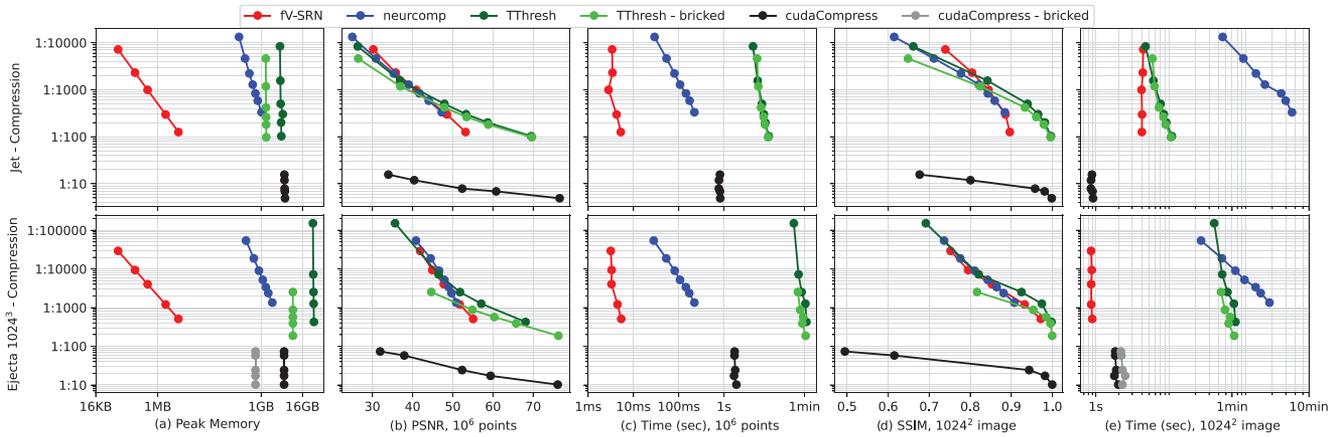
The fastest prediction is achieved by extending the output of fV-SRN to predict scalar values and gradients, see Figure 10d. However, as the network now needs to predict four outputs—density plus gradient  $x, y, z$ —instead of one within the same network weights and latent grid size, the quality is slightly reduced. For an extended comparison on further datasets, including implicit functions with analytical gradients, and a detailed study on how to design the loss function to include the gradients, we refer to the supplementary material.

If higher-order derivatives are required, e.g. for TFs incorporating curvature measures [KWTM03], *FD* and *Adjoint* become increasingly intractable. For finite differences, Kindlmann *et al.* [KWTM03] propose a stencil with a support of  $4^3$  samples. This would require 64 network evaluations per sample along the ray. Similarly, the adjoint method requires an additional adjoint pass per row in the Hessian matrix. As an outlook for future research, we show that the SRNs can be trained to jointly predict densities, gradients and also curvature estimates as a multi-valued output. First results using the shading proposed by Kindlmann *et al.* [KWTM03] on isosurface renderings are given in Figure 11.

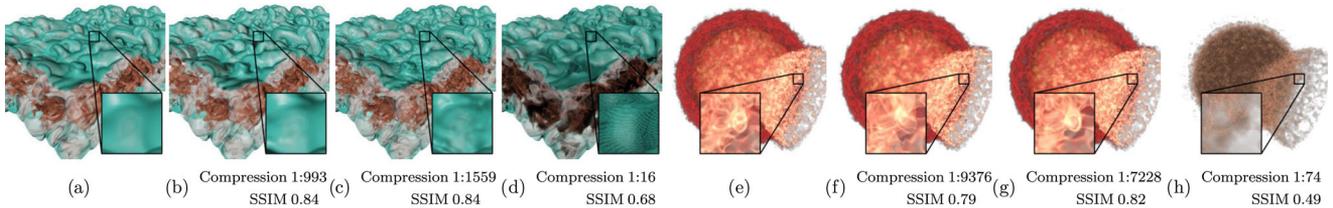
## 7. Performance and Quality Comparison

In the following, the quality and performance of fV-SRN is compared to *neurcomp* [LJLB21], TThresh [BRLP19] and cudaCompress [TRAW12, TBR\*12]. We compare to TThresh because of the extreme compression rates it can achieve, and to cudaCompress because of its decoding efficiency. The publicly available implementations of TThresh (running on the CPU) and cudaCompress (running on the GPU) are used. For the comparison, we chose Jet with Phong shading, as introduced in Section 6, and Ejecta at a resolution of  $1024^3$ , see Figure 1. To achieve a given compression ratio, fV-SRN changes the latent grid resolution, *neurcomp* adapts the number of hidden channels, TThresh modifies the bitplane cutoff, and cudaCompress adapts the stepsize for quantizing discrete wavelet coefficients. Further results on additional datasets are given in the supplementary material.

