Spatio-Temporal Depth Data Reconstruction from a Subset of Samples

Lee-Kang Liu and Truong Nguyen

Depth Data Reconstruction

Depth Data Reconstruction:

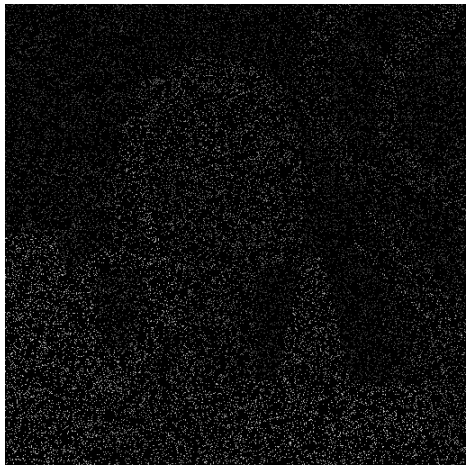
- Problem formulation

$$\min_{\boldsymbol{x}} \frac{1}{2}\|\boldsymbol{b}-\boldsymbol{S}\boldsymbol{x}\|^2 + \lambda\|\boldsymbol{W}\boldsymbol{B}\boldsymbol{x}\|_1 + \beta\|\boldsymbol{x}\|_{\mathrm{TV}}$$

$\boldsymbol{B}$: Orthonormal Matrix

$\boldsymbol{W}$: Weight Matrix (Diagonal Matrix with 1/0)

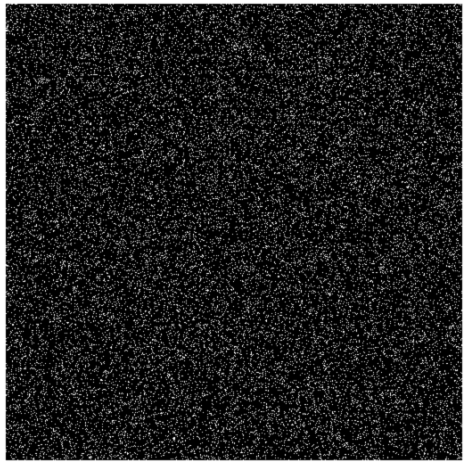
$\boldsymbol{b}$



Subset of Disparity Samples
5%, 10%, … etc.

$\boldsymbol{b}=\boldsymbol{S}\boldsymbol{x}$

$\boldsymbol{S}$



Uniformly Random
Sampling Map

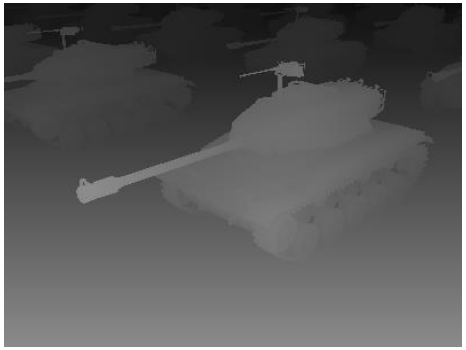
$\boldsymbol{x}$

Dense Disparity Map

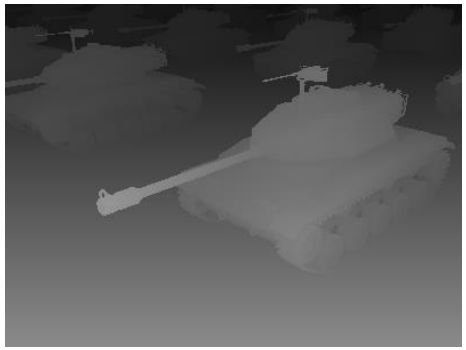
From Spatial to Spatio-Temporal

Formulation of depth video sequences:

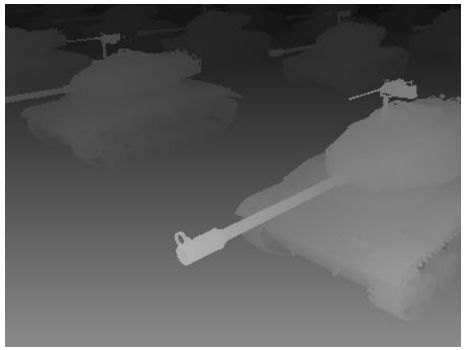
- Sequences of depth images



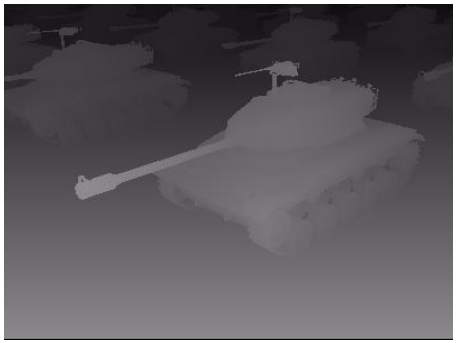
Frame no.1



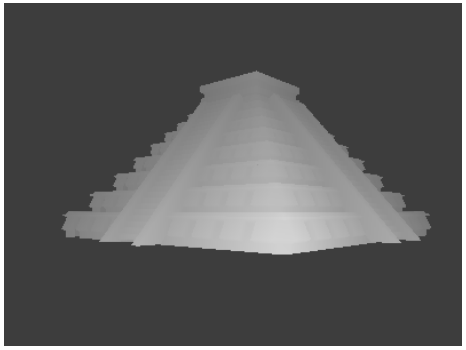
Frame no.11



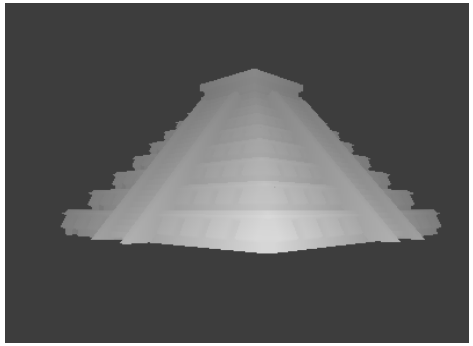
Frame no.21



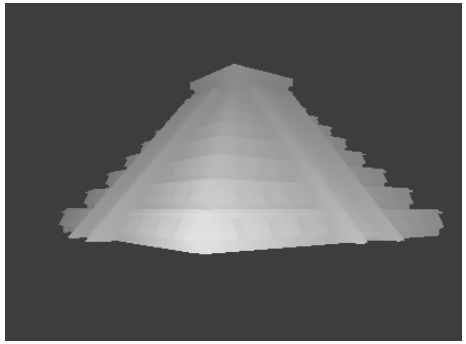
Tanks sequence



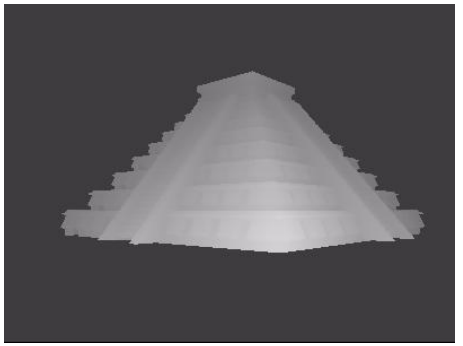
Frame no.1



Frame no.11



Frame no.21

