Adaptive Plenoptic Sampling

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Overview

- Image Based Rendering and Motivation
- Plenoptic Sampling Theory
- Spectral Analysis of a Slanted Plane
- Adaptive Sampling Algorithm
- Conclusions and Future Work

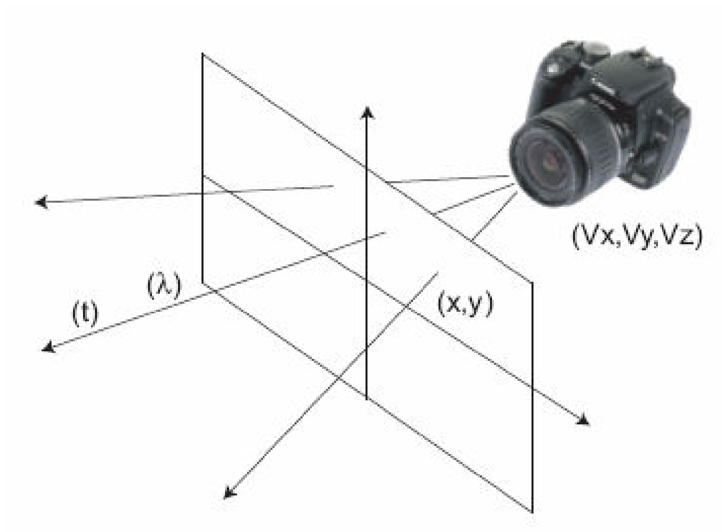
Image Based Rendering

Image Based Rendering (IBR) $\Longrightarrow$ Rendering New Viewpoints of a Scene from a Multi-View Image Set

In more detail:

- Images sample a set of lights rays from the scene to the camera
- New rendering interpolated from captured light rays
- Lights ray modelled using the 7D *Plenoptic Function* [1]

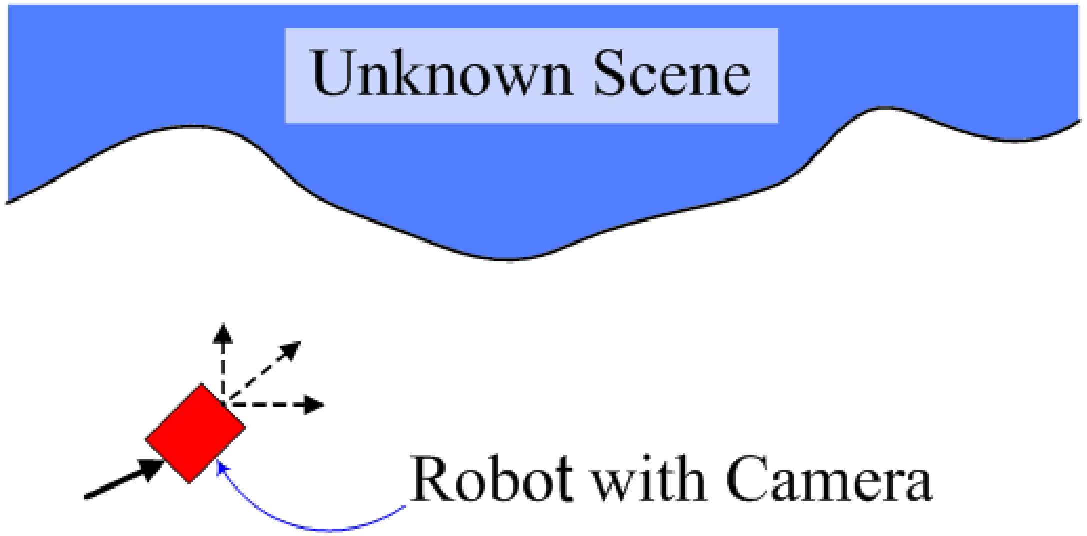
$\looparrowright$ IBR viewed as the Sampling and Reconstruction of the Plenoptic Function



- Camera centre location (v_x, v_y, v_z),
- Viewing direction (v, y),
- Wavelength ν,
- Time τ.

Motivation

Perform IBR on an Unknown Scene using a Camera Mounted to a Robot.



Important Questions:

- How should the camera travel relative to the scene?
- Where to sample along the path?
- Whether to zoom or not?

Current Work:

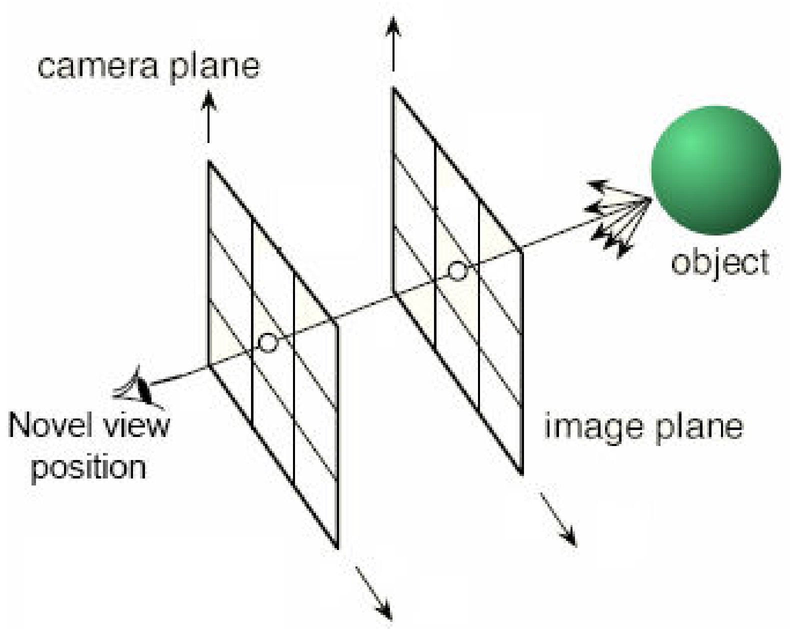
- Model the scene with a smoothly varying surface and bandlimited texture
- Non-uniform sampling based on approximating the surface with slanted planes

Reducing Plenoptic Dimensionality

Three Assumptions:

1. Static Scene $\Rightarrow$ remove τ
2. Three constant wavelength bands $\Rightarrow$ remove ν
3. Radiance of a light ray is constant along its path $\Rightarrow$ Light ray define by the intersection with two planes

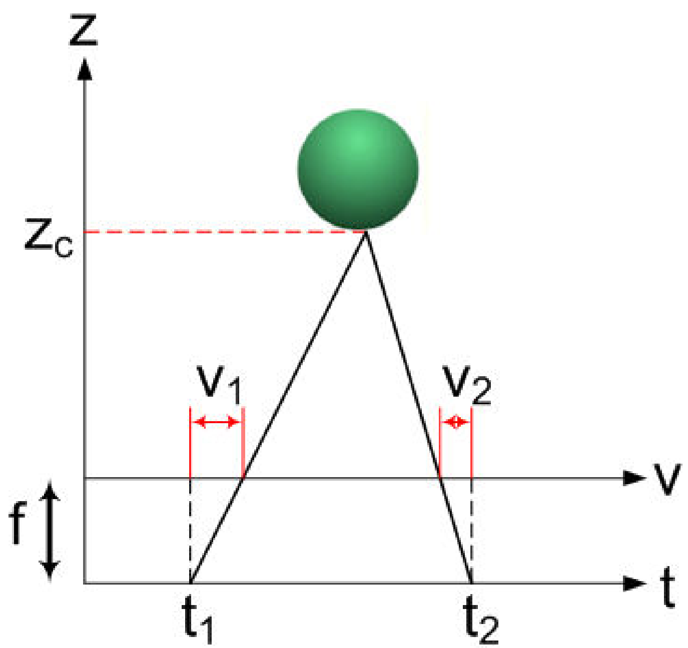
$\looparrowright$ 4D Light Field Parameterisation



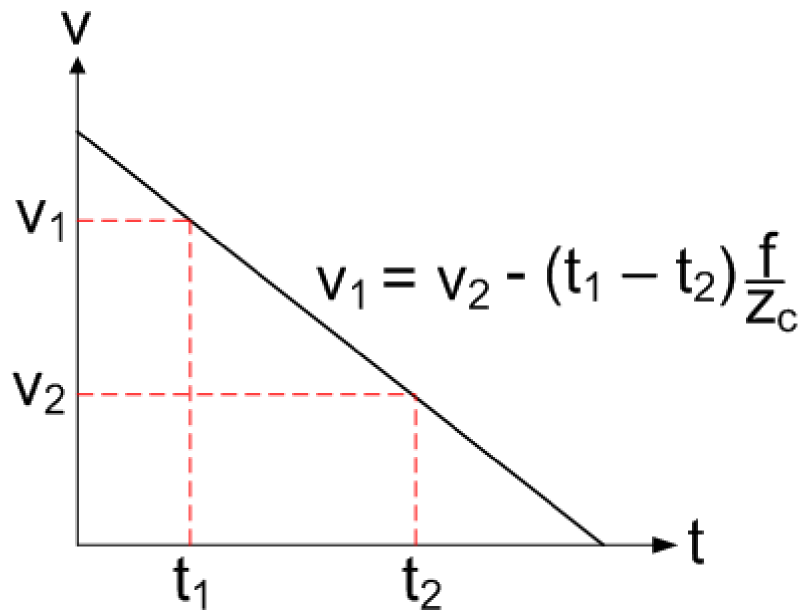
but can be reduced further......

Plenoptic Function and the Epipolar Plane Image

Consider the 2D Plenoptic Function, $p(t, v)$, known as the Epipolar Plane Image (EPI) [2]



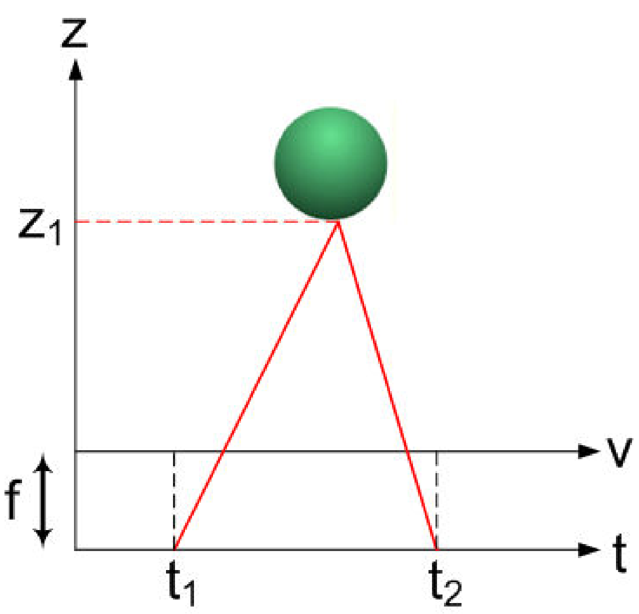
(a) Scene



(b) EPI

- Point in the scene $\Longrightarrow$ Line in the EPI plane where the slope depends on the depth
- Fixing a camera position t_1 $\Longrightarrow$ 1D image signal
- Fixing a pixel v_1 $\Longrightarrow$ 1D signal of the pixel captured by all cameras

Plenoptic Spectral Analysis



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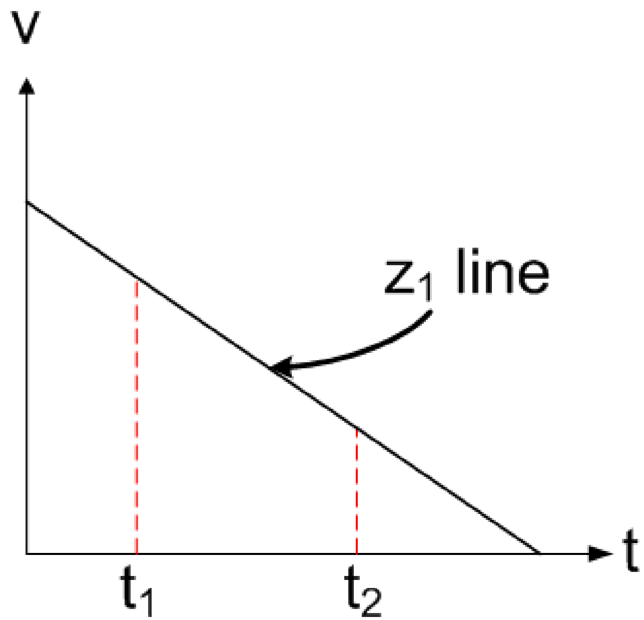
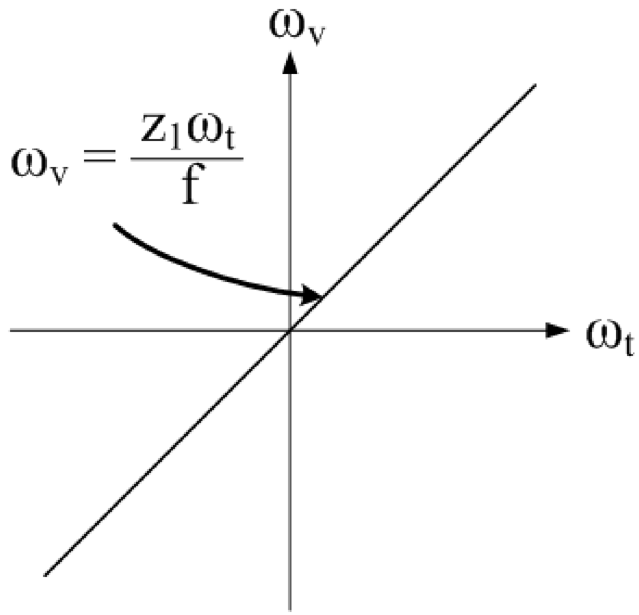
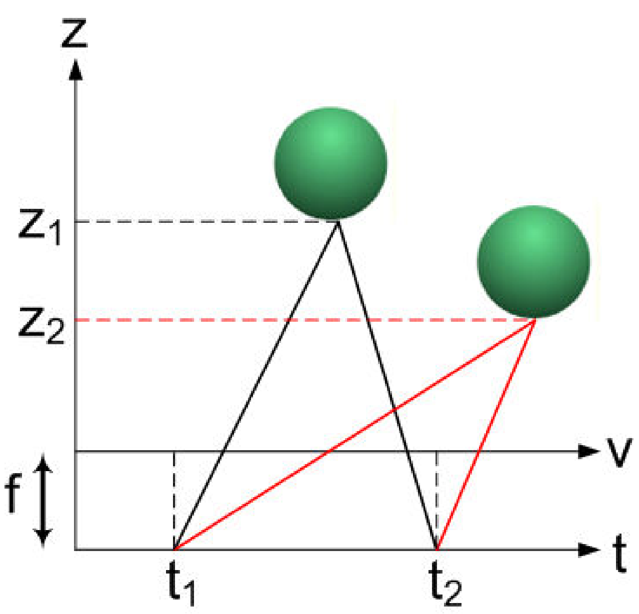