For a quantitative evaluation, compression ratios of the four methods are plotted against (a) the peak CPU and GPU memory required for decoding, (b,c) the time it requires to reconstruct  $10^6$  random locations as well as the resulting PSNR, (d,e) the time it requires to render an image of resolution  $1024^2$  with two samples per voxel on average as well as the resulting SSIM statistics, see Figure 12. All



**Figure 12:** Evaluation of different compression rates of fV-SRN, neurcomp [LJLB21], TThresh [BRLP19] and cudaCompress [TRAW12, TBR\*12], using Jet of resolution  $512 \times 336 \times 768$  with 32-bit floating-point per voxel and Ejecta of resolution  $1024^3$  with 16 bits per voxel. Jet uses Phong shading, the adjoint method is used by the network-based approaches to predict the gradients, see Section 6.



**Figure 13:** Visual comparison of volume compression schemes for Jet (a–d) and Ejecta (e–h). (a,e) Reference, (b,f) fV-SRN, (c,g) TThresh, (d–h) cudaCompress. For each scheme, the result obtained with a compression ratio closest to 1:1000 and 1:10,000 for Jet and Ejecta, respectively, is selected from Figure 12.

timing statistics are performed on an Intel Xeon CPU with 8 cores and 3.60 GHz, equipped with a NVIDIA GeForce RTX 2070 GPU.

Regarding PSNR and SSIM, fV-SRN, neurcomp and TThresh are almost on-par. For high compression ratios, the network-based approaches slightly outperform TThresh, while the opposite is true at low compression ratios. However, both TThresh and cudaCompress require additional temporal memory, as they need to decode the volume before rendering. For TThresh and cudaCompress, respectively, the temporarily required memory can grow up to 34 and 4.7 GB. neurcomp requires temporal memory to store the hidden states during network evaluation, computed here for evaluating  $1024^2$  rays in parallel. As shown in Section 4.1, fV-SRN runs completely in shared memory and requires no additional temporal memory for evaluation, besides storing the latent-space representation including network weights and latent grid—for sampling and rendering.

Treib et al. [TRAW12, TBR\*12] propose bricked decompression and rendering in combination with cudaCompress. In our case, we use a brick size of  $256^3$ . This drastically reduces the memory requirements from 4.7 GB to around 700 MB, while increasing the rendering time by roughly 13% for the Ejecta dataset. Note that this bricked rendering is only possible for the regular access pattern during rendering. For random access, the whole volume still needs to be decompressed. In a similar fashion, we applied a bricked TThresh, where each brick is compressed independently. For Ejecta, this also

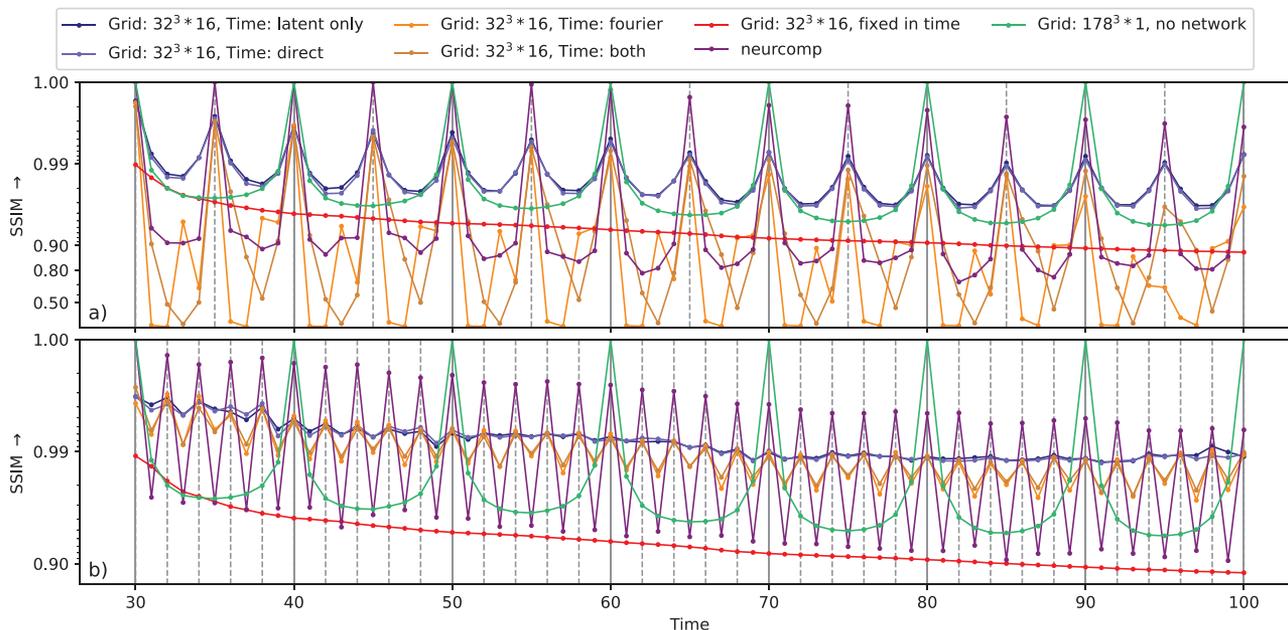
reduces the memory requirement from 34 GB to around 8 GB, but also drastically reduces the achieved compression ratio.

