

Coded Aperture Projection

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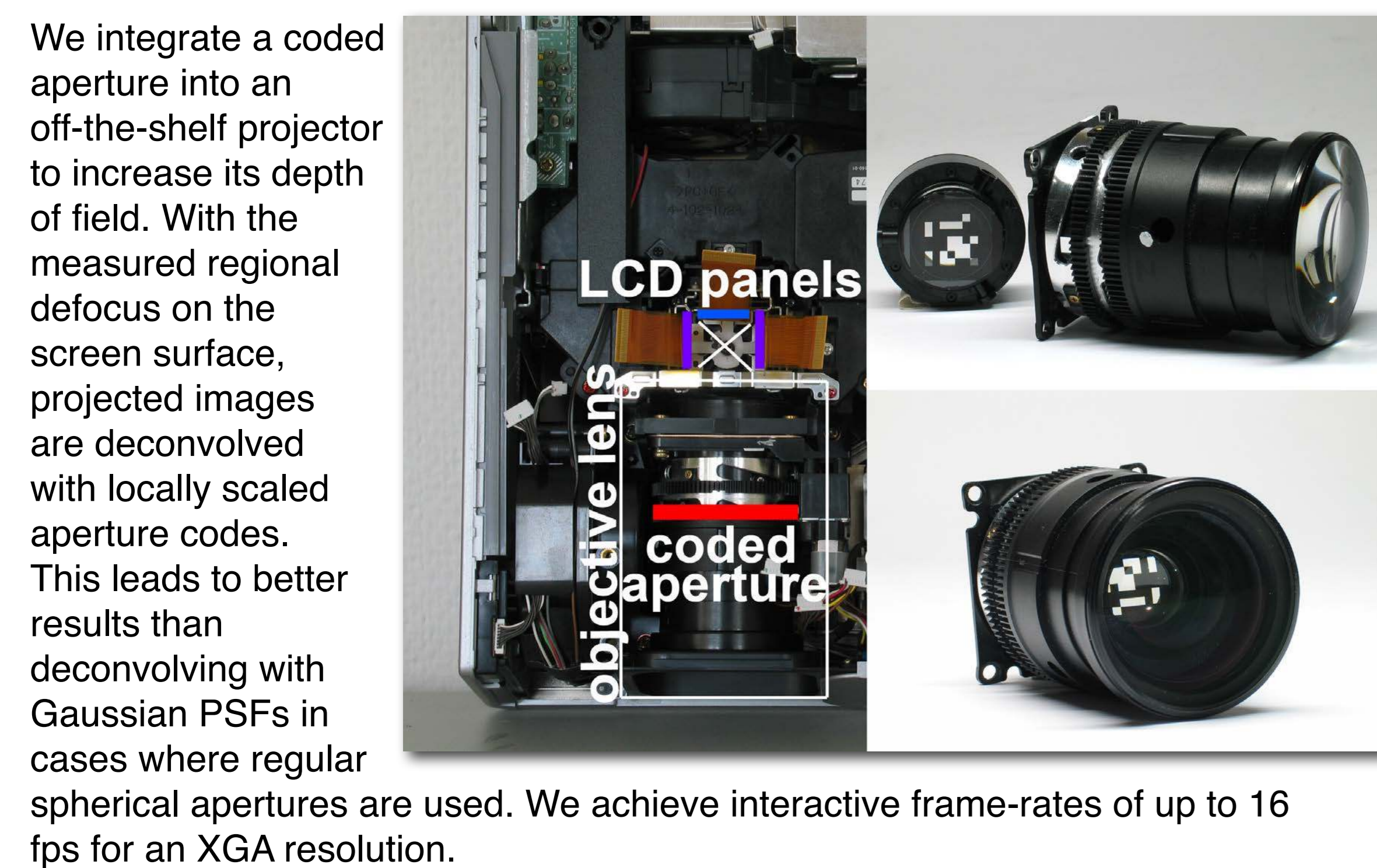
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Abstract

Introduction

Video projectors apply simple spherical apertures and suffer from a relatively short depth of field. This is problematic when images are projected onto non-planar surfaces, such as in case of spherical or cylindrical projection displays. They might be regionally defocused if the aperture of the projector is too large. Using smaller apertures for increasing the depth of field, however, decreases the light throughput.



Hardware Implementation

The selected near-optimal aperture code was printed on transparencies (Kodak film didn't resist the heat), and was inserted into the objective lens – replacing the projector's exiting spherical aperture.

Related Work

Multi-Projector approach

Several approaches have been proposed to increase the depth of field of conventional projectors. Bimber and Emmerling [1], for instance, have described a multi-focal projection concept that applies multiple projectors with differently adjusted focal planes, but overlapping image areas. The individual image contribution of each projector is computed in such a way that – when displayed simultaneously – a single, photometrically and geometrically consistent image appears which is optimally focussed over the entire surface.

Spherical aperture defocus compensation

Images can be digitally sharpened by convolving them with the inverse of a known blur function. In image processing, this process is known as deconvolution or inverse filtering. Brown et al. [2] as well as Oyamada et al. [3] apply inverse filtering to compensate optical defocus of a single projector.