(b) EPI



(c) Plenoptic Spectrum

Plenoptic Spectral Analysis



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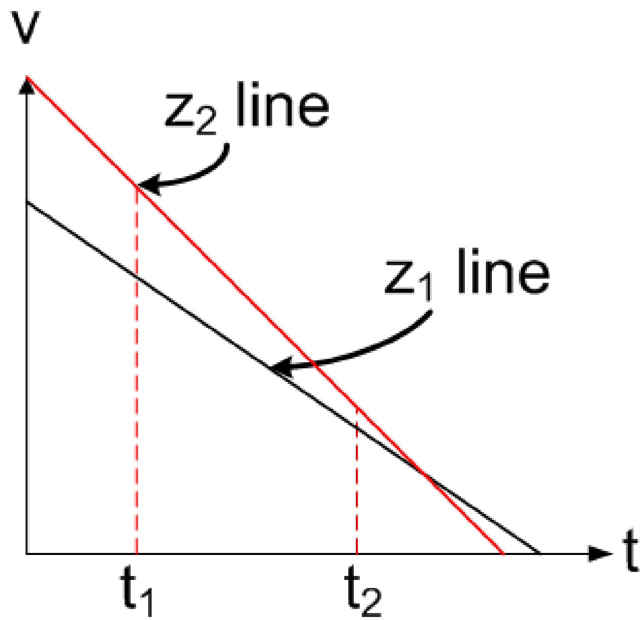
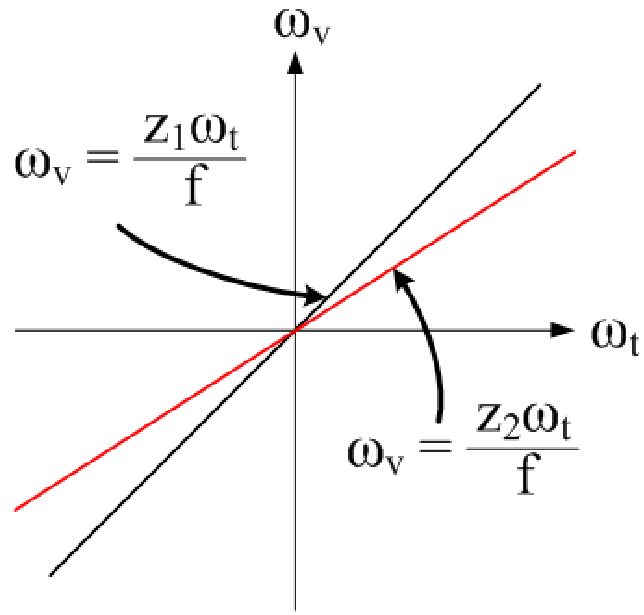


(b) EPI



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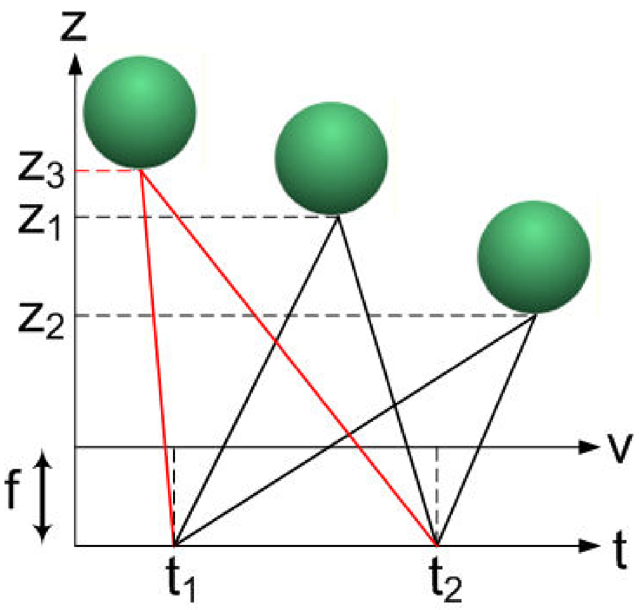

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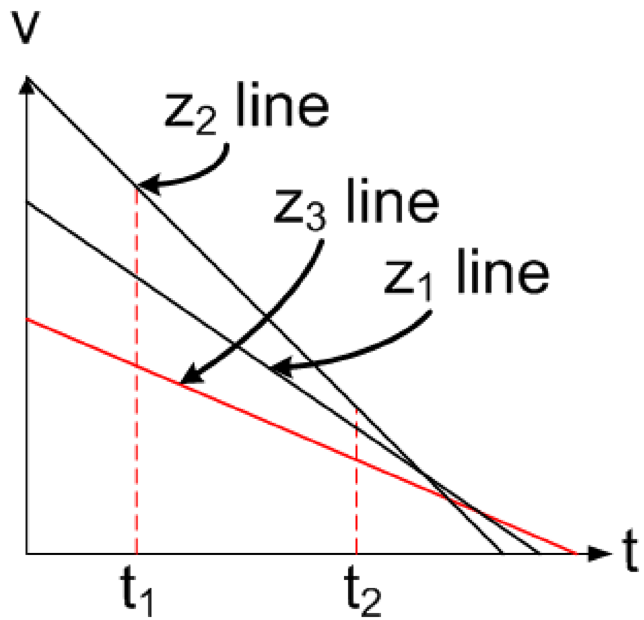
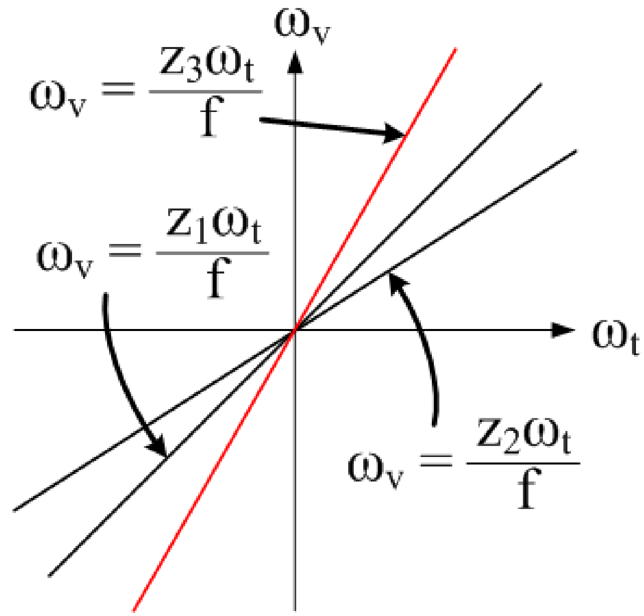


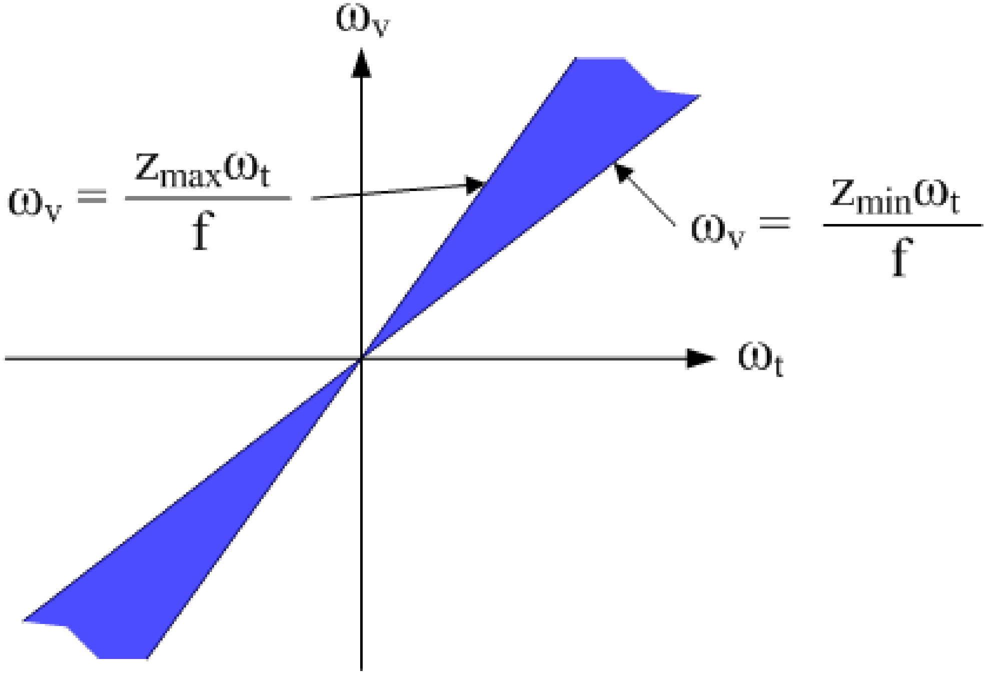
(b) EPI



(c) Plenoptic Spectrum

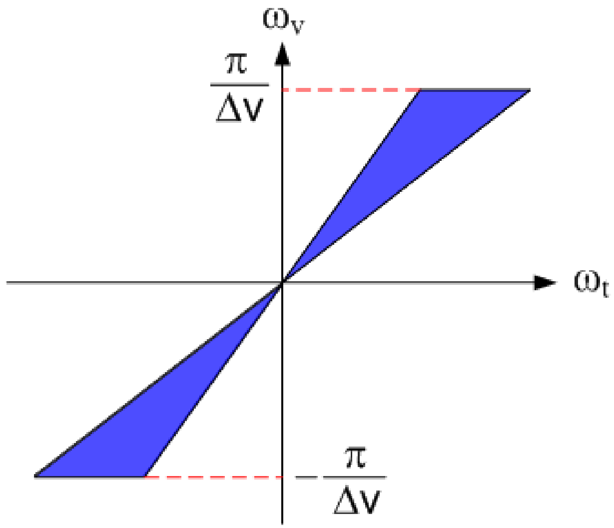
Plenoptic Spectral Analysis

Plenoptic Spectrum exactly bound within two lines relating to the minimum and maximum depths of the scene [2,3]

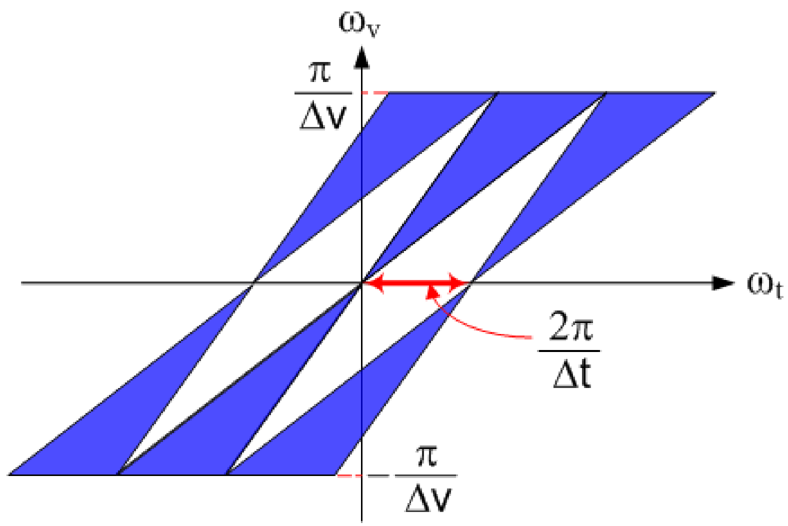


Sampled Plenoptic Spectrum

- Finite Camera Resolution $\Delta v \Longrightarrow$ Enforced Lowpass Filtering in ω_v
- Sampling in t of period $\Delta t \Longrightarrow$ Replicated Plenoptic Spectra
- Undersampling $\Longrightarrow$ Replicated Spectra Overlap $\Longrightarrow$ Aliasing



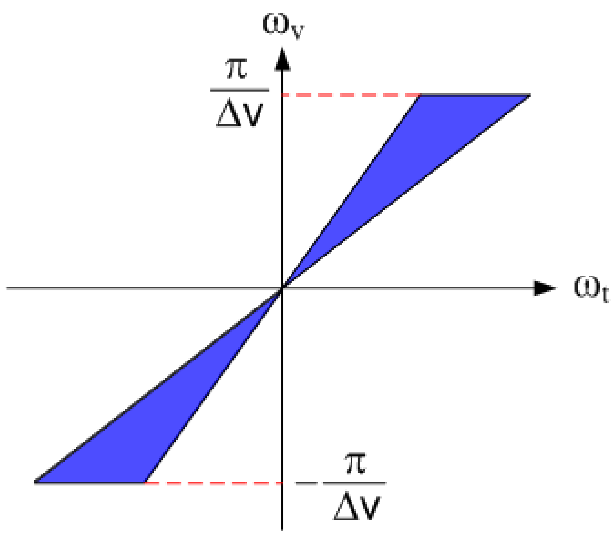
(a) Plenoptic Spectrum Sampled in v



(b) Plenoptic Spectrum Sampled in t

Sampled Plenoptic Spectrum

- Finite Camera Resolution $\Delta v \implies$ Enforced Lowpass Filtering in ω_v
- Sampling in t of period $\Delta t \implies$ Replicated Plenoptic Spectra
- Undersampling $\implies$ Replicated Spectra Overlap $\implies$ Aliasing