A qualitative comparison of the errors introduced by all compression schemes is given in Figure 13. cudaCompress quantizes the values, which introduce large errors with narrow TFs. TThresh introduces slight grid artefacts, and both fV-SRN and neurcomp blur the dataset at higher compression ratios.

## 8. fV-SRN for Temporal Super-Resolution

We now analyse the extension of fV-SRNs to interpolate between different instances in time of a scalar field. The interpolation should smoothly transition between the instances to create plausible intermediate fields, and topological changes should be handled. The proposed approach is inspired by previous works by Park et al. [PFS\*19] and Chen and Zhang [CZ19], where latent vectors representing different objects are interpolated to morph one object into another one in a feature-preserving manner. To achieve the aforementioned goals, we extend the volumetric latent spaces, see Section 5.2, to include the time domain.

Let  $\mathfrak{T}_{\text{all}} = \{1, 2, \dots, T\}$  be the indices of the  $T$  timesteps that are available in the dataset. To save memory, the volumetric latent space is provided only at certain timesteps that we call *keyframes*.



**Figure 14:** Analysis of temporal super-resolution of ScalarFlow, showing reconstruction quality for different grid sizes and time encoding schemes. The networks were trained on every 5th timestep in (a) and every 2nd timestep in (b), with a keyframe at every 10th timestep, and evaluated on all timesteps. The blue and yellow lines represent the the different time encoding schemes, green the baseline where the original volume at the keyframes is interpolated in time, and red is the method inspired by Lu et al. [LJLB21], where only a single grid is used and the time is solely interpreted by the network. The unchanged neurcomp architecture by Lu et al., where all information is stored in the network weights, is depicted in purple.

Let  $\mathcal{T}_{\text{key}} \subset \mathcal{T}_{\text{all}}$  be the timestep indices of the keyframes and the volumetric latent space is then indexed as  $G_t : \mathbb{R}^3 \rightarrow \mathbb{R}^f, t \in \mathcal{T}_{\text{key}}$ . For timesteps that are between two keyframes, the volumetric latent space is linearly interpolated in time and passed to the network. During training, timesteps from  $\mathcal{T}_{\text{train}} \subset \mathcal{T}_{\text{all}}$  are used.

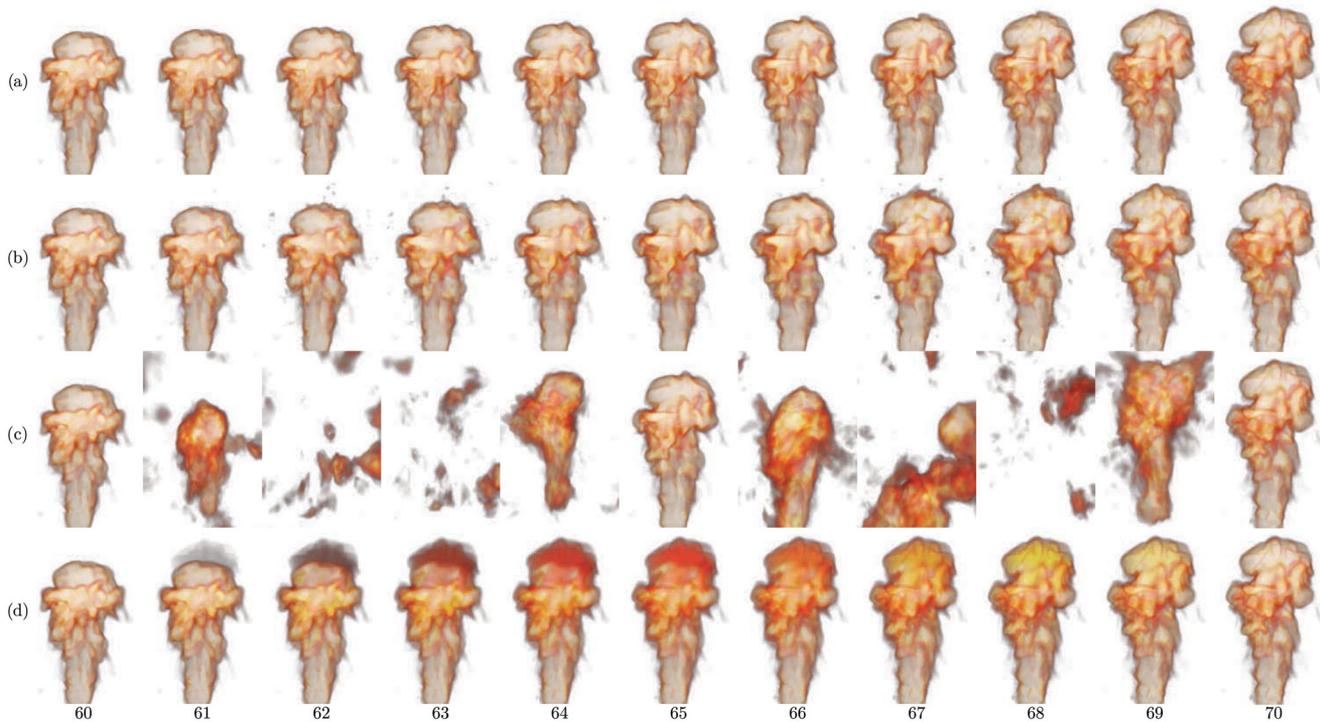
In addition to the time-dependent latent space, we evaluate four options to encode the time dimension in the network, so that plausible interpolation is achieved: no extra input (‘latent only’); time as an additional scalar input (‘direct’); time modulated by Fourier features based on Mildenhall *et al.* with  $L = 4$ , see Section 5.3 (‘Fourier’); time as scalar input and Fourier features (‘both’). Quantitative results are given in Figure 14 on the ScalarFlow dataset with a keyframe every 10<sup>th</sup> timestep for timesteps 30–100. For training, every 5th timestep (Figure 14a) or every 2nd timestep (Figure 14b) was used. For timesteps 60–70, Figure 15 shows the qualitative results.