The PSFs produced by projectors using regular spherical apertures is Gaussian. This sets clear limitations in terms of recovering fine image details with inverse filtering. Since Gaussians are low-pass filters, their inverse will cause strong ringing artifacts after deconvolution if the projector's dynamic range is not infinitely high. To reduce these artifacts, Zhang and Nayar [4] formulate the computation of the compensation image as an optimization problem that constrains the solution to the actual dynamic range of the projector while minimizing local optical defocus.

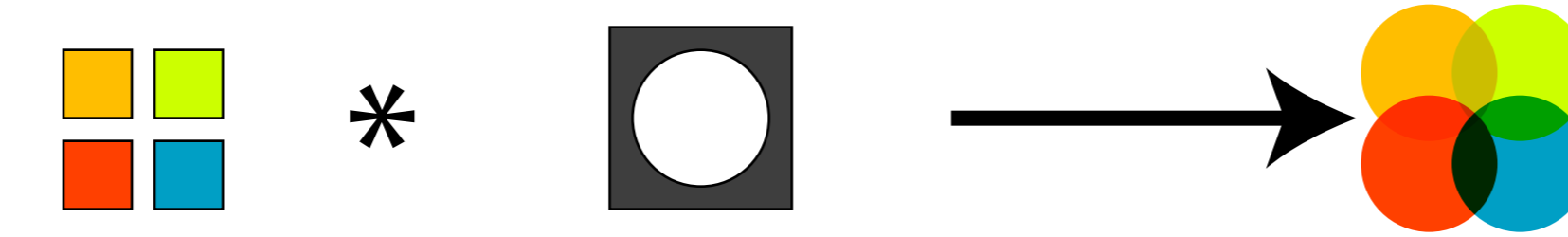
Coded Aperture Imaging

Coded aperture imaging has been presented recently in the context of computational photography [5, 6], and has been applied previously in astronomy and medical imaging. In contrast to conventional apertures, coded apertures (i.e., apertures that encode a more complex binary or intensity pattern, rather than a simple round opening) in cameras enable post-exposure refocusing, reconstructing scene depth, or recording light fields.

Principle

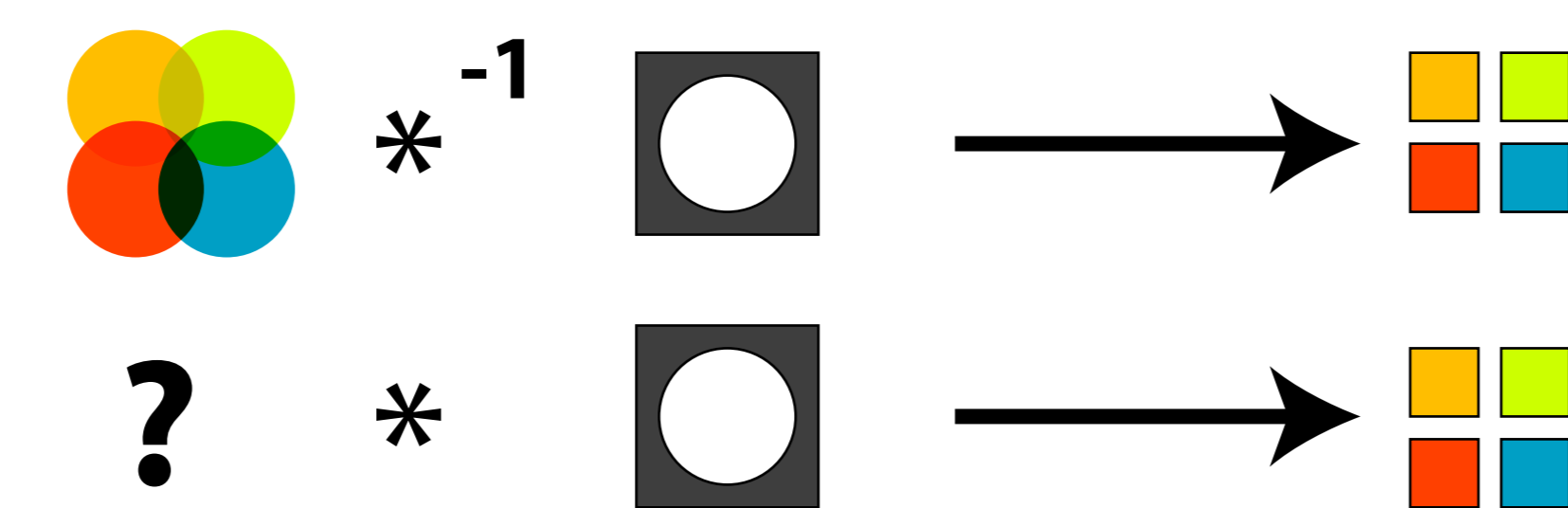
Defocus blur as a convolution

Optical defocus is often described as convolution with a filter kernel that corresponds to an image of the aperture being applied by the imaging device. The degree of defocus correlates to the scale of the kernel.



Deconvolution / Inverse filtering

Deconvolution –i.e., convolving an image with the inverse aperture kernel– will digitally sharpen the image and consequently compensate optical defocus.