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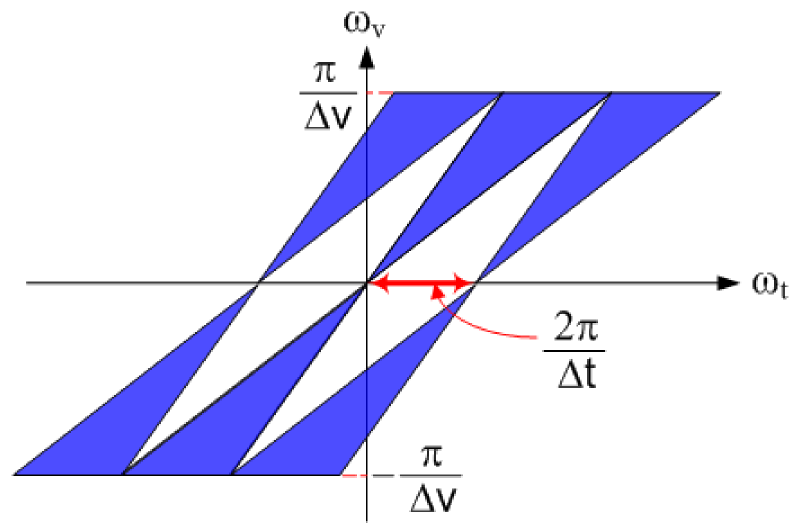

(b) Plenoptic Spectrum Sampled in t

Assumes $\implies$ Infinite Scene Width and Infinite Field of View (FoV),

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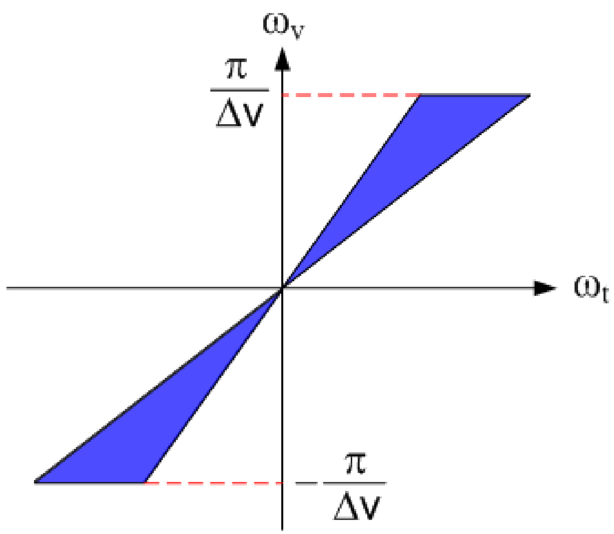

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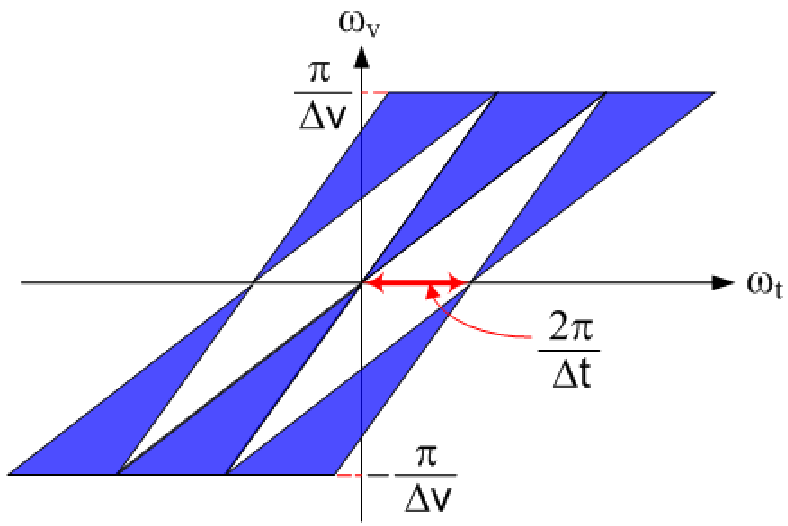
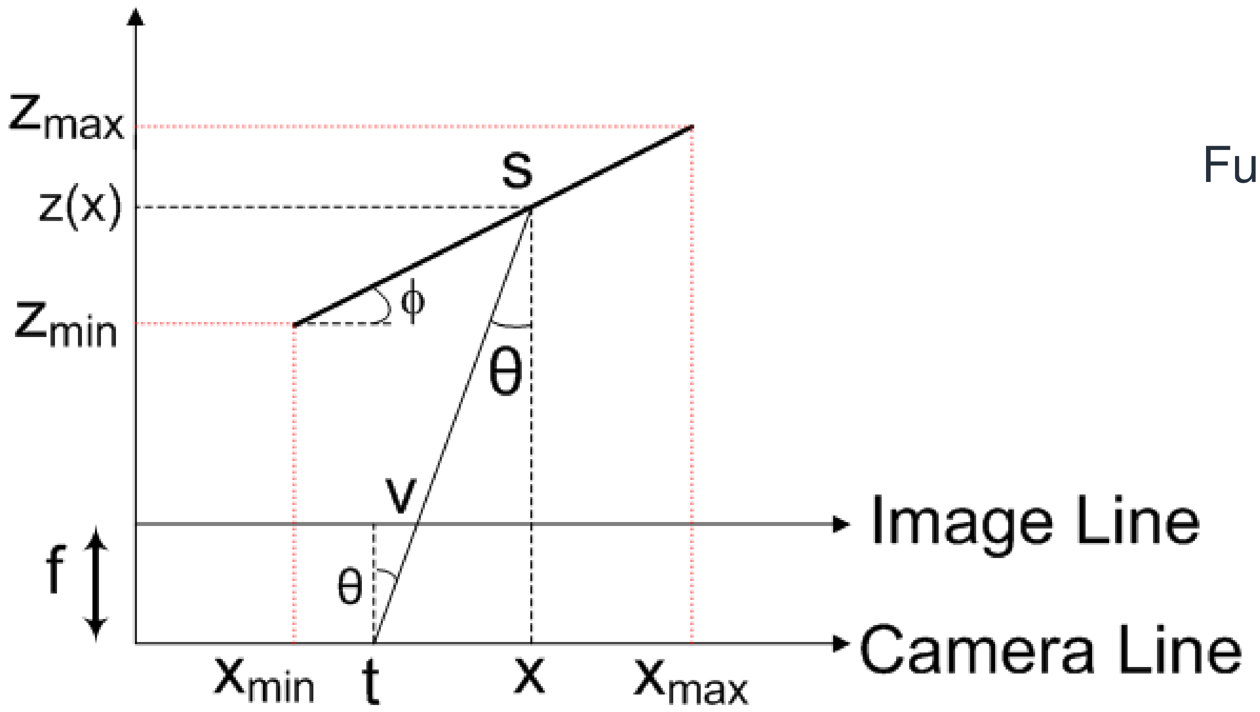


(b) Plenoptic Spectrum Sampled in t

Assumes $\Longrightarrow$ Infinite Scene Width and Infinite Field of View (FoV),

$\Longrightarrow$ Uniform Sampling in t

Slanted Plane Geometry



Functional Scene Model [3]:

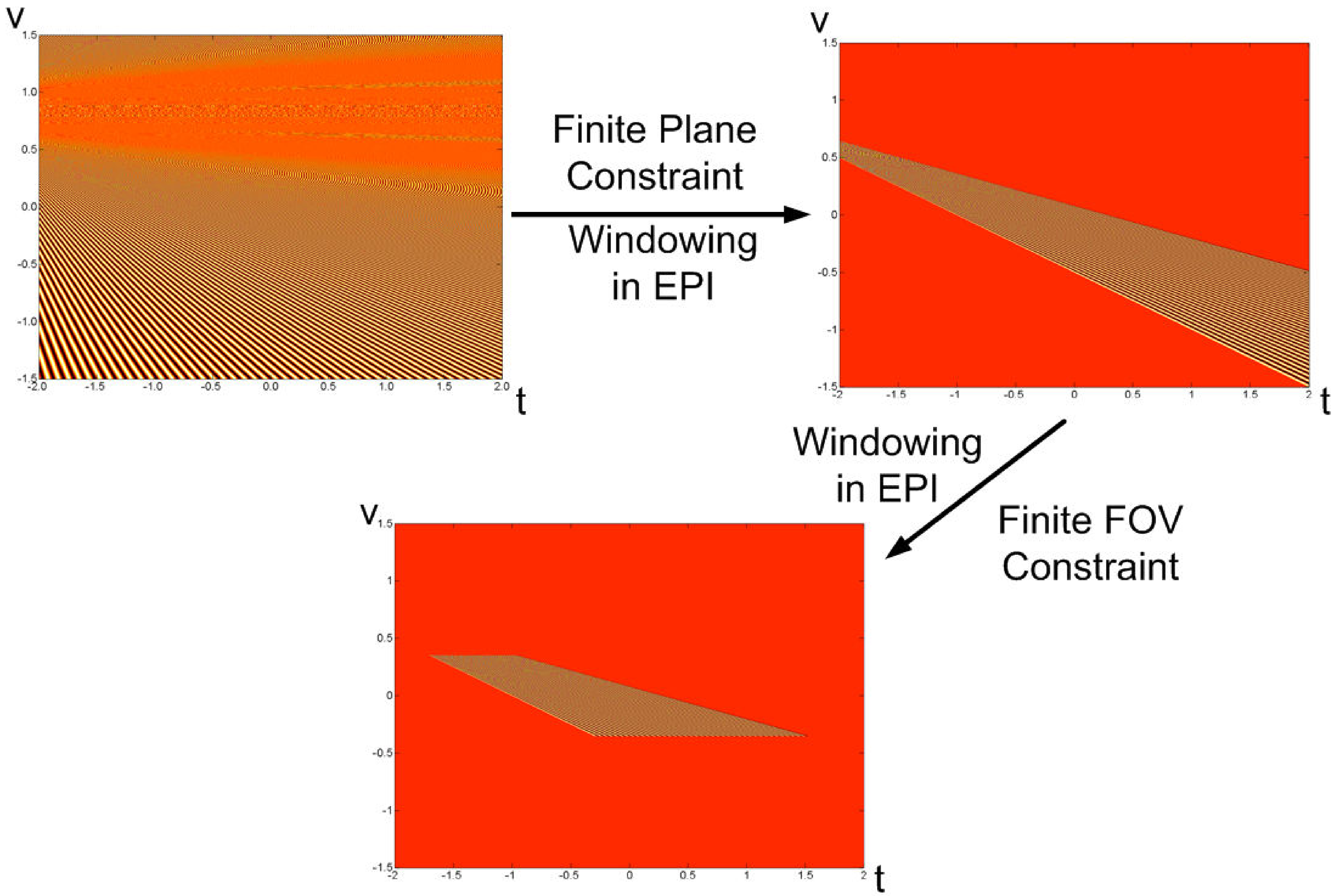
- s is the Curvilinear Coordinate
- x is the Projection of s onto t
- ϕ is the Slant of the Plane

Bandlimited Texture Signal Pasted to Scene Surface

Constraints:

- Finite Field of View (FoV) for the Cameras $\Longrightarrow v \in [-v_m, v_m]$
- Finite Plane Width $\Longrightarrow s \in [0, T]$
- Lambertian Scene

Effect of the Constraints on the EPI



Evaluating Plenoptic Spectrum for Slanted Plane

Fourier Transform of Plenoptic Function:

$$\int_{t=-\infty}^{t=\infty} \int_{v=-\infty}^{v=\infty} p(t,v)\, e^{-j(\omega_t t + \omega_v v)}\, dv dt$$

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Changing from t to x:

$$\Longrightarrow \int_{x=-\infty}^{x=\infty} \int_{v=-\infty}^{v=\infty} l(x) \left[1 - v\frac{z'(x)}{f}\right] e^{-j(\omega_v - z(x)\frac{\omega_t}{f})v} e^{-j\omega_t x}\, dv dx$$

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Finite FoV Constraint:

$$\Longrightarrow \int_{x=-\infty}^{x=\infty} l(x) \int_{v=-v_m}^{v=v_m} \left[1 - v\frac{z'(x)}{f}\right] e^{-j(\omega_v - z(x)\frac{\omega_t}{f})v} e^{-j\omega_t x}\, dv dx$$

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Finite Plane Width Constraint:

$$\Longrightarrow \int_{s=0}^{s=T} g(s)\cos(\phi) \int_{v=-v_m}^{v=v_m} \left[1 - v\frac{\tan(\phi)}{f}\right] e^{-j(\omega_v - s\frac{\sin(\phi)\,\omega_t}{f})v} e^{-j\omega_t \cos(\phi) s}\, dvds$$

Plenoptic Spectrum when $g(s) = e^{j\omega_s s}$

The Plenoptic Spectrum

$$|P| = \left| \frac{\omega_s f}{\sin(\phi)\omega_t^2} \left[\zeta(jb(c-1)) - \zeta(ja(c-1)) - \zeta(jb(c+1)) + \zeta(ja(c+1))\right] + \frac{2v_m}{\omega_t} \left[\text{sinc}(a)\, e^{-jca} - \text{sinc}(b)\, e^{-jcb}\right] \right|$$

Where $\zeta(jx)$, for $x \in \mathbb{R}$, is defined as

$$\zeta(jx) = \begin{cases} \text{E}_1(jx) + \ln(jx) + \gamma & \text{, if } x > 0 \\ \text{E}_1(-jx) - 2j\text{Si}(-x) + j\pi + \ln(jx) + \gamma & \text{, if } x < 0 \\ 0 & \text{, if } x = 0 \end{cases}$$