We found that ‘latent only’ and ‘direct’ lead to good generalization for in-between timesteps that were never seen during training, with no noticeable difference between both methods (Figure 14 blue, Figure 15b). Those two architectures lead to a semantically plausible interpolation, that becomes especially noticeable when compared against a baseline (Figure 14 green, Figure 15d) where the original grid is used at the keyframes and then linearly interpolated in time.

The options including Fourier features in the time domain (‘Fourier’ and ‘both’), however, show chaotic behaviour for in-between timesteps (Figure 14 yellow). As opposed to Fourier features in the spatial domain where all fractional positions could have been observed due to the random sampling of the positions, in the time domain, only a discrete subset of timesteps are seen. Therefore, during generalization, the Fourier encoding produces value ranges for the network that were never seen before.

Let us also emphasize that neurcomp by Lu *et al.* [LJLB21] also supports super-resolution in the time domain, by sending the time domain directly as input to the network, see Figure 14 purple. Neurcomp allows an accurate prediction of the timesteps on the training datasets, using the same compression ratio as fV-SRN, but fails to generalize to in-between timesteps. This can also be clearly seen in the qualitative comparison Figure 15c. We hypothesize that the time-interpolated latent grid acts as a regularizer in that regard. The importance of a time-varying latent grid is also supported by the following test, Figure 14 red. Using the time encoding ‘direct’, but with only a single keyframe for the grid, leads to inferior results.

In total, fV-SRN allows for an efficient and plausible interpolation in time. The training time when including the time domain, however, increases drastically. Training a network on every 5th timestep requires around 3:45 h. Using every 2nd timestep instead of every 5th improves the quality of the interpolation (Figure 14b



**Figure 15:** Qualitative results for timesteps 60–70 of ScalarFlow, shown in Figure 14a. (a) Reference, (b) best time encoding ‘direct’, (c) ‘neurcomp’, (d) linear interpolation on the initial grids.

versus a), but the training time increases accordingly to almost 8 h.

## 9. Conclusion

We have analysed SRNs for compression domain volume rendering, and introduced fV-SRN as a novel extension to achieve significantly accelerated reconstruction performance. Accelerated training as well as the adaptation of fV-SRN to facilitate temporal super-resolution have been proposed. As key findings, we see that

- 1) by using custom evaluation kernels and a latent grid, SRNs have the potential to be used in interactive volume rendering applications,
- 2) fV-SRN is an alternative to existing volume compression schemes at comparable quality and significantly improved decoding speed, or similar performance but significantly higher compression ratios,
- 3) SRNs using latent space interpolation can preserve features that are lost using traditional interpolation and enable temporal super-resolution at arbitrary temporal resolution.

For now, the full volume has to be kept in GPU memory to generate the training data. To support terra-scale datasets in future work, out-of-core strategies for training SRNs will be investigated.

In the context of volume rendering, it will be important to investigate the capabilities of SRNs to learn mappings that consider a view-dependent level-of-detail (LoD). In particular, the network

might be able to infer more than just values of a low-pass filtered signal, but infer values as they would be perceived when looking at the data through a pixel and perform area-weighted super-sampling. Such a view-dependent learning of LoDs can avoid missing details, which are smoothed out using the classical low-pass filtering approach.

We see further potential in SRNs for scientific data visualization due to their ability to randomly access samples from the compressed feature representation. Due to this property, we see a promising application in the context of flow visualization. By using SRNs to encode position-velocity relationships, particle tracing or streamline tracing, with its sparse and highly irregular data access patterns, can work on a compactly encoded vector field representation.

As another interesting use case for fV-SRN, we see ensemble visualization. In particular, we intend to investigate whether the idea of multiple latent grids introduced for time-dependent fields can be used to represent similar and dissimilar parts in each ensemble member. An interesting experiment will be to generate Mean-SRNs, which are trained using position-density encodings corresponding to different datasets. This may also give rise to alternative ensemble compression schemes, where differences to a reference are encoded. Furthermore, we plan to investigate whether time and ensemble information can be decoupled in the latent grid. This can eventually enable to retrain ensemble features for a novel ensemble member, and vary the temporal features to predict the temporal evolution. Finally, we note that including the time domain vastly increases the training time. Thus, similar to the adaptive

spatial sampling presented in this work, we plan to investigate adaptive (re-)sampling strategies in time, to focus only on those timesteps that exhibit the largest prediction errors.