Mathematics of convolution and deconvolution

A convolution of an image I with a kernel K of scale s results in a convolved image I'

$$I * K_s = I'$$

Applying the Fourier transform, the convolution operator becomes a simple multiplication

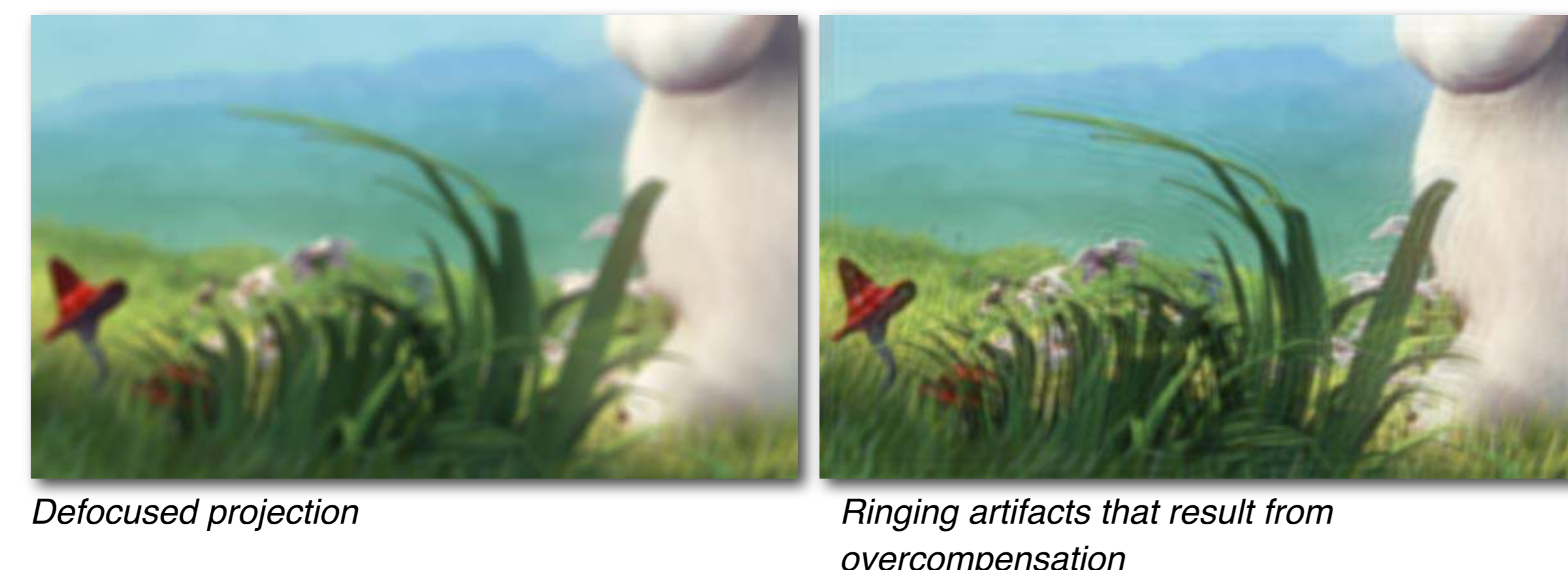
$$\hat{I} \cdot \hat{K}_s = \hat{I}'$$

This enables us to invert the equation and calculate the deconvolution. As the Fourier transform of K might have values of very small magnitude, division leads to intensities in spacial domain that exceed the projectors displayable range, resulting in ringing artifacts.