$\text{E}_1(w)$ is the Exponential Integral, $\text{Si}(w)$ is the Sine Integral and γ is Euler's Constant [1]

and $a = \omega_v v_m - \omega_t \frac{z_{max} v_m}{f}$, $b = \omega_v v_m - \omega_t \frac{z_{min} v_m}{f}$, $c = \frac{-f(\omega_t \cos(\phi) - \omega_s)}{\sin(\phi)\omega_t v_m}$

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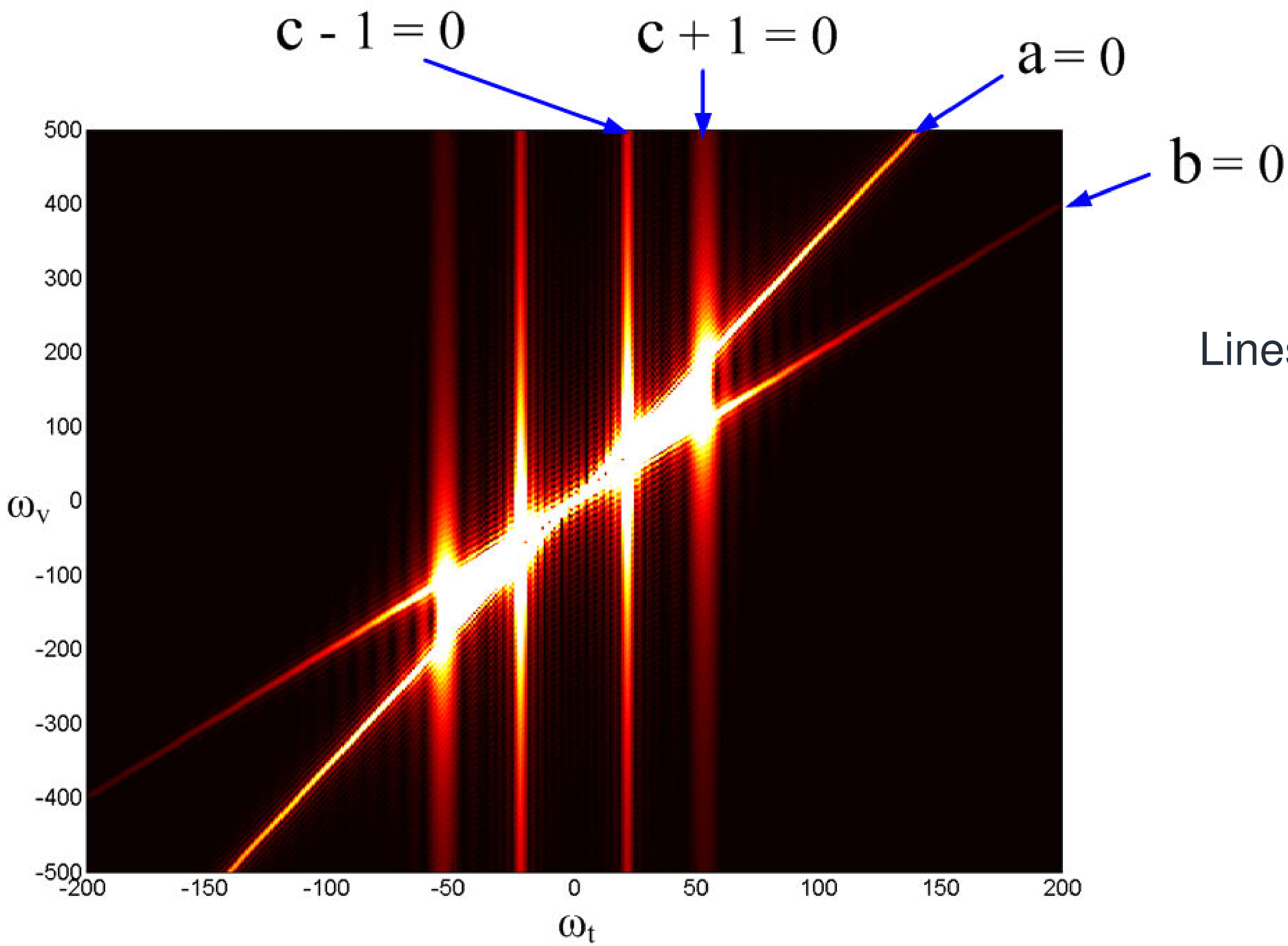
Slanted Plane Plenoptic Spectrum



Lines Relating to Depth:

$$a = 0 \Longrightarrow \omega_v = \frac{z_{max}\omega_t}{f}$$

$$b = 0 \Longrightarrow \omega_v = \frac{z_{min}\omega_t}{f}$$

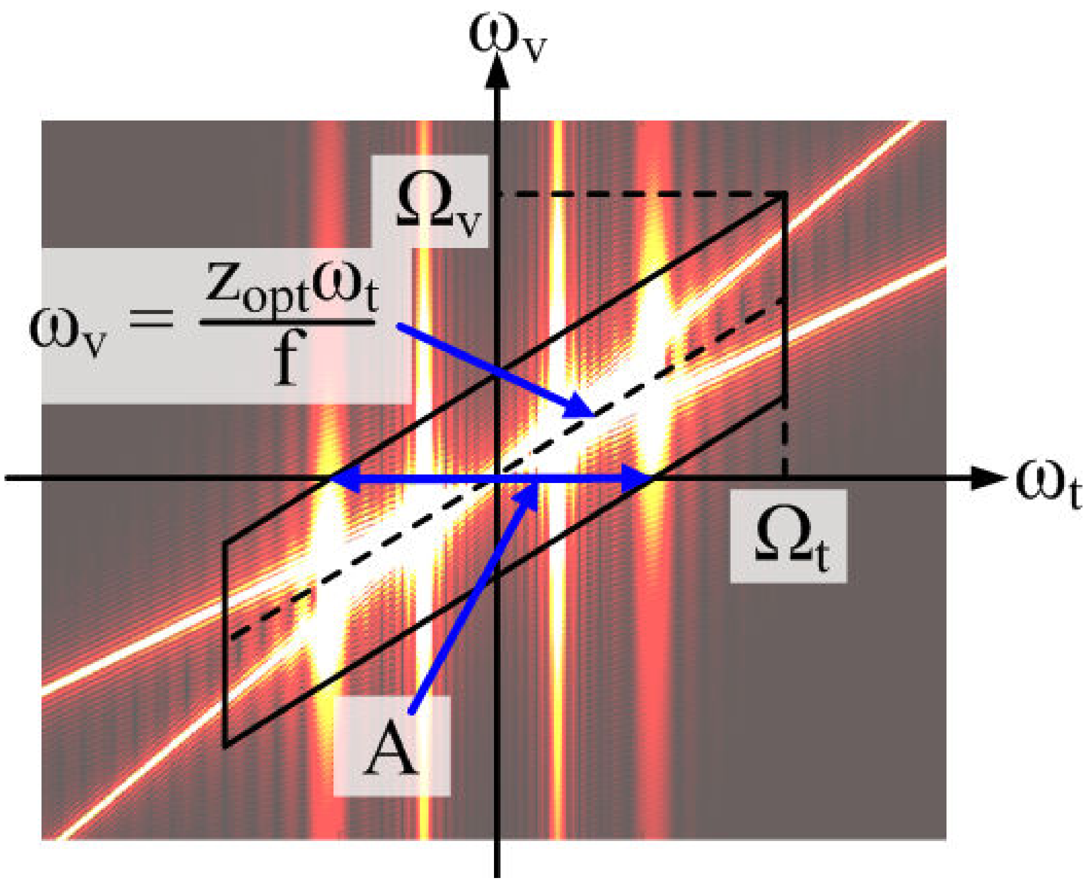
Lines Relating to Finite FoV:

$(c-1) = 0 \Longrightarrow$ Minimum Modulated Frequency Projected onto the Image

$(c+1) = 0 \Longrightarrow$ Maximum Modulated Frequency Projected onto the Image

Essential Bandwidth for a Slanted Plane

Parametric model of the essential bandwidth, consisting of 4 parameters:



$$\Omega_t = \frac{\omega_s f}{f\cos(\phi) - v_m|\sin(\phi)|} + \frac{2\pi}{T},$$

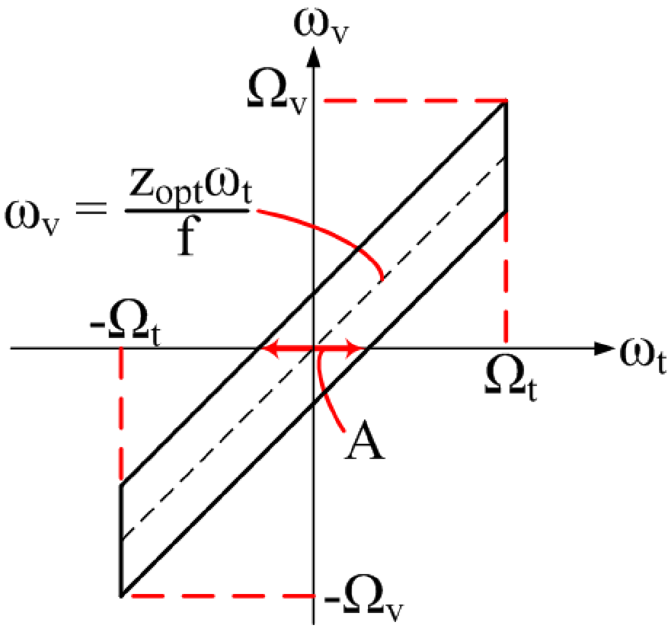
$$\Omega_v = \Omega_t \frac{z_{max}}{f} + \frac{\pi}{v_m},$$

$$z_{opt} = \frac{z_{max} + z_{min}}{2},$$

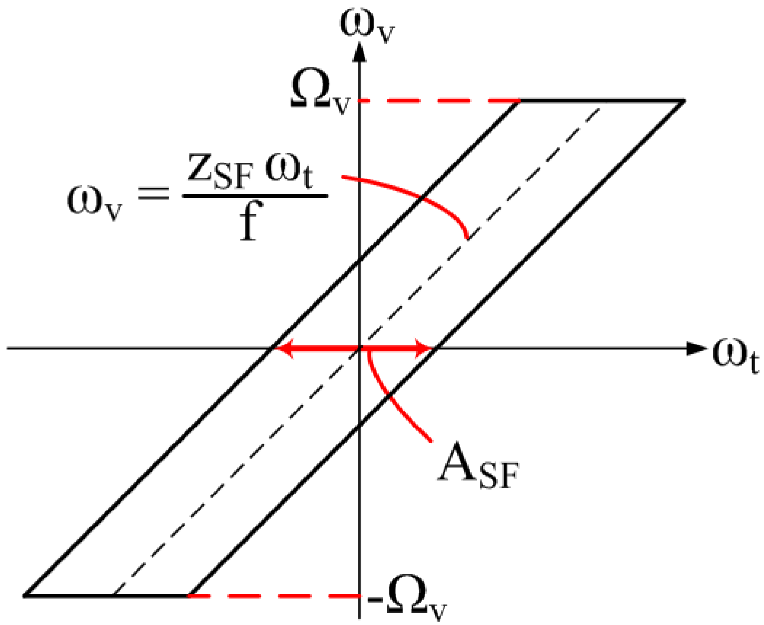
$$A = \frac{T|\sin(\phi)|\Omega_t}{z_{opt}} + \frac{2\pi f}{z_{opt} v_m}$$

Plenoptic Sampling of a Slanted Plane

Comparison between the essential bandwidth and the standard filter:



(a) Essential Bandwidth



(b) Standard Filter [2]

The differences:

$$z_{opt} = \frac{z_{max} + z_{min}}{2} \qquad z_{SF} = \frac{2}{z_{max}^{-1} + z_{min}^{-1}}$$

$$A = \frac{T\,|\sin(\phi)|\,\Omega_t}{z_{opt}} + \frac{2\pi f}{z_{opt} v_m} \qquad A_{SF} = \Omega_v f \left(\frac{1}{z_{min}} - \frac{1}{z_{max}} \right)$$

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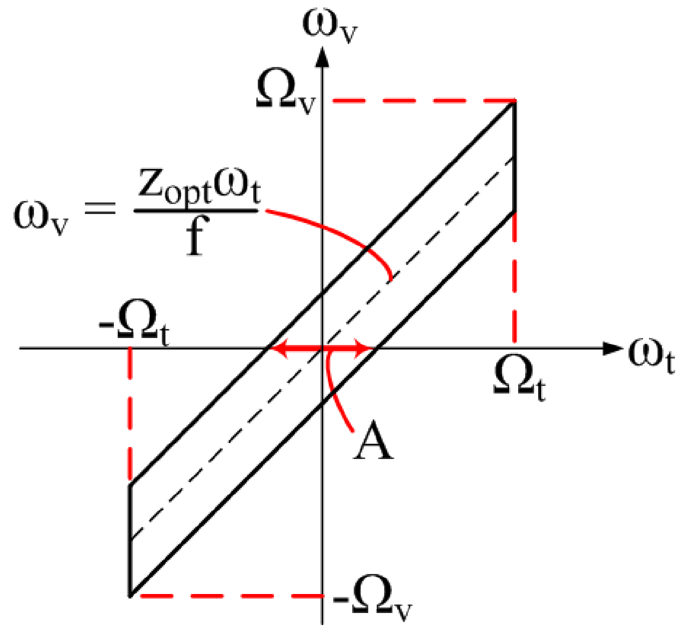
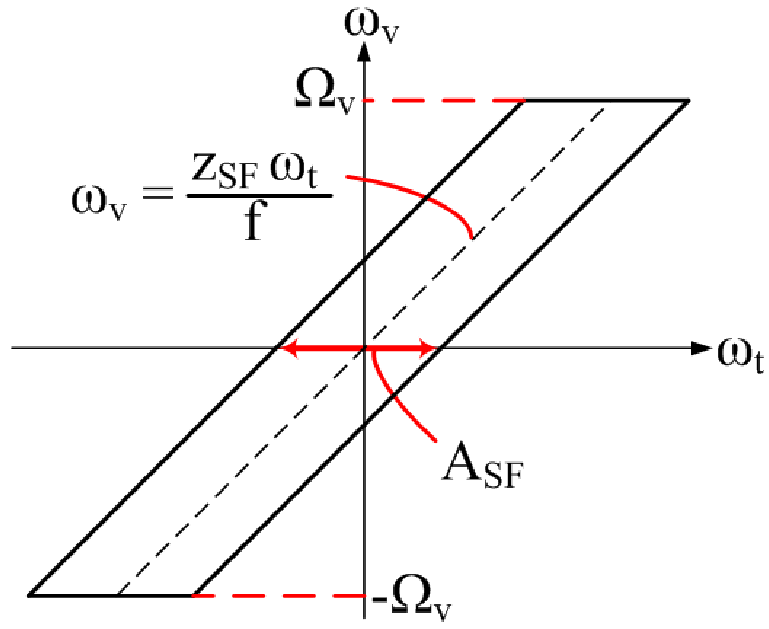