## ACKNOWLEDGMENTS

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## References

- [BHP14] BEYER J., HADWIGER M., PFISTER H.: A survey of GPU-based large-scale volume visualization. In *Proceedings of the EuroVis—STARs (2014)*, R. Borgo, R. Maciejewski and I. Viola (Eds.), The Eurographics Association.
- [BLL19] BERGER M., LI J., LEVINE J. A.: A generative model for volume rendering. *IEEE Transactions on Visualization and Computer Graphics* 25, 4 (2019), 1636–1650.
- [BMT\*21] BARRON J. T., MILDENHALL B., TANCIK M., HEDMAN P., MARTIN-BRUALLA R., SRINIVASAN P. P.: Mip-NeRF: A multi-scale representation for anti-aliasing neural radiance fields. *Proceedings of the IEEE/CVF International Conference on Computer Vision (ICCV)* (2021), 5855–5864.
- [BRLP19] BALLESTER-RIPOLL R., LINDSTROM P., PAJAROLA R.: TTHRESH: Tensor compression for multidimensional visual data. *IEEE Transactions on Visualization and Computer Graphics* 26, 9 (2019), 2891–2903.
- [CLI\*20] CHABRA R., LENSSEN J. E., ILG E., SCHMIDT T., STRAUB J., LOVEGROVE S., NEWCOMBE R.: Deep local shapes: Learning local SDF priors for detailed 3D reconstruction. In *Proceedings of the European Conference on Computer Vision* (2020), Springer, pp. 608–625.
- [CZ19] CHEN Z., ZHANG H.: Learning implicit fields for generative shape modeling. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition* (2019), pp. 5939–5948.
- [DC16] DI S., CAPPELLO F.: Fast error-bounded lossy HPC data compression with SZ. In *Proceedings of the 2016 IEEE International Parallel and Distributed Processing Symposium (IPDPS)* (2016), IEEE, pp. 730–739.
- [DMG20] DÍAZ J., MARTON F., GOBBETTI E.: Interactive spatio-temporal exploration of massive time-varying rectilinear scalar volumes based on a variable bit-rate sparse representation over learned dictionaries. *Computers & Graphics* 88 (2020), 45–56.
- [DNJ20] DAVIES T., NOWROUZEZHAI D., JACOBSON A.: On the effectiveness of weight-encoded neural implicit 3D shapes. *arXiv preprint* (2020). <http://arxiv.org/abs/2009.09808>.
- [EUT19] ECKERT M.-L., UM K., THUREY N.: ScalarFlow: A large-scale volumetric data set of real-world scalar transport flows for computer animation and machine learning. *ACM Transactions on Graphics* 38, 6 (Nov. 2019), 1–16.
- [Fen03] FENNEY S.: Texture compression using low-frequency signal modulation. In *Proceedings of the ACM SIGGRAPH/EUROGRAPHICS Conference on Graphics Hardware* (2003), pp. 84–91.
- [FM07] FOUT N., MA K.-L.: Transform coding for hardware-accelerated volume rendering. *IEEE Transactions on Visualization and Computer Graphics* 13, 6 (2007), 1600–1607.
- [Gav20] GAVRILESCU M.: A supervised generative model for efficient rendering of medical volume data. In *Proceedings of the 2020 International Conference on e-Health and Bioengineering (EHB)* (2020), IEEE, pp. 1–4.
- [GG16] GUTHE S., GOESELE M.: Variable length coding for GPU-based direct volume rendering. In *Proceedings of the Conference on Vision, Modeling and Visualization* (2016), pp. 77–84.
- [GIGM12] GOBBETTI E., IGLESIAS GUTIÁN J. A., MARTON F.: COVRA: A compression-domain output-sensitive volume rendering architecture based on a sparse representation of voxel blocks. *Computer Graphics Forum* (2012), 31 (2021) pp. 1315–1324.
- [GKJ\*21] GARBIN S. J., KOWALSKI M., JOHNSON M., SHOTTON J., VALENTIN J.: FastNeRF: High-fidelity neural rendering at 200FPS. *Proceedings of the IEEE/CVF International Conference on Computer Vision (ICCV)* (2021), pp. 14346–14355.
- [GYH\*20] GUO L., YE S., HAN J., ZHENG H., GAO H., CHEN D. Z., WANG J.-X., WANG C.: SSR-VFD: Spatial super-resolution for vector field data analysis and visualization. In *Proceedings of the 2020 IEEE Pacific Visualization Symposium (PacificVis)* (2020), IEEE Computer Society, pp. 71–80.
- [HSB\*21] HOANG D. T. A., SUMMA B., BHATIA H., LINDSTROM P., KLACANSKY P., USHER W., BREMER P.-T., PASCUCCI V.: Efficient and flexible hierarchical data layouts for a unified encoding of scalar field precision and resolution. *IEEE Transactions on Visualization and Computer Graphics* 27 (2021), 603–613.
- [HSM\*21] HEDMAN P., SRINIVASAN P. P., MILDENHALL B., BARRON J. T., DEBEVEC P.: Baking neural radiance fields for real-time view synthesis. In *Proceedings of the IEEE/CVF International Conference on Computer Vision* (2021), pp. 5875–5884.
- [HW19] HAN J., WANG C.: TSR-TVD: Temporal super-resolution for time-varying data analysis and visualization. *IEEE Transactions on Visualization and Computer Graphics* 26, 1 (2019), 205–215.
- [HW20] HAN J., WANG C.: SSR-TVD: Spatial super-resolution for time-varying data analysis and visualization. *IEEE Transactions on Visualization and Computer Graphics* (2020).
- [HZCW21] HAN J., ZHENG H., CHEN D. Z., WANG C.: STNet: An end-to-end generative framework for synthesizing spatiotemporal super-resolution volumes. *IEEE Transactions on Visualization and Computer Graphics* 28, 1 (2022), 270–280.