$$\hat{I} = \frac{\hat{I}'}{\hat{K}_s}$$

Ringing artifacts

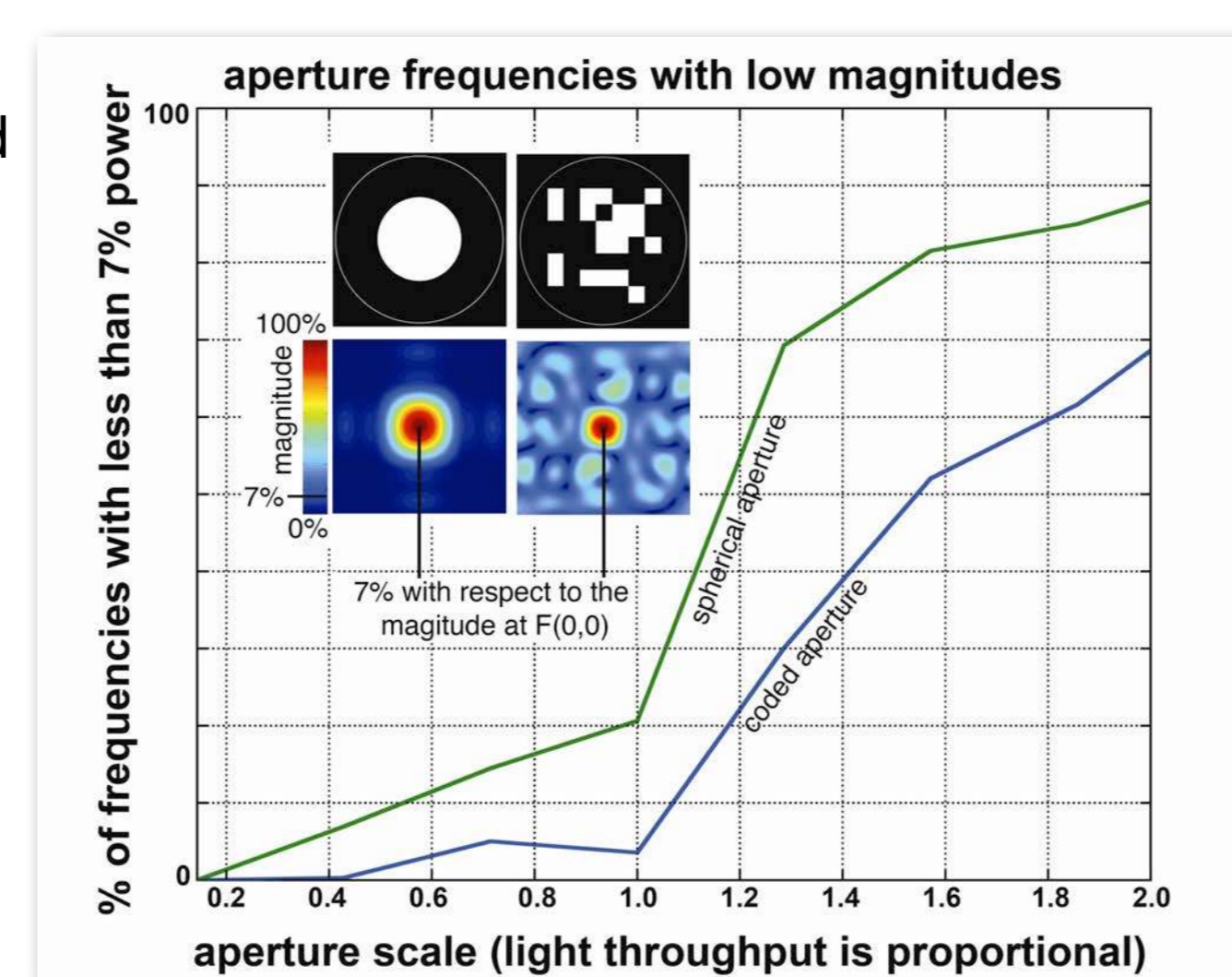
If the magnitudes in frequency domain of the used aperture are very low at some positions, which is the case for ordinary spherical apertures, strong ringing artifacts will be visible.



Coded Aperture Projection

We introduce coded aperture projection, and show that if coded apertures are applied instead of simple spherical ones, ringing artifacts as a result from deconvolution can be reduced and more image details can be recovered from optical defocus.

The coded aperture has less low-magnitude frequencies and preserves high frequencies over all scales.



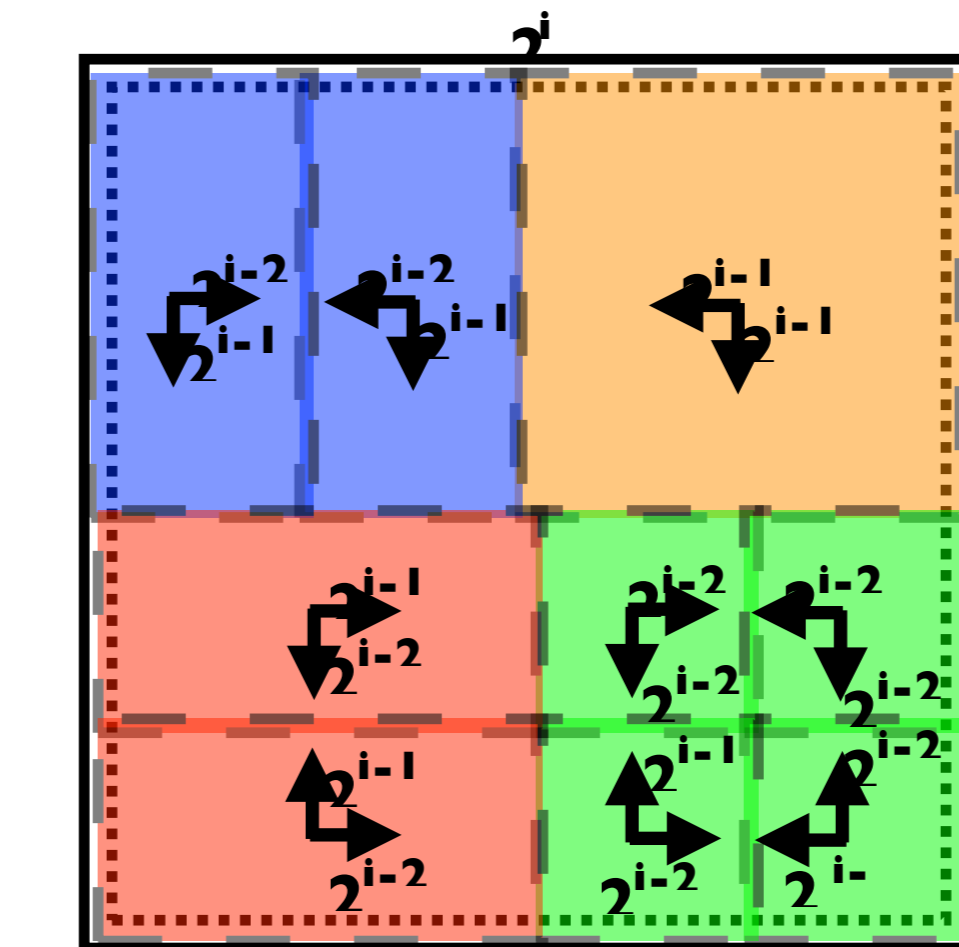
Implementation

Software implementation

For measuring the local defocus of each projector pixel, we apply the momentum preserving principle used in [1]. Principally, each pixel of the original image would have to be deconvolved individually depending on its defocus. To reach interactive frame-rates, larger image portions have to be processed instead. One option is to deconvolve the entire image for all determined aperture scales [2] and compose the compensation image from the different scale results. However, this technique is also not very efficient, since many pixels are deconvolved for unnecessary aperture scales. Partitioning the image with a simple uniform grid structure [3] does not consider the (possibly nonuniform) local distribution of aperture scales, and can therefore still cause a significant amount of overhead.