(a) Essential Bandwidth



(b) Standard Filter [2]

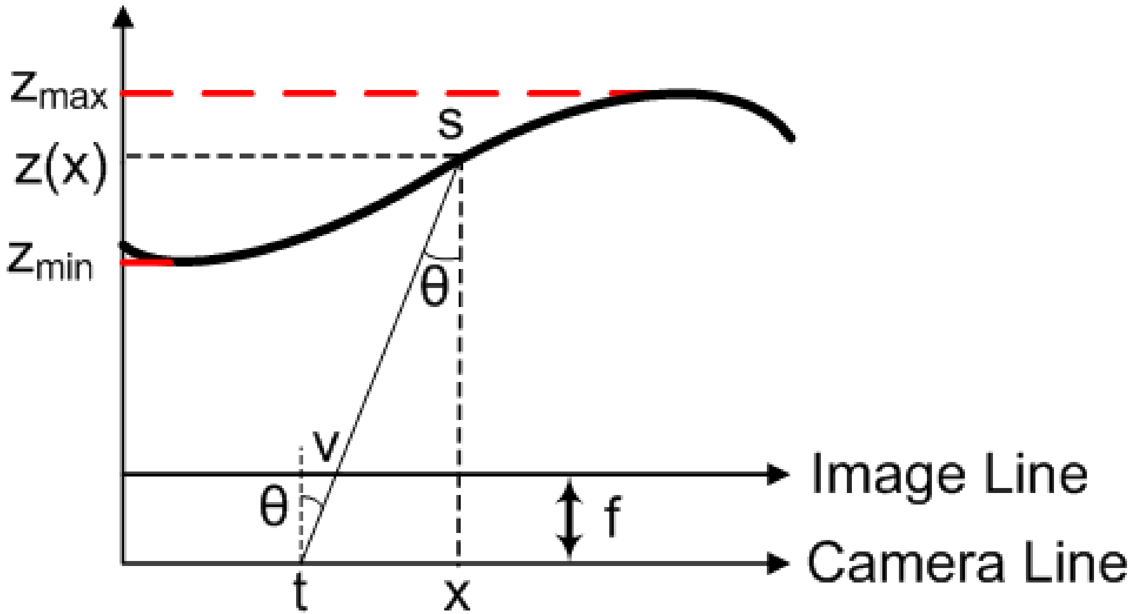
At Critical Sampling:

$$\Delta t_c = \frac{2\pi}{A}, \quad = \frac{2\pi\, z_{opt}\, v_m}{v_m \Omega_t T\,|\sin(\phi)| + 2\pi f}$$

$$\Delta t_c = \frac{2\pi}{A_{SF}}, \quad = \frac{2\pi\, z_{max}\, z_{min}}{f\Omega_v\,(z_{max} - z_{min})}$$

Sampling More Realistic Scenes

Smoothly varying scene surface with bandlimited texture:



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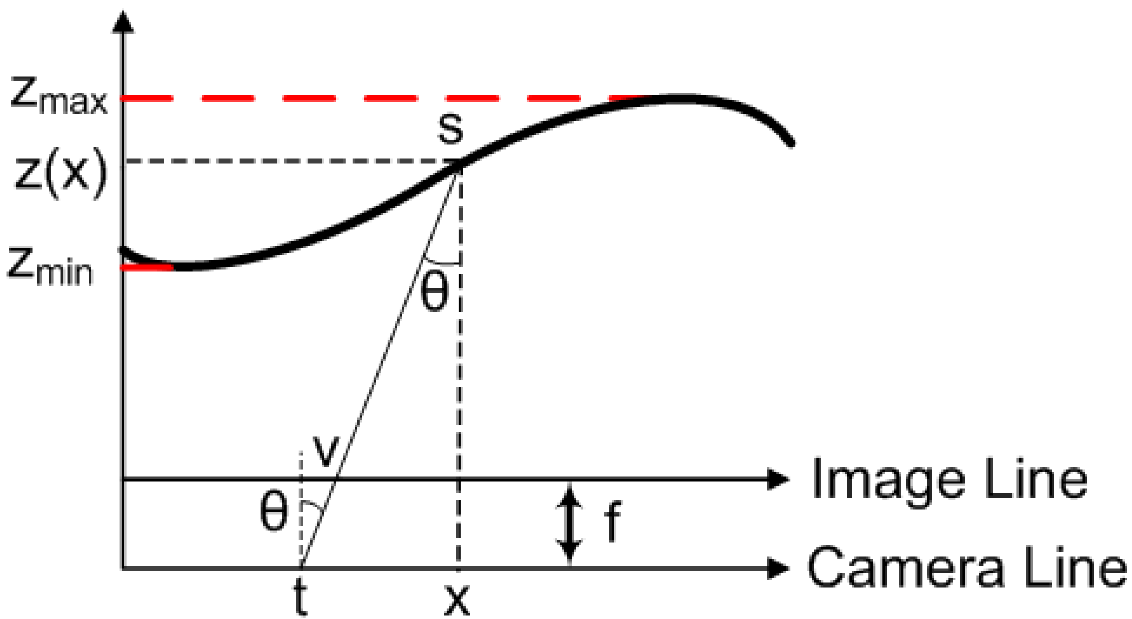

Our approach:

- Approximate the scene surface using a set of L slanted planes.
- Use the previous theory to determine non-uniformly sampling and reconstructing the scene.

Important Questions:

↬ How best to approximate the scene and with how many planes?

↬ How should we allocate the samples?

Evaluating the Surface Approximation

Define the distortion function, D, as the measure of the distortion in the plenoptic domain due to approximating the surface.

Consists of two Parts:

$$D(N_i) = \underbrace{\gamma_i}_{\text{Geometric Error}} + \underbrace{\alpha_i(N_i)}_{\text{Aliasing Error}}$$

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The error between the actual plenoptic function, $p(t, v)$ and the plenoptic function generated by the approximate surface, $\hat{p}(t, v)$.

However

Need to consider a limited number of samples, N_T.

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$$D(N_i) = \underbrace{\gamma_i}_{\text{Geometric Error}} + \underbrace{\alpha_i(N_i)}_{\boxed{\text{Aliasing Error}}}$$

$\alpha_i(N_i)$ is the error caused by undersampling the ith plane with N_i samples.

Therefore:

Small number of samples $\Longrightarrow$ Aliasing error dictates the surface approximation.

Large number of samples $\Longrightarrow$ Geometric error dictates the surface approximation.

Sample Allocation per Plane

The sample allocation problem is defined in terms minimising the distortion function given N_T samples:

The problem:

$$\min \left\{ \sum_{i=1}^{L} D_i(N_i) \right\} \text{ s.t. } N_T = \sum_{i=1}^{L} N_i,$$

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The sample allocation problem is defined in terms minimising the distortion function given N_T samples:

The problem:

$$\min \left\{ \sum_{i=1}^{L} D_i(N_i) \right\} \text{ s.t. } N_T = \sum_{i=1}^{L} N_i,$$

Solved using a Lagrange multiple λ, thus the cost function:

$$\sum_{i=1}^{L} \left(D_i(N_i) + \lambda N_i \right)$$

where

$$\lambda = -\frac{d}{dN_1}\left\{D_1(N_1)\right\} = -\frac{d}{dN_2}\left\{D_2(N_2)\right\} = \ldots = -\frac{d}{dN_L}\left\{D_L(N_L)\right\}$$

Sample Allocation per Plane

Approximating $\alpha_i(N_i)$ as twice the amount of energy outside the reconstruction filter, the cost function becomes:

$$\sum_{i=1}^{L} \left(\gamma_i + \frac{16 K_i \Delta v}{A_i \pi} + \frac{4 A_i K_i \Delta v}{\pi} + \frac{8 \pi K_i}{\Delta v} \tan^{-1} \left(\frac{r_i W_i}{\pi N_i} \right) + \lambda N_i \right) .$$

where

- A_i is the width of the essential bandwidth of the ith plane (in ω_t).
- W_i is the width in t that the ith plane is visible.
- K_i and r_i are coefficients of the approximation for the i plane.

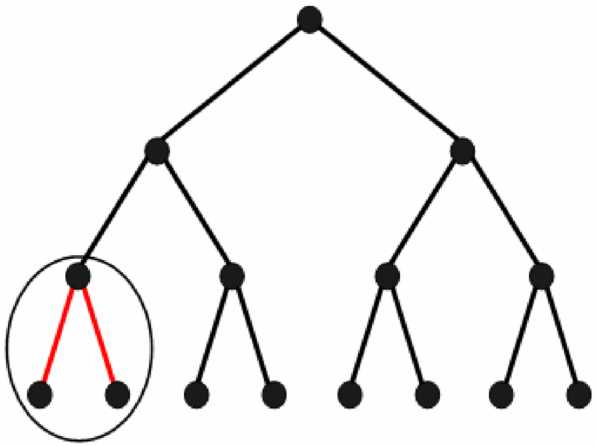
As a result, λ is the solution to

$$N_T - 1 = \sum_{i=1}^{L} \sqrt{\frac{8 K_i W_i r_i}{\Delta v \lambda} - \left(\frac{r_i W_i}{\pi} \right)^2}$$

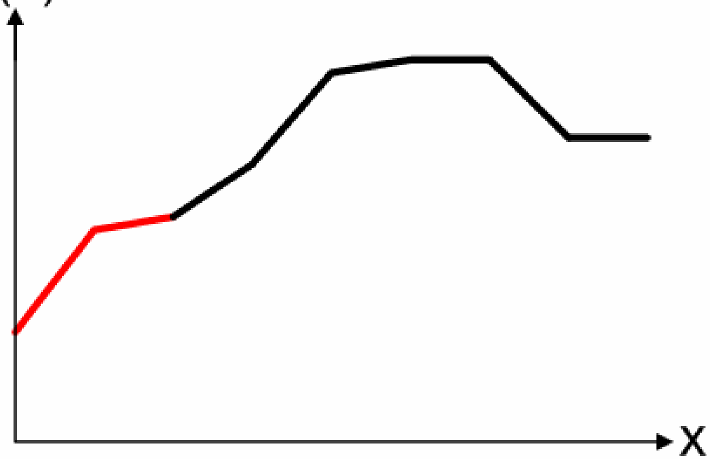
Optimising the Surface Approximation

Determining the optimum surface approximation:

- Binary-tree approach $\Longrightarrow$ Start with an initial ‘fine-grain’ approximation.
- Initially split the surface into 2^k equal pieces resulting in L planes.
- Determine the initial λ and sample allocation between the L planes by solving the minimisation problem.
- Merge the leaves of the tree to reduce the overall distortion.