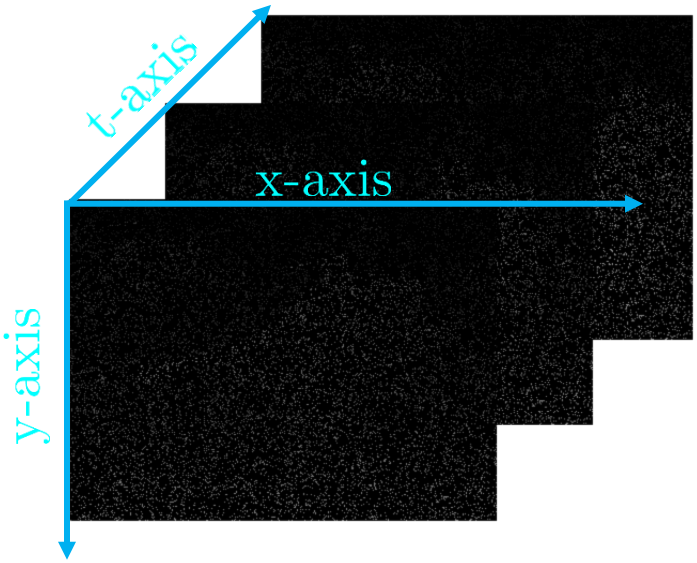


Temples sequence

Spatio-Temporal Depth Data

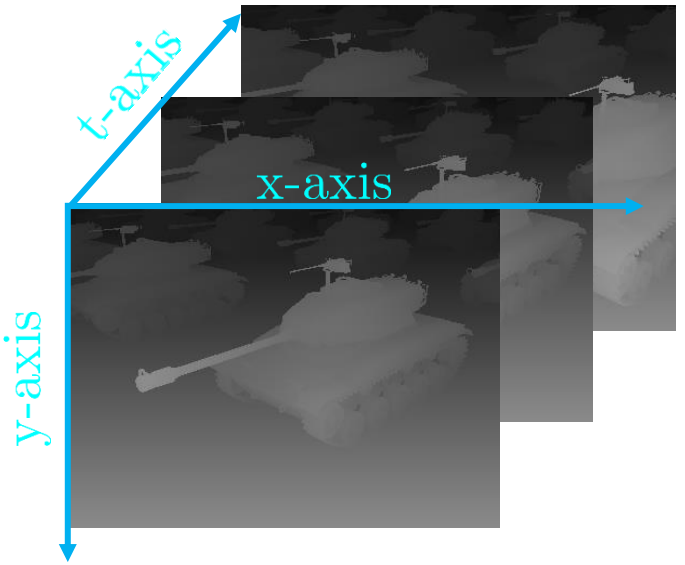
Formulation of depth video sequences:

- Sequences of depth images
- Spatio-Temporal Depth Data



Sparse Depth Samples in Spatiotemporal Volume $(\boldsymbol{b})$

$\boldsymbol{b=Sx}$



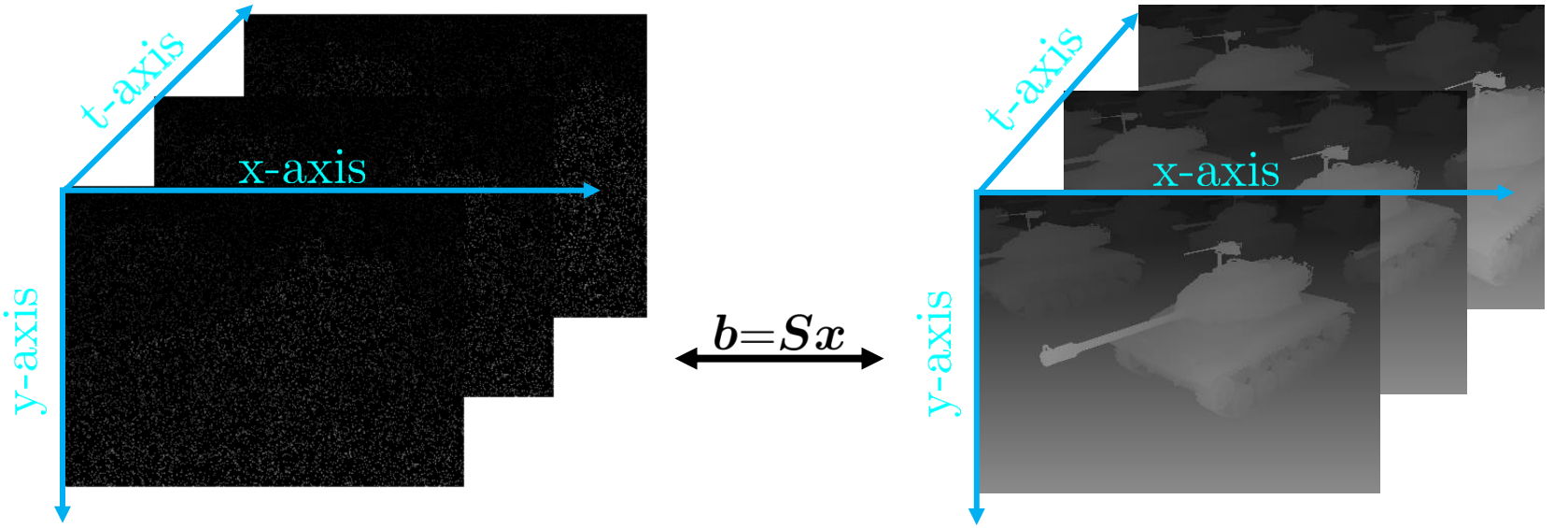
A Sequence of Disparity Maps$(\boldsymbol{x})$