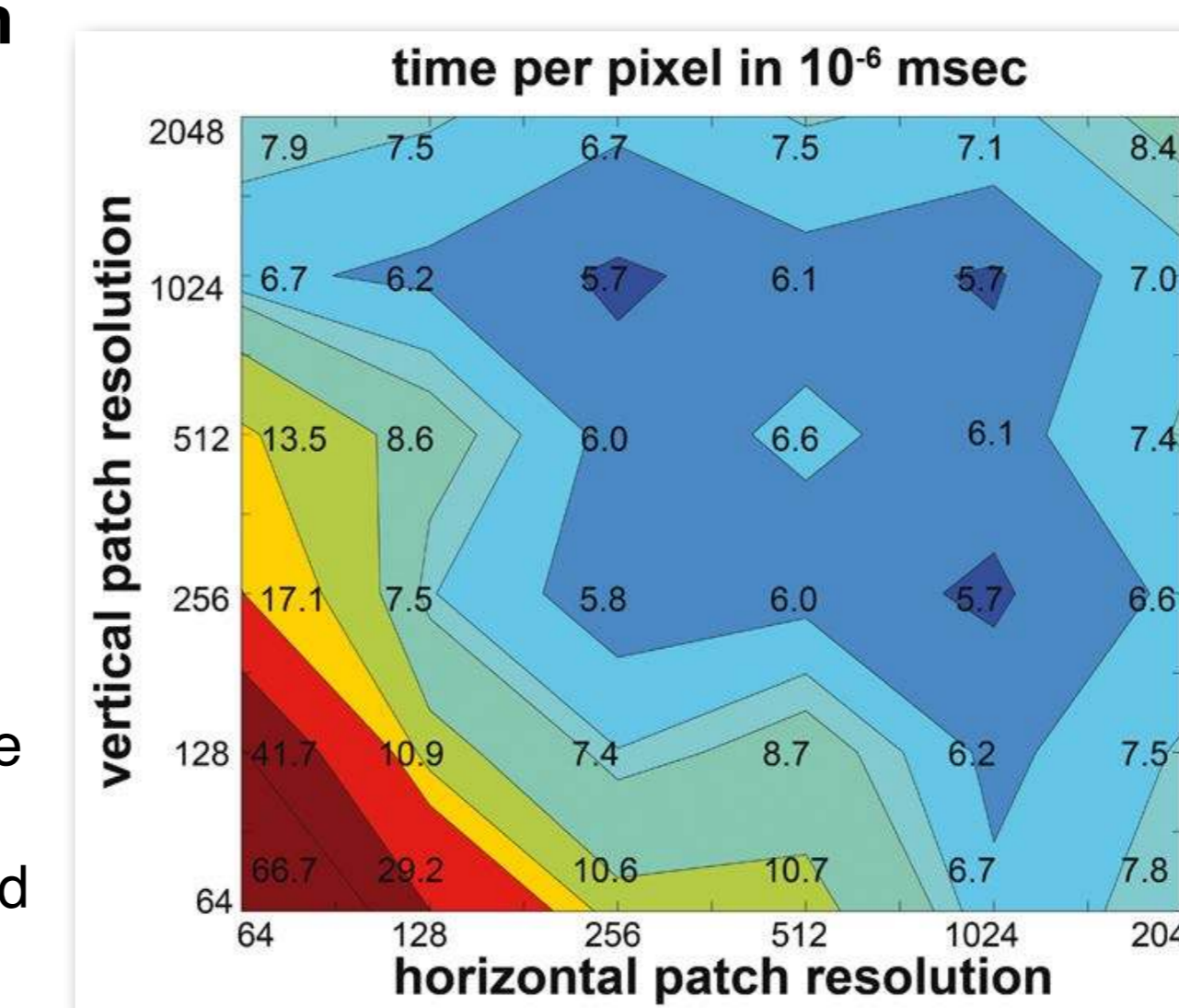
Image partitioning

To overcome this, our method partitions the image in a non-uniform way based on the actual distribution of the aperture scales and on the capabilities of the graphics hardware being used. The entire partitioning operation can be carried out off-line, since it is independent from the image content.