(a) Quad-tree



(b) Surface Approximation

Optimising the Surface Approximation

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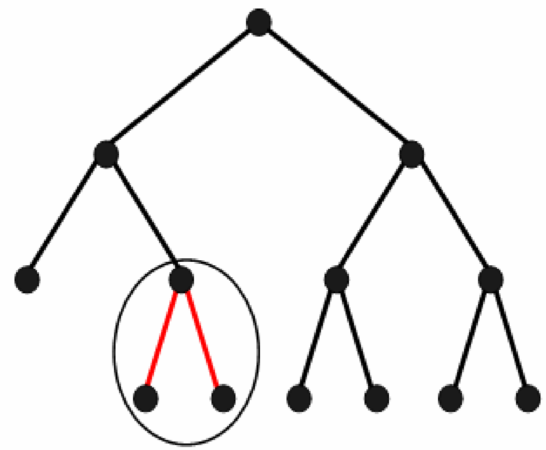
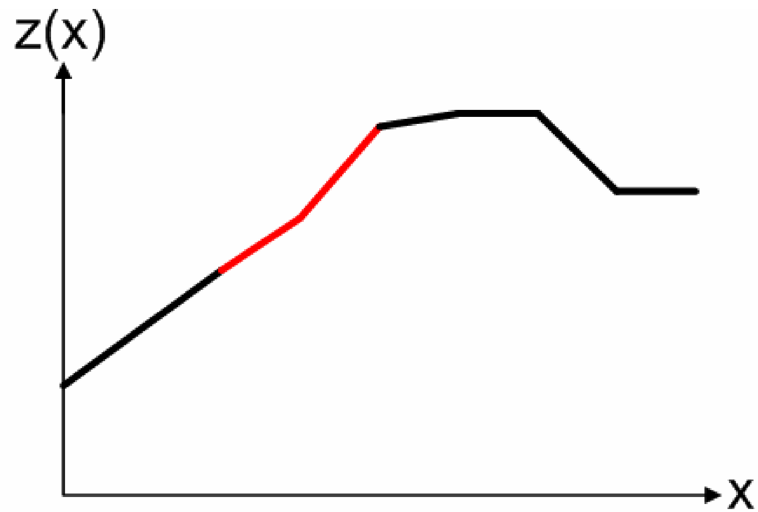


(a) Quad-tree



(b) Surface Approximation

Optimising the Surface Approximation

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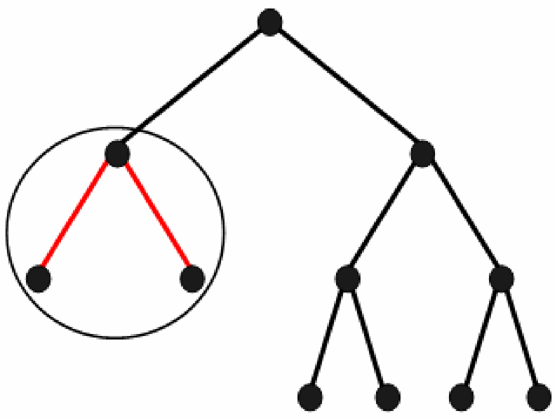
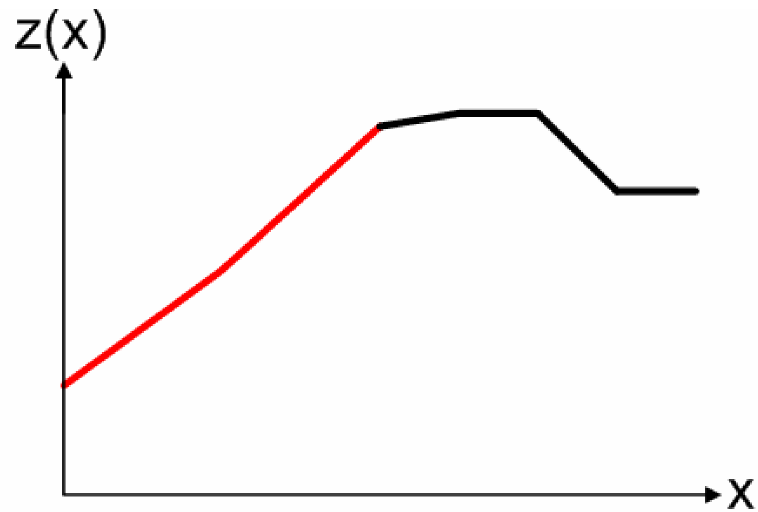


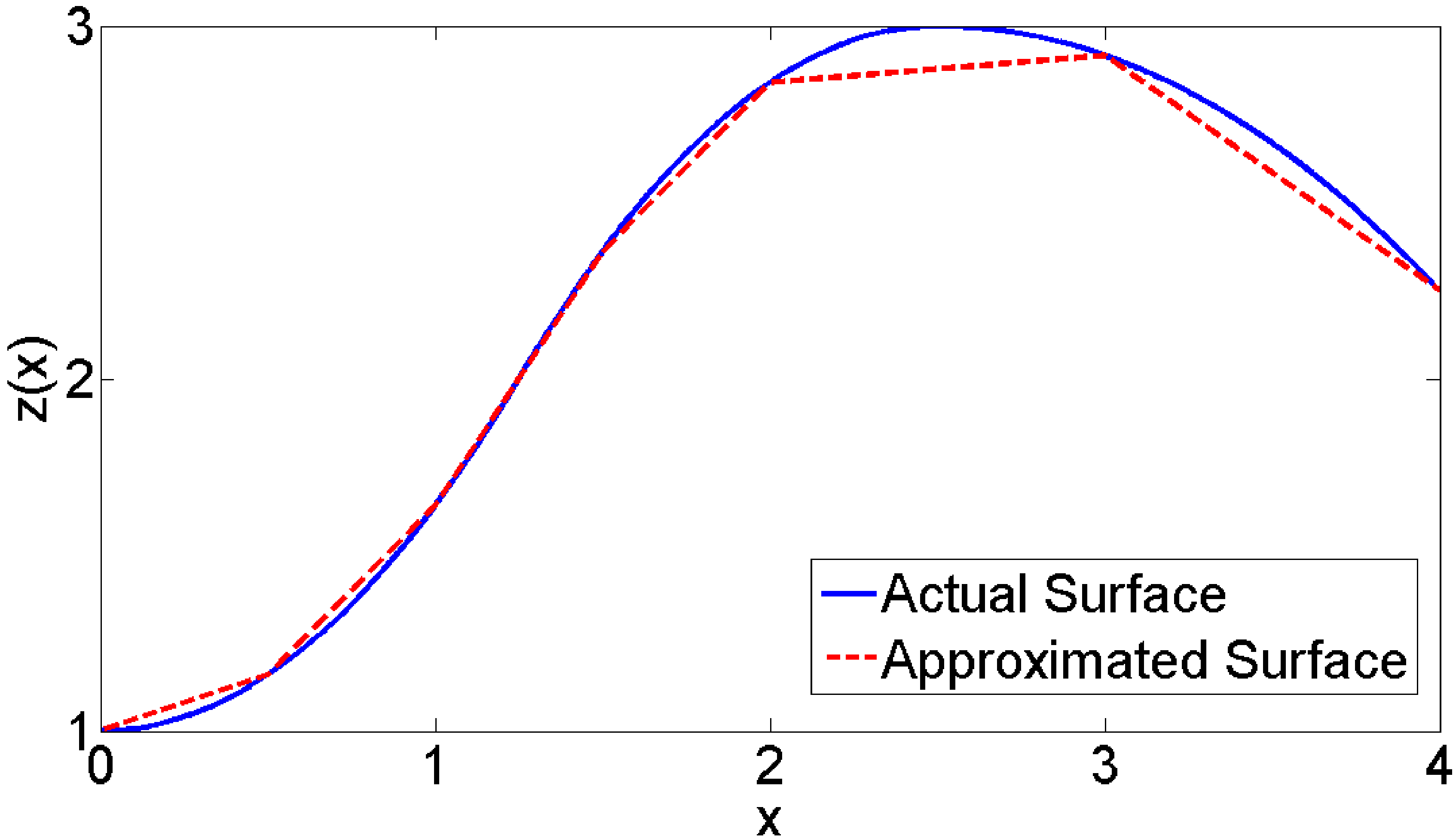
(a) Quad-tree



(b) Surface Approximation

Surface Approximation Simulations

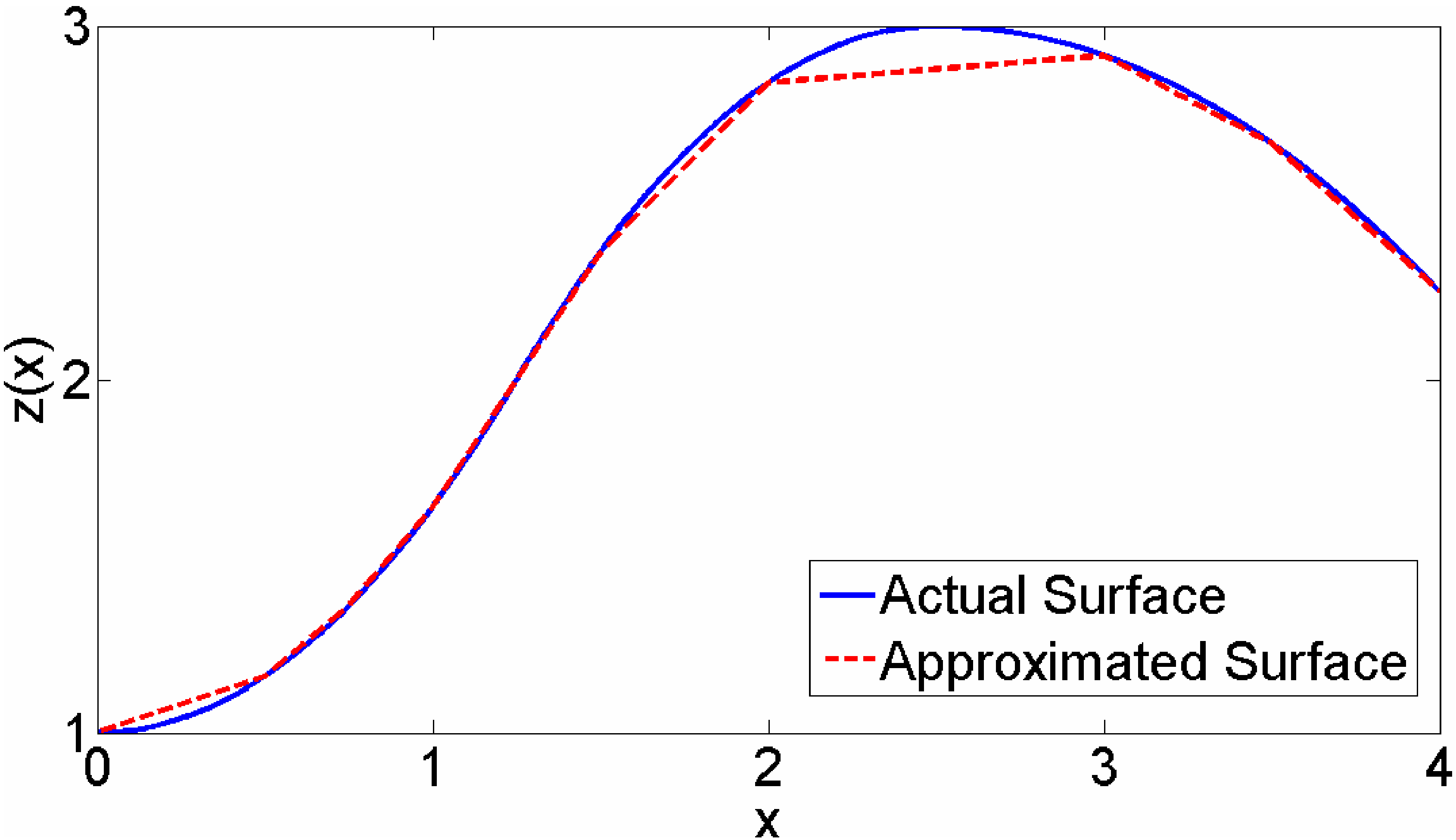
Approximation of the Piecewise Quadratic Surface using $N_T = 20$:



Initial Number of Planes = 16, Final Number of Planes = 6

Surface Approximation Simulations

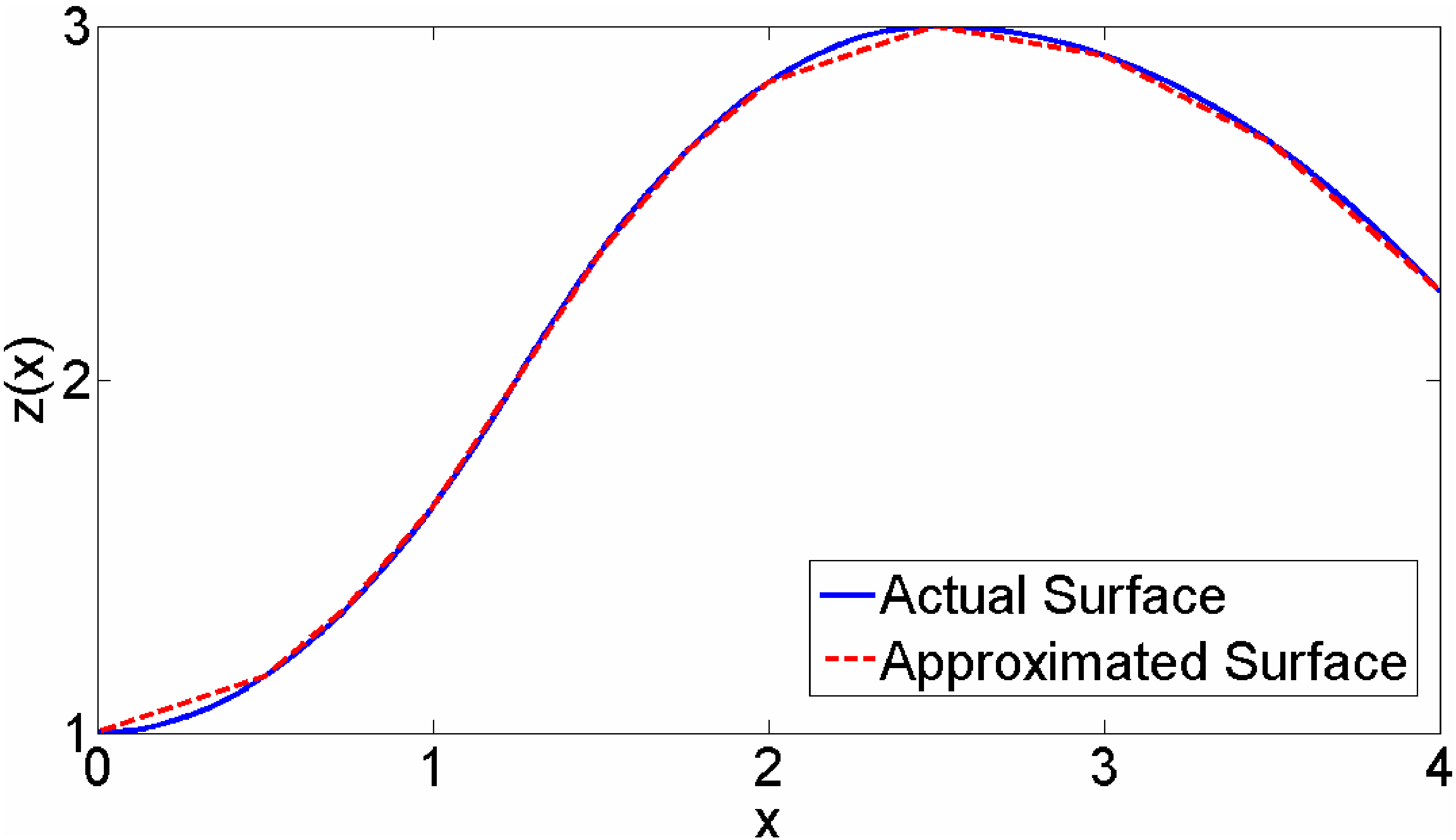
Approximation of the Piecewise Quadratic Surface using $N_T = 150$:



Initial Number of Planes = 16, Final Number of Planes = 8

Surface Approximation Simulations

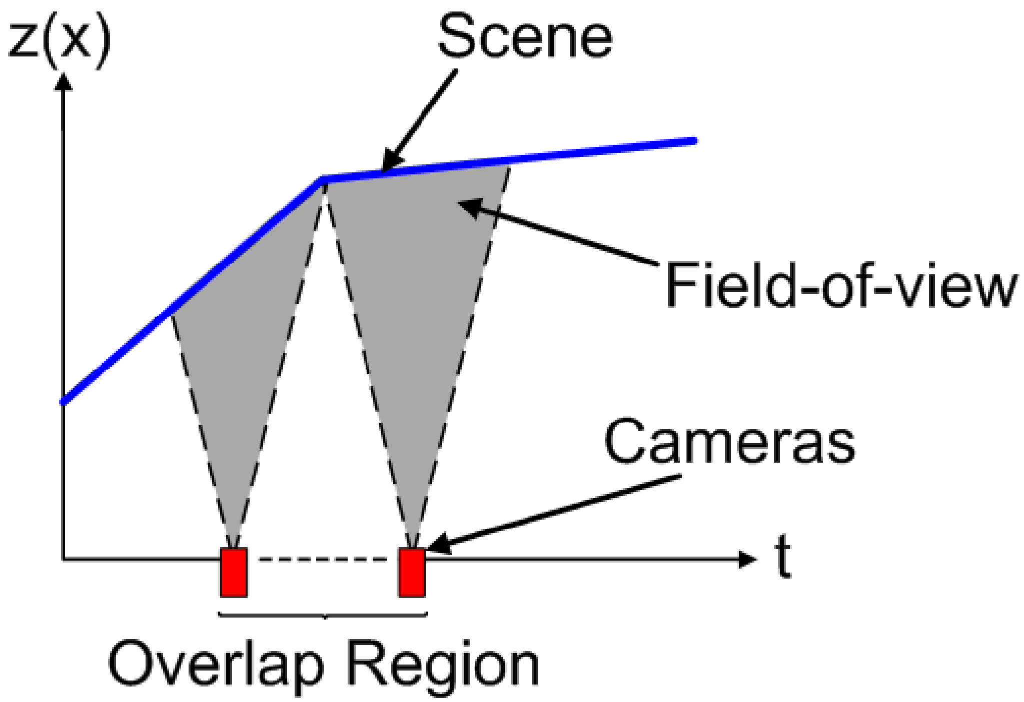
Approximation of the Piecewise Quadratic Surface using $N_T = 300$:



Initial Number of Planes = 16, Final Number of Planes = 10

Sample Allocation to Sample Positions

Remember that multiple planes are visible in a single image

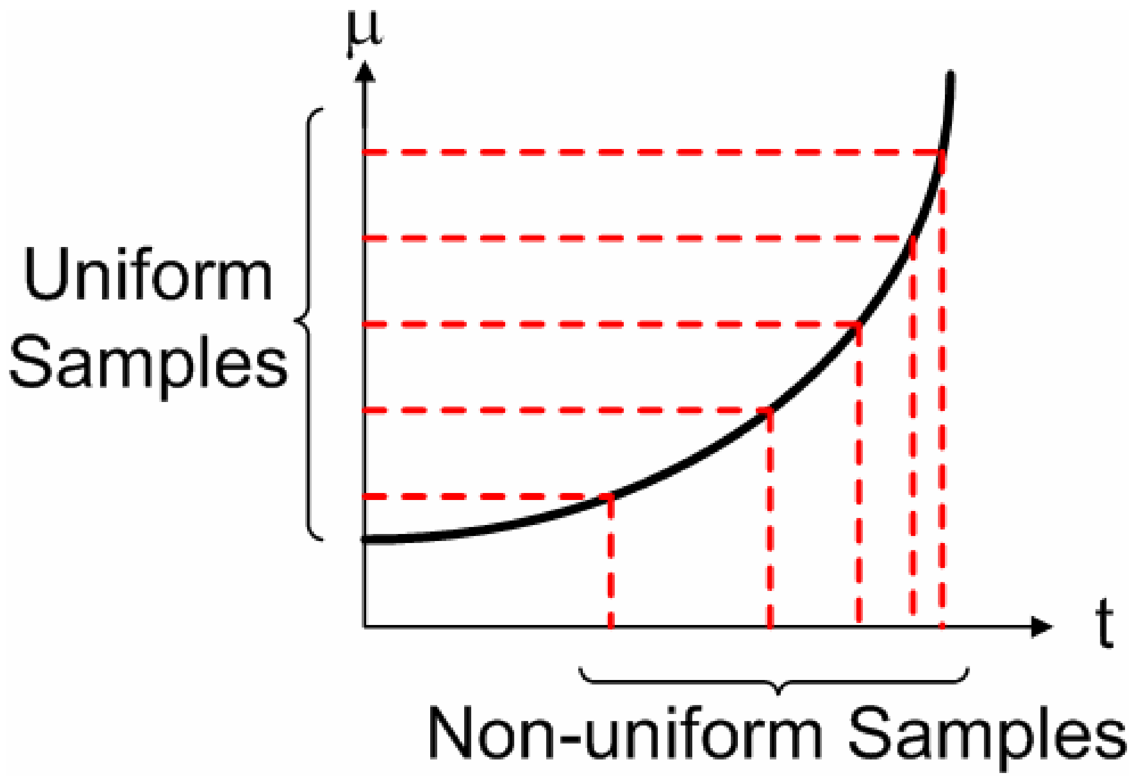


↬ Choose the highest sample rate in overlap region.

End result $\Longrightarrow$ A piecewise constant sample rate profile in t.

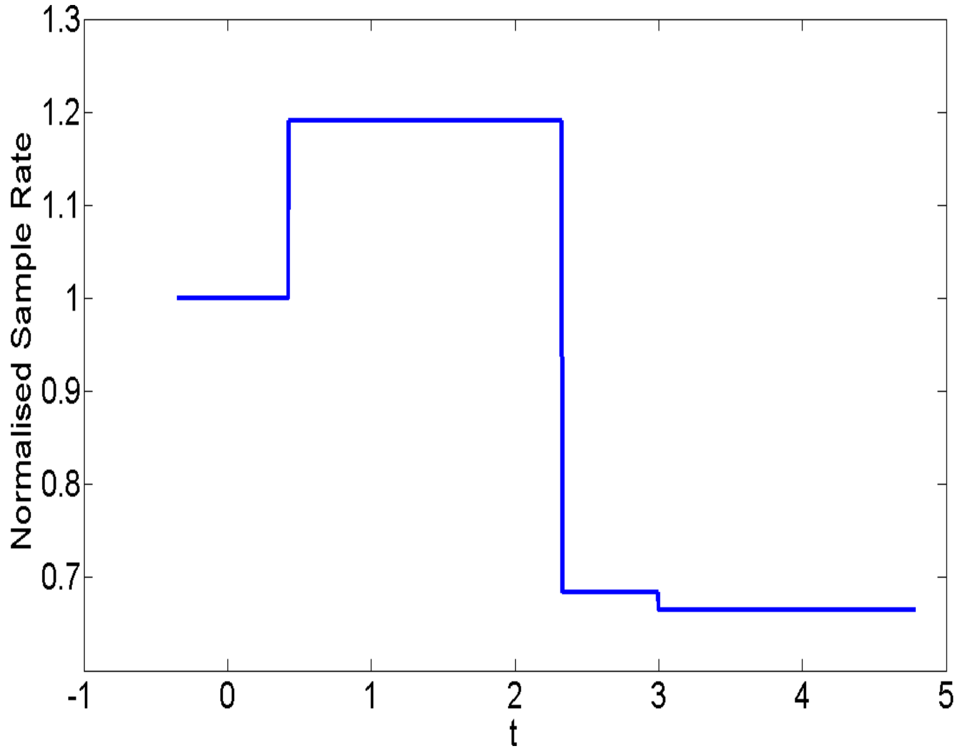
Sample Allocation to Sample Positions

Integrate sample rate profile to give a warping function $\Longrightarrow$ allowing coherent non-uniform samples