Spatio-Temporal Depth Data

Formulation of depth video sequences:

- Sequences of depth images
- Spatio-Temporal Depth Data

Can we reconstruct on depth sequences in the form of spatio-temporal volume?



Sparse Depth Samples in Spatiotemporal Volume $(\boldsymbol{b})$

A Sequence of Disparity Maps$(\boldsymbol{x})$

S.-T. Depth Reconstruction

Spatio-Temporal Depth Data Reconstruction:

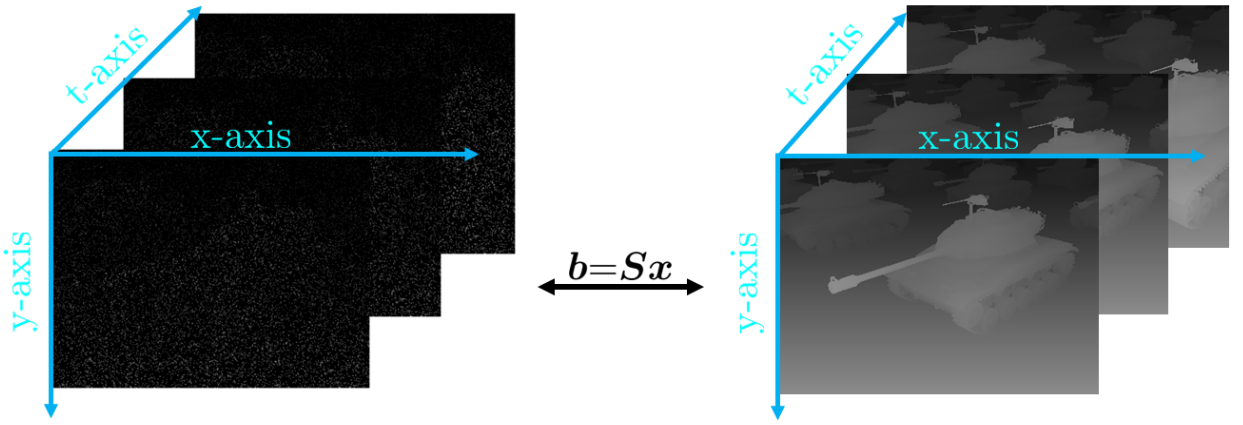
- Problem Formulation

  - Dictionary

$$\min_{\boldsymbol{x}} \frac{1}{2}\|\boldsymbol{b}-\boldsymbol{S}\boldsymbol{x}\|^2+\lambda\|\|\boldsymbol{W}\boldsymbol{B}\boldsymbol{x}\|_1+\beta\|\boldsymbol{x}\|_{\mathrm{TV}}$$

$\boldsymbol{B}$: Orthonormal Matrix — 3-Dimensional Wavelet Transform (3D-DWT)

$\boldsymbol{W}$: Weight Matrix (Diagonal Matrix with 1/0)