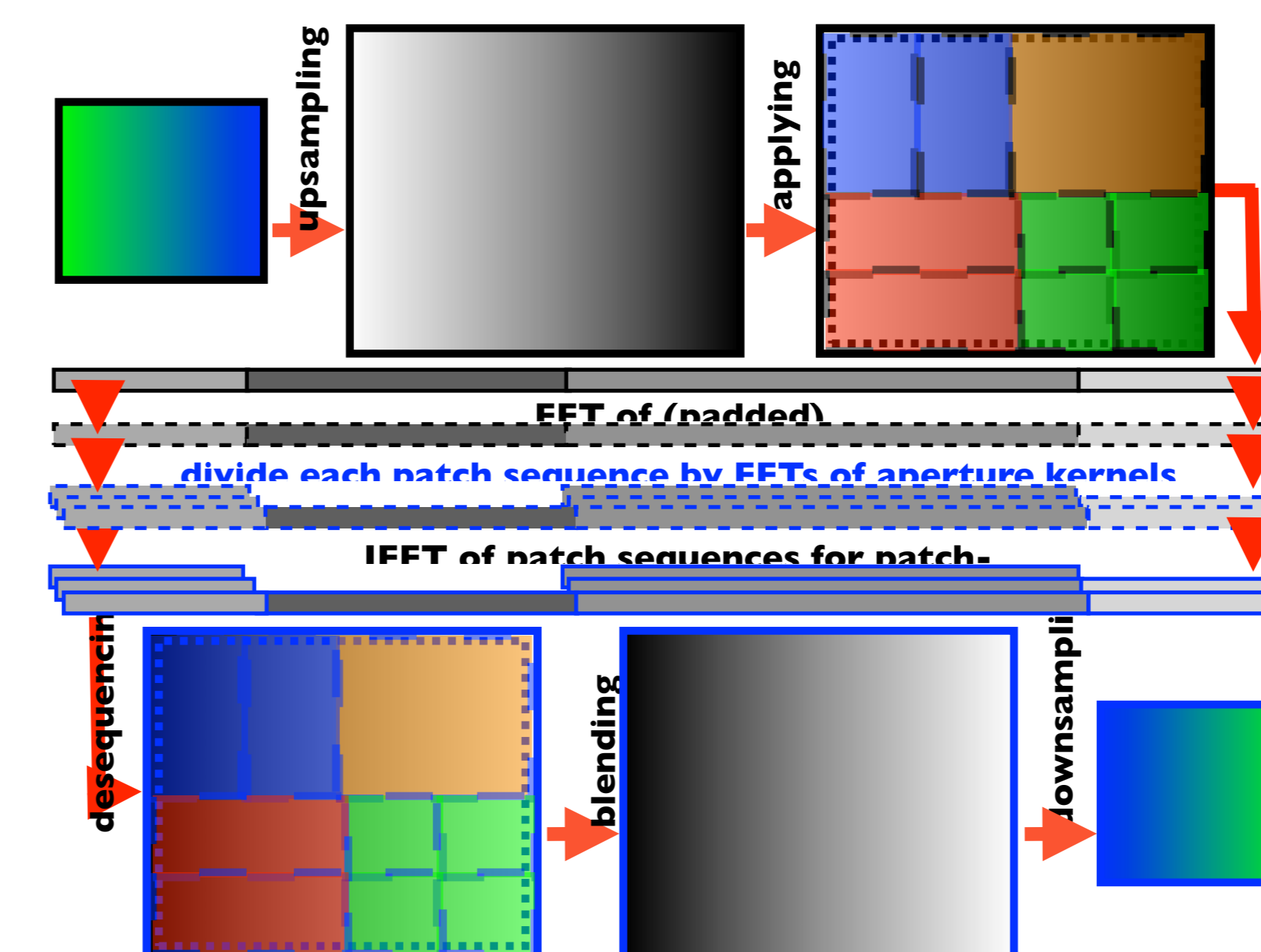
GPU Fourier transformation

The Fourier transformation and its inverse require the largest amount of computation time for deconvolution. We apply CUDA's GPU implementation of the Fast Fourier Transformation (FFT). We decide to subdivide the image into patches whose edge lengths are powers-of-two. First, we measure the efficiency of the entire deconvolution for each possible patch size directly on the GPU, and compute the average time that is required to process one pixel in each case. In theory, this should be in the order of $\lg(N)$ for patches with N pixels. In practice, the overhead of hardware and software specific implementations of the FFT/IFFT can be significant.