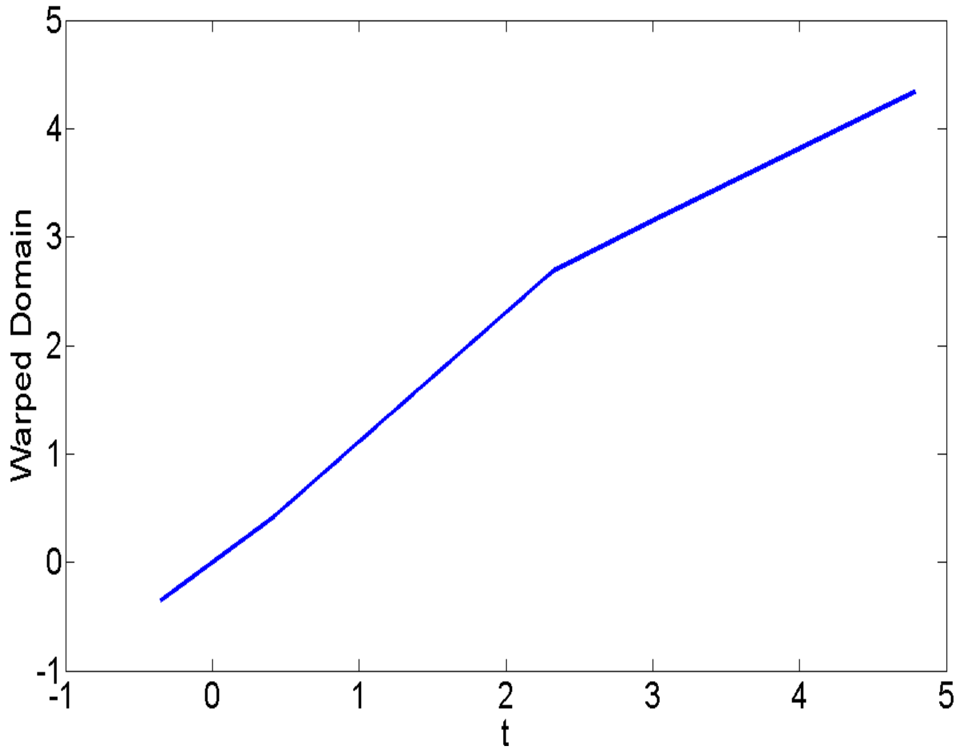


Sample Allocation to Sample Positions Example

An example when $N_T = 150$,



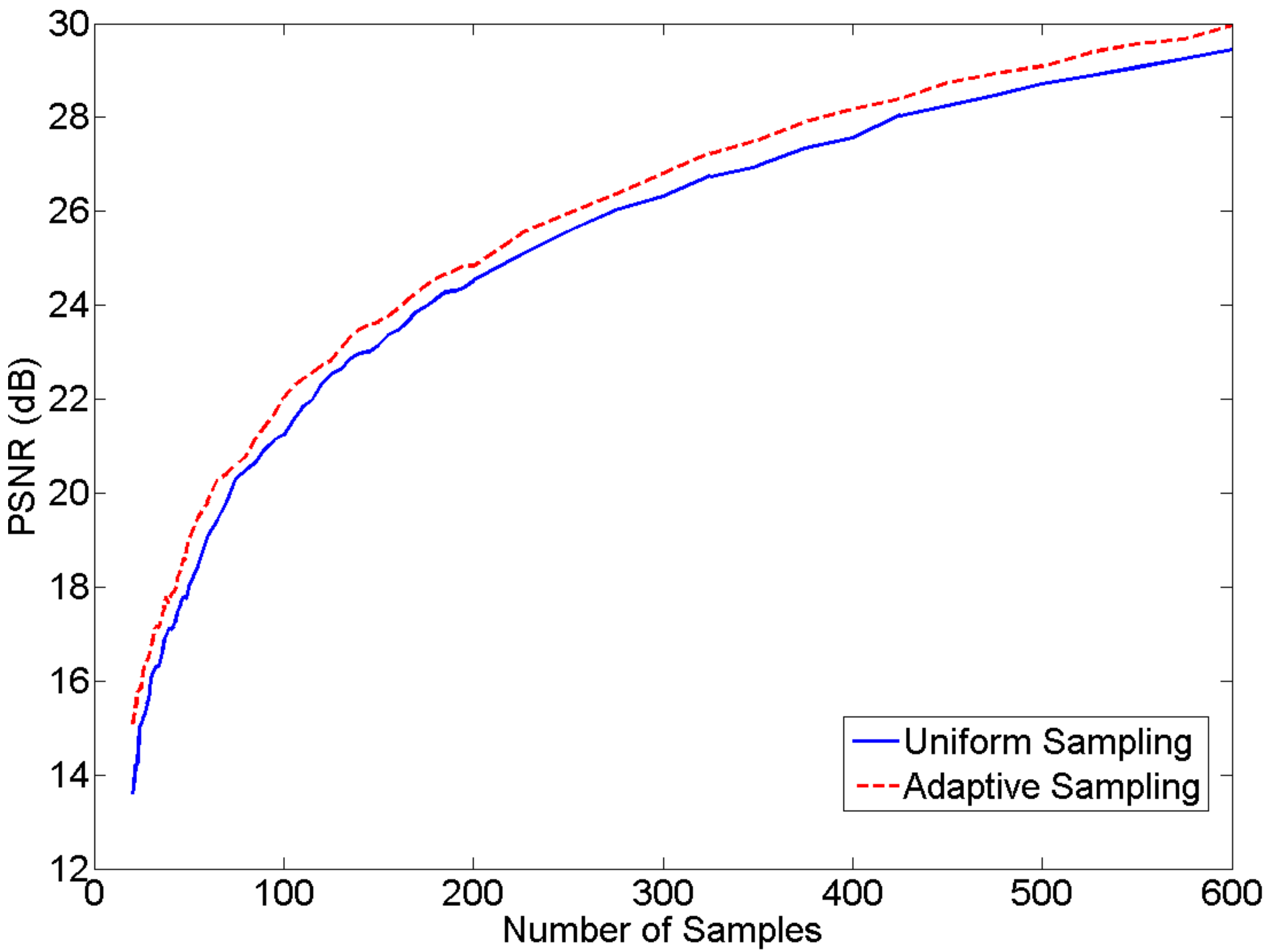
(a) Sample Rate Profile



(b) Warping Function

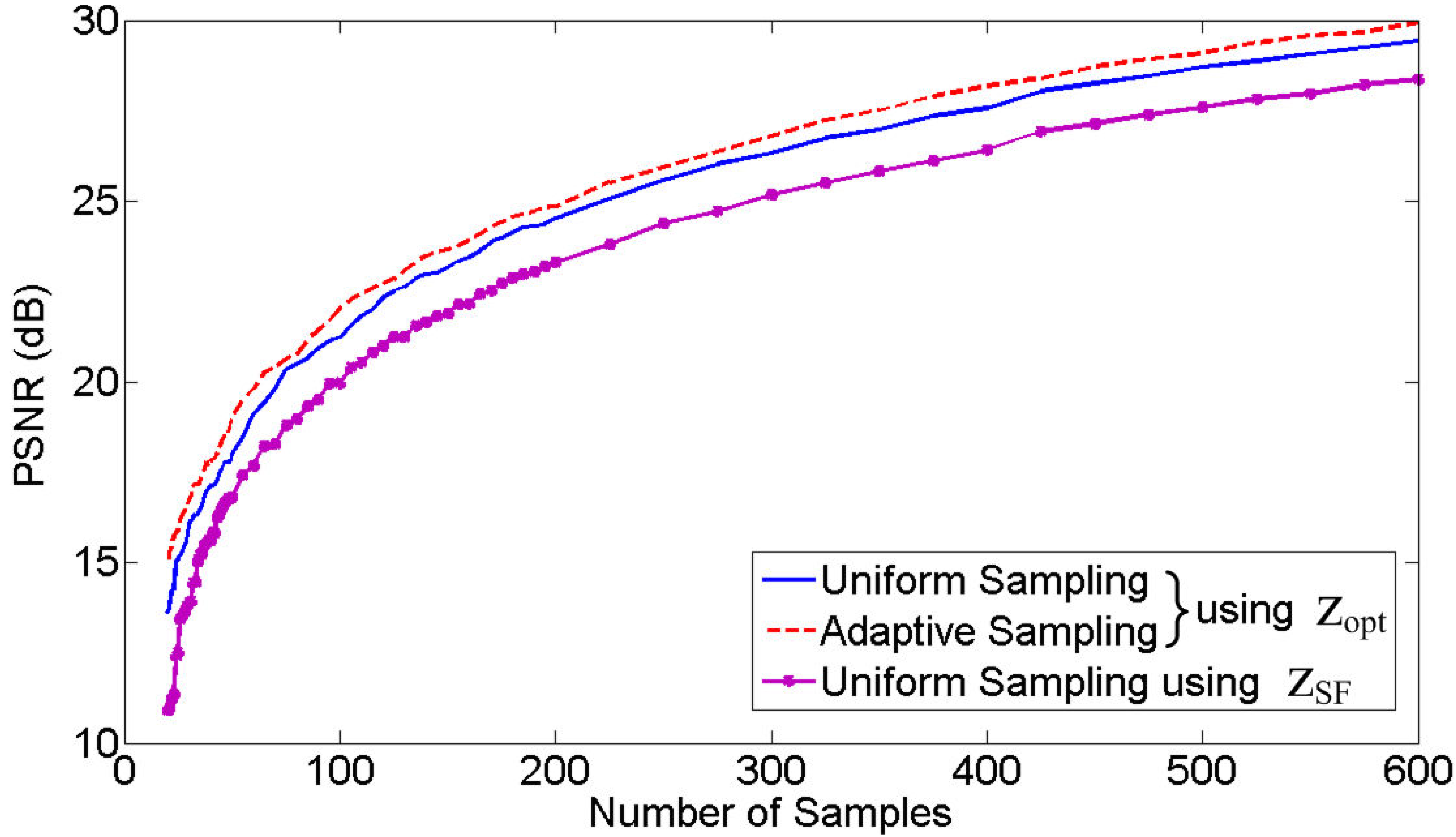
Simulations Results

Comparison between uniform and adaptive reconstruction for the piecewise quadratic surface.



Comparison with Standard Filter

Comparison between the reconstruction of the piecewise quadratic surface when using the standard filter and the new filter.

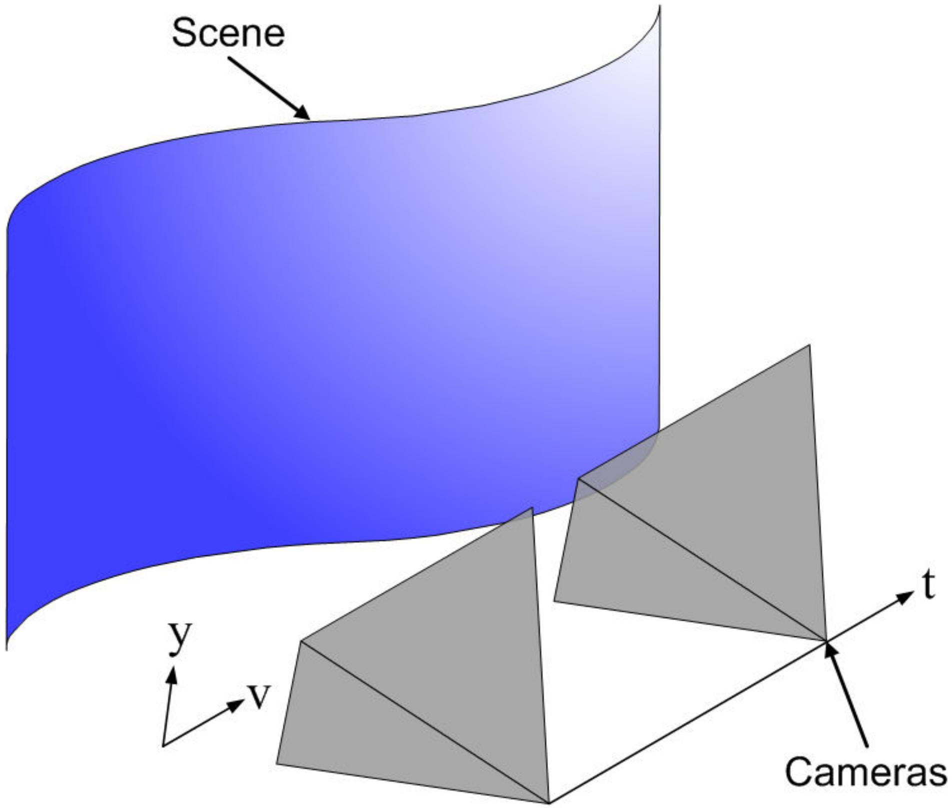


Conclusions

- We present a method for adaptively sampling a scene with a smoothly varying surface by approximate the surface with a set of slanted planes.
- For a given approximation the samples are adaptive allocated to minimise the distortion in the plenoptic function, using a Lagrange multiplier.
- The surface approximation is optimised in a binary-tree framework, going from fine to coarse, depending on the number of samples.
- The plenoptic sampling theory for a single slanted plane is used to determine a piecewise constant sample rate $\Longrightarrow$ Non-uniform samples.
- Non-uniform sampling scheme outperforms normal uniform sampling.

Future Work

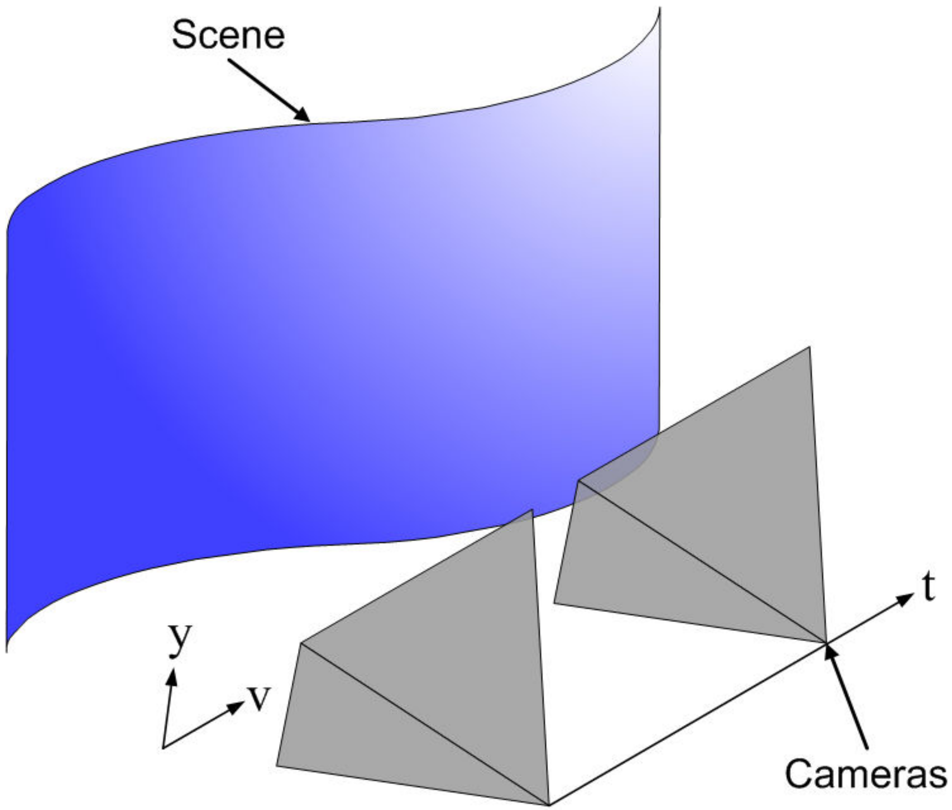
Extending the adaptive algorithm to higher dimensions:



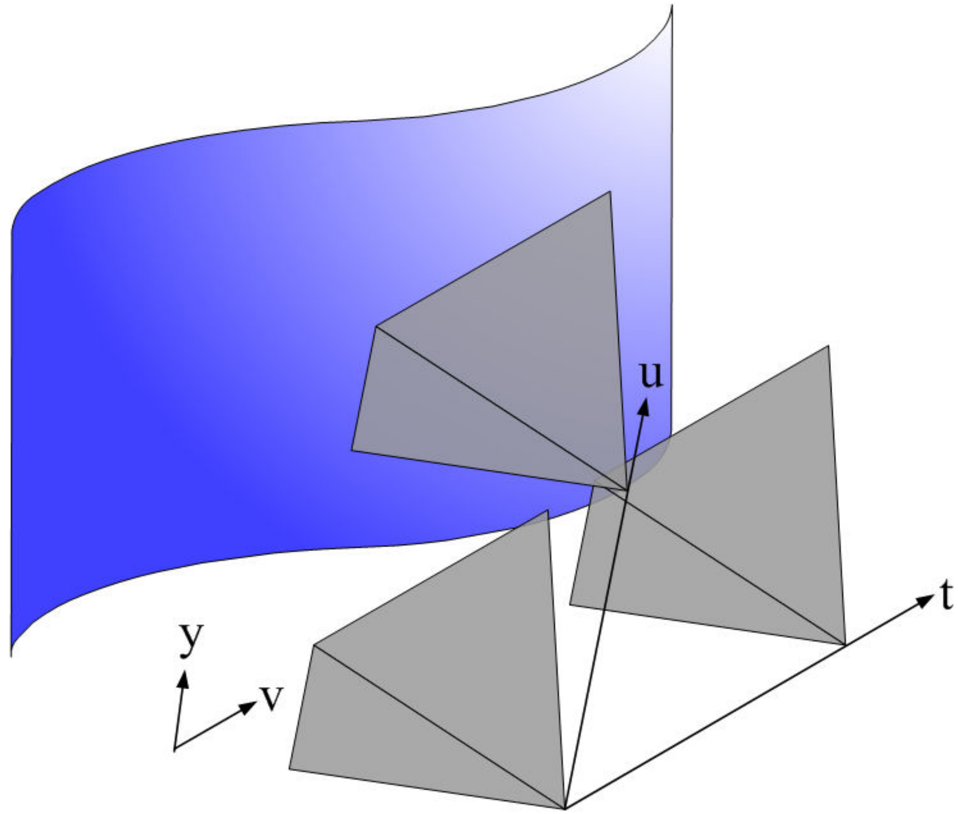
(a) 3D Lightfield

Future Work

Extending the adaptive algorithm to higher dimensions:



(a) 3D Lightfield



(b) 4D Lightfield

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3. M.N. Do, D Marchand-Maillet, and M. Vetterli. On the bandwidth of the plenoptic function. IEEE Transactions on Image Processing, 2009. Preprint.
4. C. Gilliam, P.L. Dragotti, and M. Brookes. A closed-form expression for the bandwidth of the plenoptic function under finite field of view constraints. IEEE ICIP 2010, pages 3965-3968.
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