- [INH99] IOURCHA K., NAYAK K., HONG Z.: System and method for fixed-rate block-based image compression with inferred pixel values. US Patent 5,956,431, 1999.
- [KWTM03] KINDLMANN G., WHITAKER R., TASDIZEN T., MOLLER T.: Curvature-based transfer functions for direct volume rendering: Methods and applications. In *Proceedings of the IEEE Visualization, 2003. VIS 2003.* (2003), IEEE, pp. 513–520.
- [LCA08] LEE M.-C., CHAN R. K., ADJEROH D. A.: Fast three-dimensional discrete cosine transform. *SIAM Journal on Scientific Computing* 30, 6 (2008), 3087–3107.
- [Lev88] LEVOY M.: Display of surfaces from volume data. *IEEE Computer graphics and Applications* 8, 3 (1988), 29–37.
- [LHU20] LIU Z., HARTWIG T., UEDA M.: Neural networks fail to learn periodic functions and how to fix it. In *Advances in Neural Information Processing Systems*, H. Larochelle, M. Ranzato, R. Hadsell, M. F. Balcan and H. Lin (2020), Curran Associates, Inc pp. 1583–1594. <https://proceedings.neurips.cc/paper/2020/file/1160453108d3e537255e9f7b931f4e90-Paper.pdf>
- [LJLB21] LU Y., JIANG K., LEVINE J. A., BERGER M.: Compressive neural representations of volumetric scalar fields. *Computer Graphics Forum* 40 (2021), 135–146.
- [LJM21] LEI J., JIA K., MA Y.: Learning and meshing from deep implicit surface networks using an efficient implementation of analytic marching. *IEEE Transactions on Pattern Analysis and Machine Intelligence* (2021), 1. <https://doi.org/10.1109/TPAMI.2021.3135007>
- [LMW21] LINDELL D. B., MARTEL J. N., WETZSTEIN G.: Autoint: Automatic integration for fast neural volume rendering. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition* (2021), pp. 14556–14565.
- [MAG19] MARTON F., AGUS M., GOBBETTI E.: A framework for GPU-accelerated exploration of massive time-varying rectilinear scalar volumes. *Computer Graphics Forum* 38, 3 (2019), 53–66.
- [MDCL\*18] MARKIDIS S., DER CHIEN S. W., LAURE E., PENG I. B., VETTER J. S.: NVIDIA tensor core programmability, performance & precision. In *Proceedings of the 2018 IEEE International Parallel and Distributed Processing Symposium Workshops (IPDPSW)* (2018), IEEE, pp. 522–531.
- [MESK22] MÜLLER T., EVANS A., SCHIED C., KELLER A.: Instant neural graphics primitives with a multiresolution hash encoding. *ACM Transactions on Graphics* 41, 4 (July 2022), 102:1–102:15.
- [MLL\*21] MARTEL J. N. P., LINDELL D. B., LIN C. Z., CHAN E. R., MONTEIRO M., WETZSTEIN G.: ACORN: Adaptive coordinate networks for neural scene representation. *ACM Transactions on Graphics* 40, 4 (Aug. 2021), 1–13.
- [MON\*19] MESCHEDER L., OECHSLE M., NIEMEYER M., NOWOZIN S., GEIGER A.: Occupancy networks: Learning 3D reconstruction in function space. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition* (2019), pp. 4460–4470.
- [MRNK21] MÜLLER T., ROUSSELLE F., NOVÁK J., KELLER A.: Real-time neural radiance caching for path tracing. *ACM Transactions on Graphics* 40, 4 (Aug. 2021), 36:1–36:16.
- [MST\*20] MILDENHALL B., SRINIVASAN P. P., TANCIK M., BARRON J. T., RAMAMOORTHY R., NG R.: NeRF: Representing scenes as neural radiance fields for view synthesis. In *Proceedings of the European Conference on Computer Vision* (2020), Springer, pp. 405–421.
- [NLP\*12] NYSTAD J., LASSEN A., POMIANOWSKI A., ELLIS S., OLSON T.: Adaptive scalable texture compression. In *Proceedings of the Fourth ACM SIGGRAPH/Eurographics Conference on High-Performance Graphics* (2012), pp. 105–114.
- [NSP\*21] NEFF T., STADLBAUER P., PARGER M., KURZ A., MUELLER J. H., CHAITANYA C. R. A., KAPLANYAN A., STEINBERGER M.: DONeRF: Towards real-time rendering of compact neural radiance fields using depth oracle networks. *Computer Graphics Forum* 40 (2021), 45–59.
- [PCPMN21] PUMAROLA A., CORONA E., PONS-MOLL G., MORENO-NOGUER F.: D-NeRF: Neural radiance fields for dynamic scenes. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition* (2021), pp. 10318–10327.
- [PFS\*19] PARK J. J., FLORENCE P., STRAUB J., NEWCOMBE R., LOVEGROVE S.: DeepSDF: Learning continuous signed distance functions for shape representation. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition* (2019), pp. 165–174.
- [PGM\*19] PASZKE A., GROSS S., MASSA F., LERER A., BRADBURY J., CHANAN G., KILLEEN T., LIN Z., GIMELSHEIN N., ANTIGA L., DESMAISON A., KOPF A., YANG E., DEVITO Z., RAISON M., TEJANI A., CHILAMKURTHY S., STEINER B., FANG L., BAI J., CHINTALA S.: PyTorch: An imperative style, high-performance deep learning library. In *Proceedings of the Advances in Neural Information Processing Systems* 32 (2019), H. Wallach, H. Larochelle, A. Beygelzimer, F. d'Alché-Buc, E. Fox and R. Garnett (Eds.), Curran Associates, Inc., pp. 8024–8035.
- [RGG\*13] RODRIGUEZ M. B., GOBBETTI E., GUITIÁN J. A. I., MAKHINYA M., MARTON F., PAJAROLA R., SUTER S. K.: A survey of compressed GPU-based direct volume rendering. In *Proceedings of the Eurographics (State of the Art Reports)* (2013), pp. 117–136.
- [RTW13] REICHL F., TREIB M., WESTERMANN R.: Visualization of big SPH simulations via compressed octree grids. In *Proceedings of the 2013 IEEE International Conference on Big Data* (2013), IEEE, pp. 71–78.
- [SB21] SAHOO S., BERGER M.: Integration-aware vector field super resolution. In *Proceedings of the EuroVis 2021—Short Papers* (2021), M. Agus, C. Garth and A. Kerren (Eds.), The Eurographics Association.