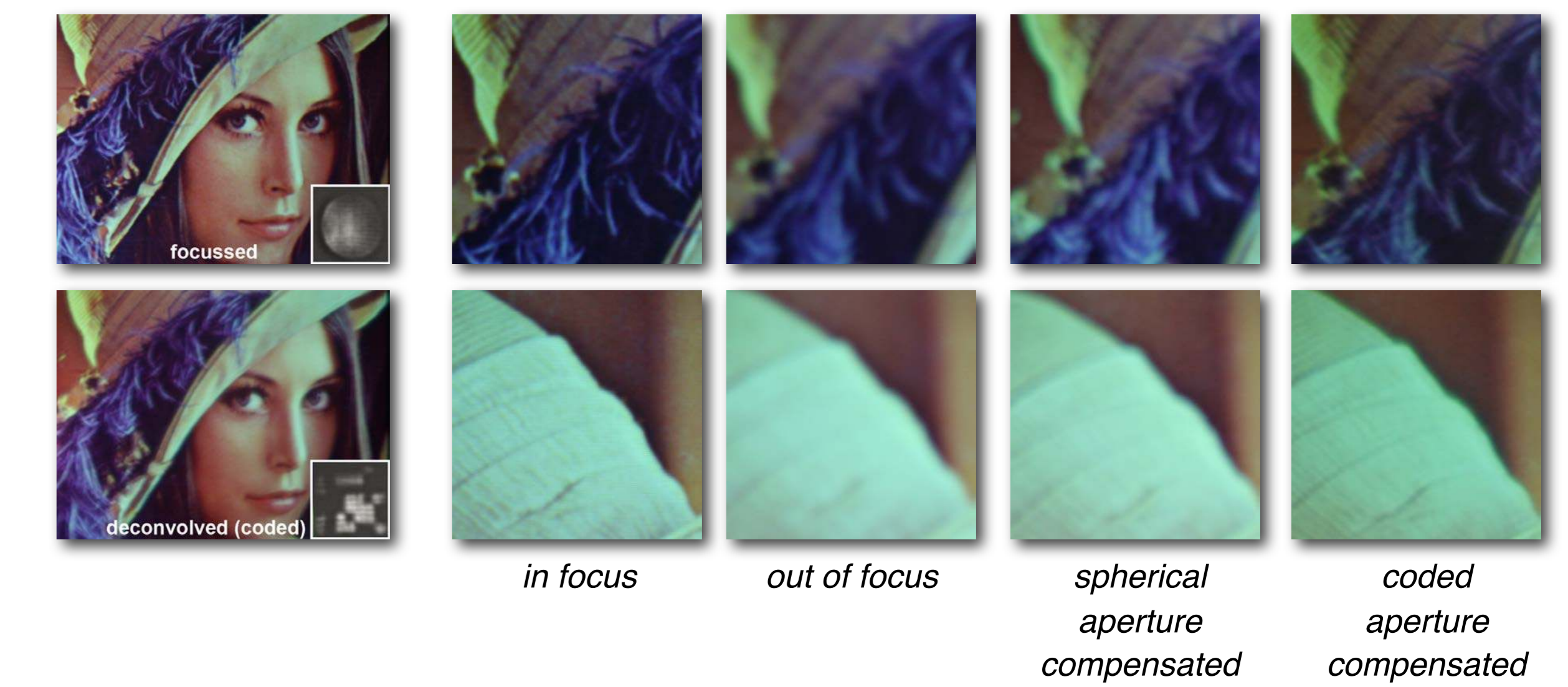
Steps per frame of deconvolution process on GPU

1. luminance conversion and up-sampling,
2. partitioning and padding,
3. sequencing to array,
4. FFT of patch sequences,
5. divisions in frequency domain for all scales required for each patch,
6. IFFT for all patches and all scales,
7. de-sequencing to 2D image while selecting pixels' luminance values from correct scale array,
8. blending of overlapping patches in spatial domain,
9. down-sampling to original size and recombination with chrominances.



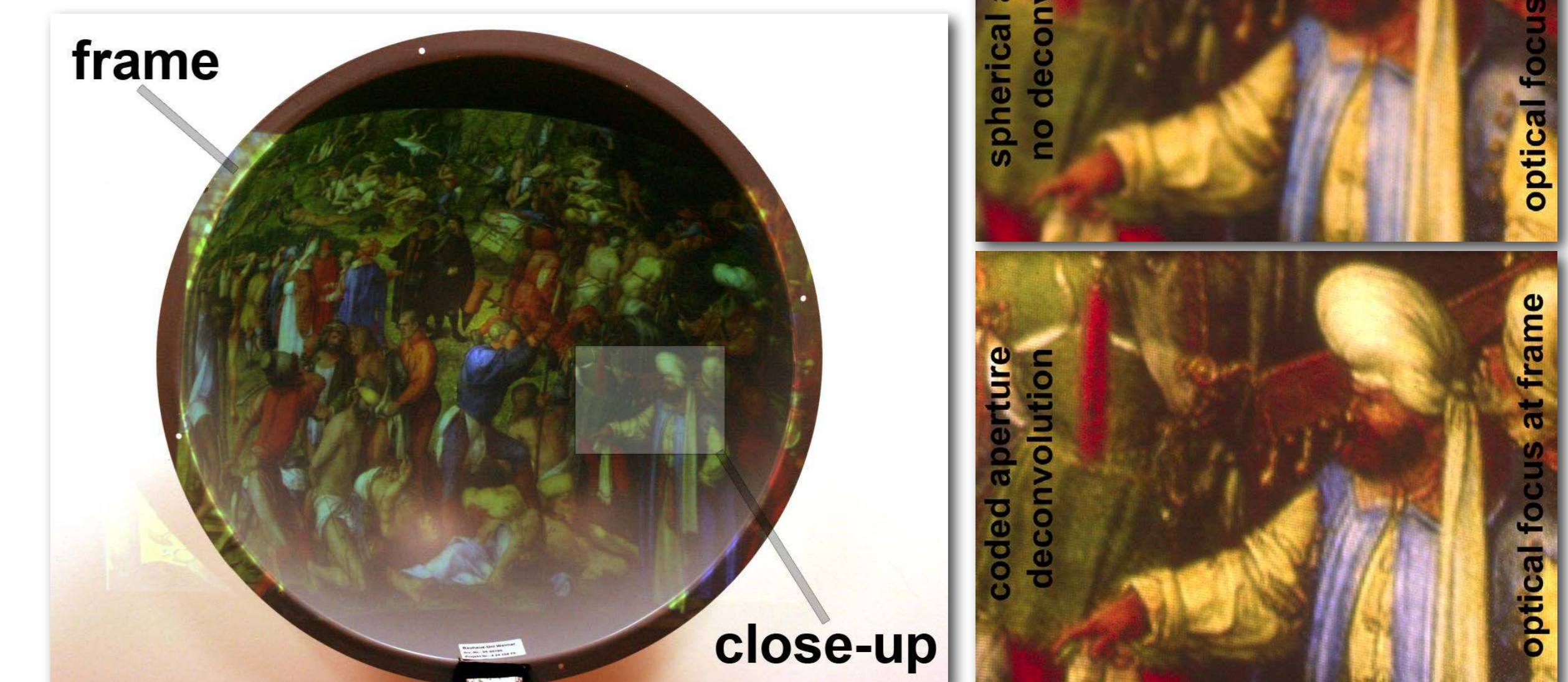
Results

Optimized aperture codes always perform better for digital defocus compensation than ordinary round openings with the same light throughput



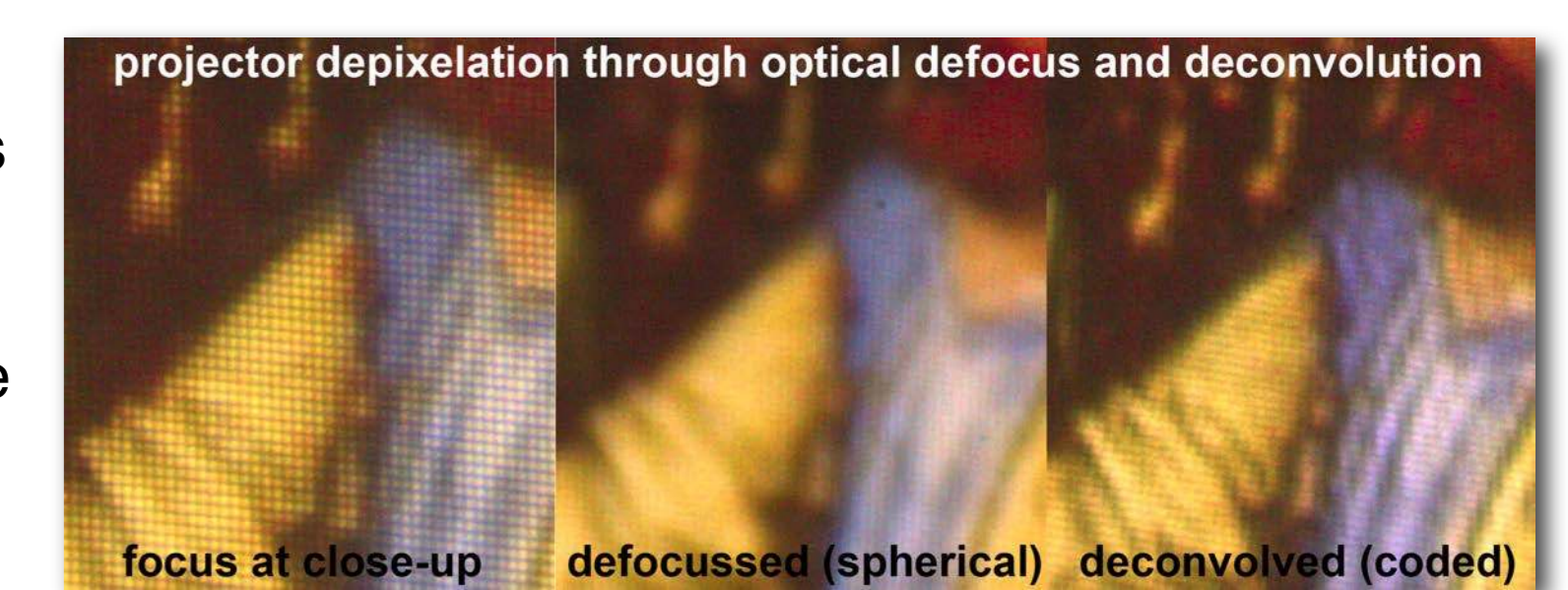
Increasing depth of field

Depth of field for non planar surfaces can be significantly increased



Depixelation

Optical defocus diminishes the appearance of the projected pixel grid while deconvolution recovers the image details. This has been referred to as projector depixelation [4], which is another application of projector defocus compensation.



Interactive framerates

Using our technique, we achieve interactive framerates of 12-16 fps on a NVidia GeForce 8800 Ultra for 1-14 blur different blur levels and an XGA resolution.

References

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- [2] BROWN, M. S., SONG, P., AND CHAM, T.-J. 2006. Image Preconditioning for Out-of-Focus Projector Blur. In Proc. of IEEE Conference on Computer Vision and Pattern Recognition (CVPR), vol. II, 1956–1963.
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- [6] VEERARAGHAVAN, A., RASKAR, R., AGRAWAL, A., MOHAN, A., AND TUMBLIN, J. 2007. Dappled photography: mask enhanced cameras for heterodyned light fields and coded aperture refocusing. ACM Trans. Graph. (SIGGRAPH) 26, 3, 69.