- [SDZ\*21] SRINIVASAN P. P., DENG B., ZHANG X., TANCİK M., MILDENHALL B., BARRON J. T.: NeRV: Neural reflectance and visibility fields for relighting and view synthesis. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition* (2021), pp. 7495–7504.
- [SW03] SCHNEIDER J., WESTERMANN R.: Compression domain volume rendering. In *Proceedings of the IEEE Visualization, 2003. VIS 2003.* (2003), pp. 293–300.
- [SZW19] SITZMANN V., ZOLLHÖFER M., WETZSTEIN G.: Scene representation networks: Continuous 3D-structure-aware neural scene representations. *Advances in Neural Information Processing Systems* Curran Associates, Inc 32 (2019). <https://proceedings.neurips.cc/paper/2019/file/b5dc4e5d9b495d0196f61d45b26ef33e-Paper.pdf>
- [TBR\*12] TREIB M., BÜRGER K., REICHL F., MENEVEAU C., SZALAY A., WESTERMANN R.: Turbulence visualization at the terascale on desktop PCs. *IEEE Transactions on Visualization and Computer Graphics* 18, 12 (2012), 2169–2177.
- [TFT\*20] TEWARI A., FRIED O., THIES J., SITZMANN V., LOMBARDI S., SUNKAVALLI K., MARTIN-BRUALLA R., SIMON T., SARAGIH J., NIEBNER M., PANDEY R., FANELLO S., WETZSTEIN G., ZHU J.-Y., THEOBALT C., AGRAWALA M., SHECHTMAN E., GOLDMAN D. B., ZOLLHÖFER M.: State of the art on neural rendering. In *Computer Graphics Forum* 39 (2020), 701–727.
- [TLY\*21] TAKIKAWA T., LITALIEN J., YIN K., KREIS K., LOOP C., NOWROUZEZAHRAI D., JACOBSON A., MCGUIRE M., FIDLER S.: Neural geometric level of detail: Real-time rendering with implicit 3D shapes. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition* (2021), pp. 11358–11367.
- [TRAW12] TREIB M., REICHL F., AUER S., WESTERMANN R.: Interactive editing of GigaSample terrain fields. *Computer Graphics Forum* 31 (2012), 383–392.
- [TSM\*20] TANCİK M., SRINIVASAN P. P., MILDENHALL B., FRIDOVICH-KEIL S., RAGHAVAN N., SINGHAL U., RAMAMOORTHY R., BARRON J. T., NG R.: Fourier features let networks learn high frequency functions in low dimensional domains. *arXiv preprint* (2020). <http://arxiv.org/abs/2006.10739>.
- [WBSS04] WANG Z., BOVIK A. C., SHEIKH H. R., SIMONCELLI E. P.: Image quality assessment: from error visibility to structural similarity. *IEEE Transactions on Image Processing* 13, 4 (2004), 600–612.
- [WCTW19] WEISS S., CHU M., THUREY N., WESTERMANN R.: Volumetric isosurface rendering with deep learning-based super-resolution. *IEEE Transactions on Visualization and Computer Graphics* 27, 6 (2019), 3064–3078. <https://doi.org/10.1109/TVCG.2019.2956697>
- [Wes95] WESTERMANN R.: Compression domain rendering of time-resolved volume data. In *Proceedings of the Visualization '95* (1995), pp. 168–175.
- [WITW20] WEISS S., IŞIK M., THIES J., WESTERMANN R.: Learning adaptive sampling and reconstruction for volume visualization. *IEEE Transactions on Visualization and Computer Graphics* 28, 7 (2020), 2654–2667. <https://doi.org/10.1109/TVCG.2020.3039340>
- [WSG\*21] WURSTER S. W., SHEN H.-W., GUO H., PETERKA T., RAJ M., XU J.: Deep hierarchical super-resolution for scientific data reduction and visualization. 2021. <http://arxiv.org/abs/2107.00462>.
- [WW21] WEISS S., WESTERMANN R.: Differentiable direct volume rendering. *IEEE Transactions on Visualization and Computer Graphics* 28, 1 (2022), 562–572. <https://doi.org/10.1109/TVCG.2021.3114769>
- [YFKT\*21] YU A., FRIDOVICH-KEIL S., TANCİK M., CHEN Q., RECHT B., KANAZAWA A.: Plenoxels: Radiance fields without neural networks. *arXiv preprint arXiv:2112.05131* (2021).
- [YL95] YEO B.-L., LIU B.: Volume rendering of DCT-based compressed 3D scalar data. *IEEE Transactions on Visualization and Computer Graphics* 1, 1 (1995), 29–43.
- [YLT\*21] YU A., LI R., TANCİK M., LI H., NG R., KANAZAWA A.: Plenotrees for real-time rendering of neural radiance fields. In *Proceedings of the IEEE/CVF International Conference on Computer Vision* (2021), pp. 5752–5761.
- [ZDL\*20] ZHAO K., DI S., LIANG X., LI S., TAO D., CHEN Z., CAPPELLO F.: Significantly improving lossy compression for HPC datasets with second-order prediction and parameter optimization. In *HPDC'20: Proceedings of the 29th International Symposium on High-Performance Parallel and Distributed Computing* (New York, NY, USA, 2020), Association for Computing Machinery, pp. 89–100.
- [ZHW\*17] ZHOU Z., HOU Y., WANG Q., CHEN G., LU J., TAO Y., LIN H.: Volume upscaling with convolutional neural networks. In *Proceedings of the Computer Graphics International Conference* (2017), pp. 1–6.
- [ZIE\*18] ZHANG R., ISOLA P., EFROS A. A., SHECHTMAN E., WANG O.: The unreasonable effectiveness of deep features as a perceptual metric. In *Proceedings of the CVPR* (2018).

## Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

**Table 1:** Evaluation of different activation functions on rendered images.

**Table 2:** Quality comparison between training in world-space and in screen-space with different input encodings and stepsizes for the TF from Fig. 1.

**Figure 1:** Screen- vs. world-space training, using a TF with sharp peaks.

**Figure 2:** Renderings with a gradient-dependent TF with a different stepsize  $h$  for the finite differences approximation: a)  $h = 4R$ , b)  $h = R$ , c)  $h = R/16$ , where  $R$  is the voxel size.

**Figure 3:** A hyperparameter study was conducted on two datasets, a human skull ( $256^3$ , top) and a Richtmyer-Meshkov simulation ( $512^3$ , bottom).

**Figure 4:** Evaluation of analytic datasets, “Blobby” [SN09] and “Marschner Lobb” [ML94]

**Table 3:** Performance comparison of the three tested methods for computing the density and gradients for  $2^{24}$  samples.

**Figure 5:** We explore different methods on how density gradients can be computed using volumetric SRNs, shown here on two exemplary datasets

**Figure 6:** Influence of fine-tuning the weighting value  $\alpha$  in the loss function for the datasets from Fig. 5: The default setting for the gradient weighting  $\alpha$  (see Sec. 3.3) leads to the configuration highlighted in green.

**Figure 7:** Evaluation of different compression rates for fV-SRN.

**Figure 8:** Visual comparison of fV-SRN for different compression ratios on the Richtmyer Meshkov dataset (a-d) and the Miranda dataset (e-h). (a,e) Reference, (b,f) fV-SRN, (c,g) TThresh, (d-h) cudaCompress.