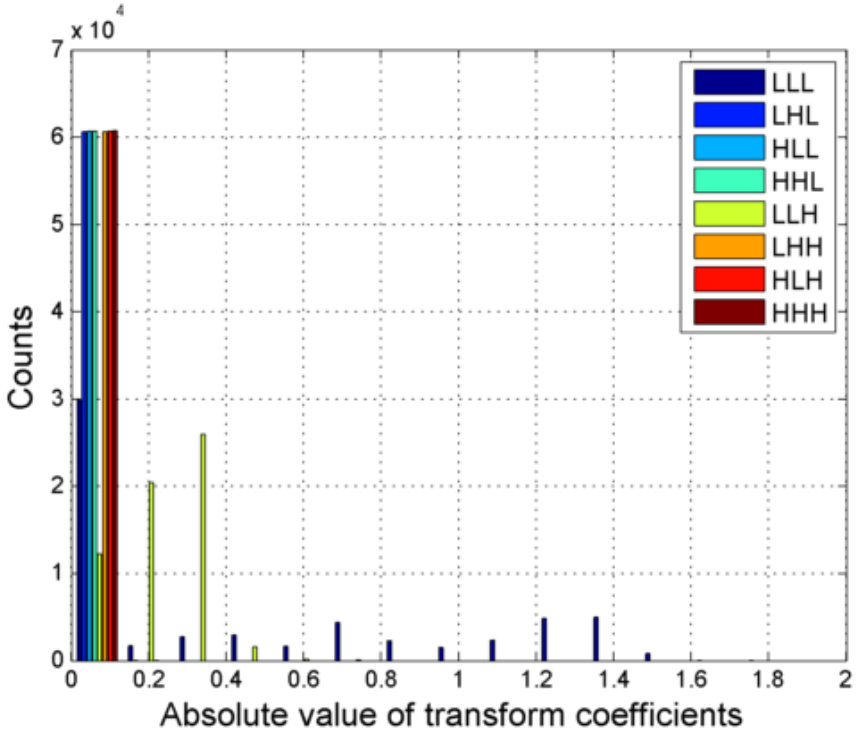
Sparse Depth Samples in Spatiotemporal Volume $(\boldsymbol{b})$

A Sequence of Disparity Maps$(\boldsymbol{x})$

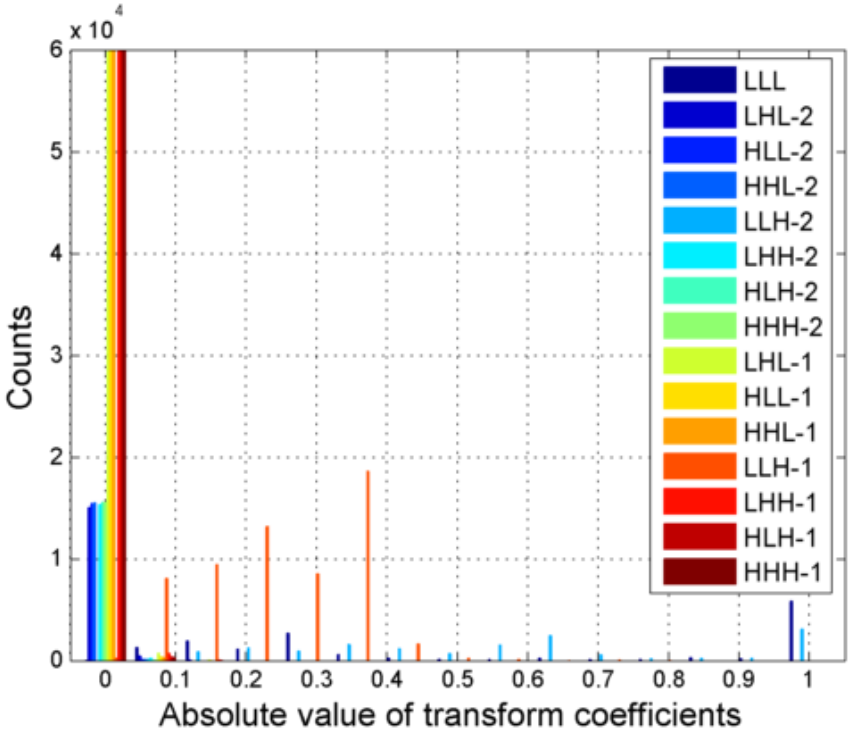
S.-T. Depth Reconstruction

Spatio-Temporal Depth Data Reconstruction:

- Problem Formulation
  - Dictionary
  - Weight matrix design



Level = 1

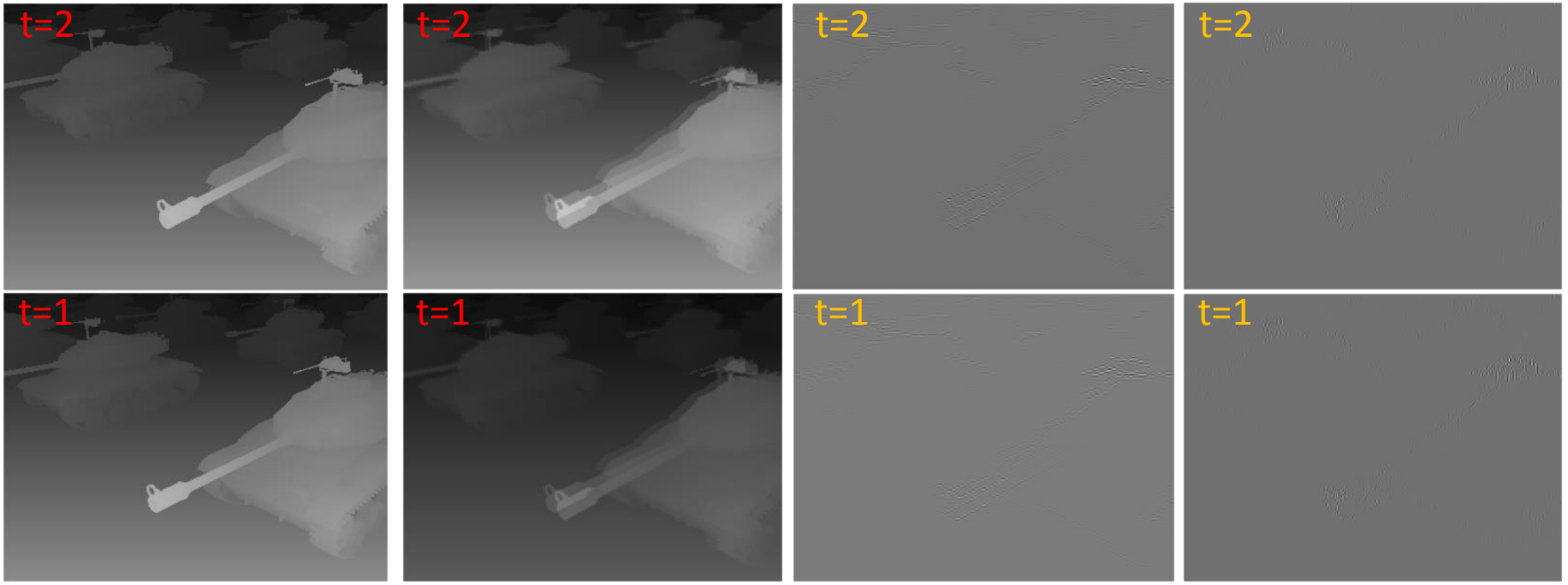


Level = 2

S.-T. Depth Reconstruction

Spatio-Temporal Depth Data Reconstruction:

- Problem Formulation
  - Dictionary
  - Weight matrix design

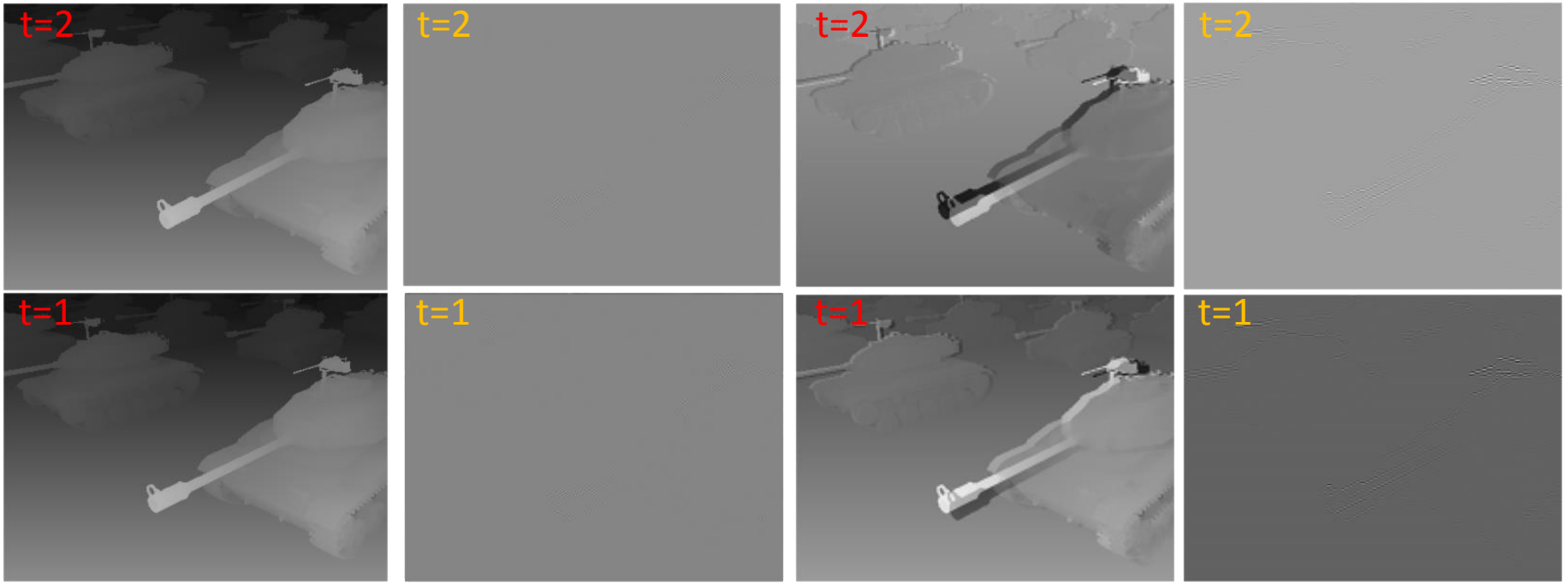


x $\hat{x}$, LLL $\hat{x}$, LHL $\hat{x}$, HLL

S.-T. Depth Reconstruction

Spatio-Temporal Depth Data Reconstruction:

- Problem Formulation
  - Dictionary
  - Weight matrix design

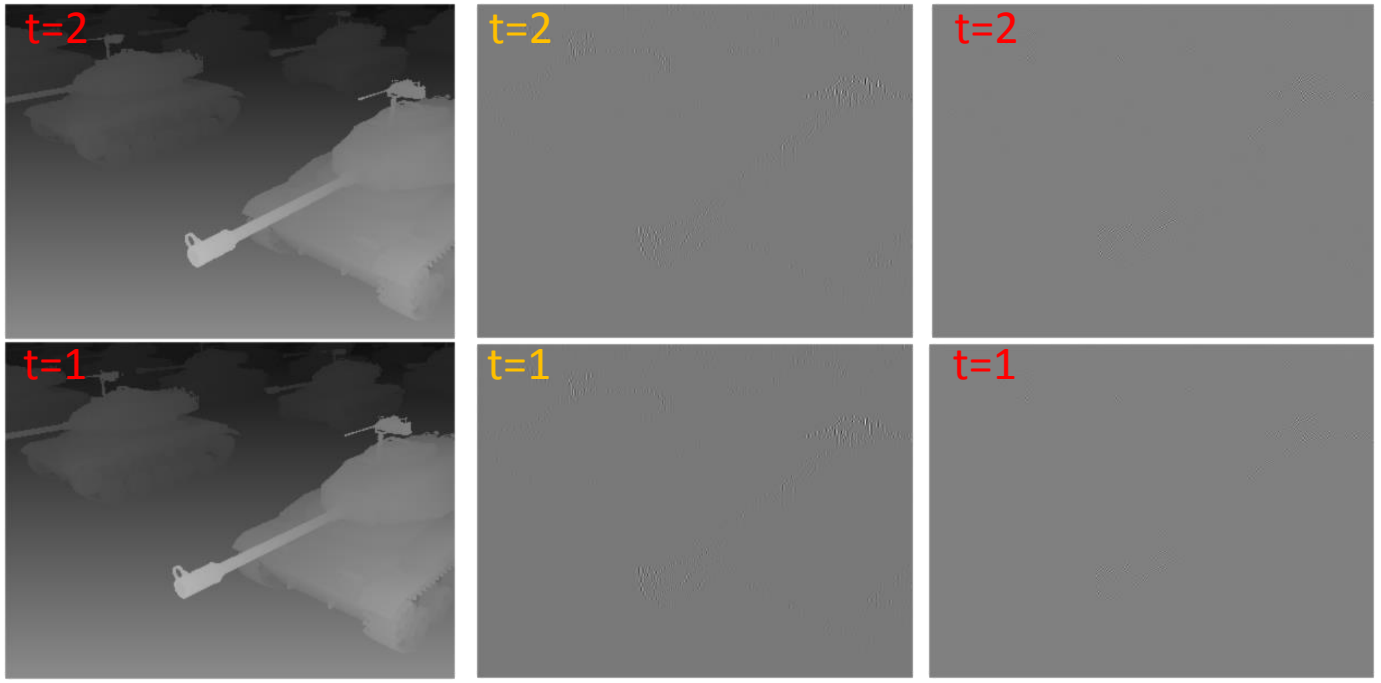


x $\hat{x}$, HHL $\hat{x}$, LLH $\hat{x}$, LHH

S.-T. Depth Reconstruction

Spatio-Temporal Depth Data Reconstruction:

- Problem Formulation
  - Dictionary
  - Weight matrix design: **Constrained on the bands {LHL, HLL, HHL, LHH, HLH, HHH}**



x $\quad$ $\hat{x}$, HLH $\quad$ $\hat{x}$, HHH

S.-T. Depth Reconstruction

Spatio-Temporal Depth Data Reconstruction:

- Problem Formulation
  - Dictionary
  - Weight matrix design: Constrained on the bands {LHL, HLL, HHL, LHH, HLH, HHH}
- Alternating Direction Method of Multipliers (ADMM)
  - Auxiliary variables

$$\min_{\boldsymbol{x}} \frac{1}{2}\|\boldsymbol{b}-\boldsymbol{S}\boldsymbol{x}\|^2+\lambda\|\boldsymbol{W}\boldsymbol{B}\boldsymbol{x}\|_1+\beta\|\boldsymbol{x}\|_{\mathrm{TV}}$$

Subject to $\boldsymbol{r}=\boldsymbol{x}, \boldsymbol{u}_1=\boldsymbol{B}\boldsymbol{x}$ and $\boldsymbol{u}_2=\boldsymbol{D}\boldsymbol{x}$.

S.-T. Depth Reconstruction

Spatio-Temporal Depth Data Reconstruction:

- Problem Formulation
  - Dictionary
  - Weight matrix design: Constrained on the bands {LHL, HLL, HHL, LHH, HLH, HHH}
- Alternating Direction Method of Multipliers (ADMM)
  - Auxiliary variables
  - Augmented Lagrangian

$$\begin{aligned}\mathcal{L}(\boldsymbol{x}, \boldsymbol{r}, \boldsymbol{u}_1, \boldsymbol{u}_2, \boldsymbol{w}, \boldsymbol{q}_1, \boldsymbol{q}_2) = & \frac{1}{2}\|\boldsymbol{b} - \boldsymbol{S}\boldsymbol{r}\|_2^2 + \lambda\|\boldsymbol{W}\boldsymbol{u}_1\|_1 + \beta\|\boldsymbol{u}_2\|_1 \\ & - \boldsymbol{w}^T(\boldsymbol{r} - \boldsymbol{x}) - \boldsymbol{q}_1^T(\boldsymbol{u}_1 - \boldsymbol{B}\boldsymbol{x}) - \boldsymbol{q}_2^T(\boldsymbol{u}_2 - \boldsymbol{D}\boldsymbol{x}) \\ & + \frac{\rho}{2}\|\boldsymbol{r} - \boldsymbol{x}\|_2^2 + \frac{\gamma_1}{2}\|\boldsymbol{u}_1 - \boldsymbol{B}\boldsymbol{x}\|_2^2 + \frac{\gamma_2}{2}\|\boldsymbol{u}_2 - \boldsymbol{D}\boldsymbol{x}\|_2^2.\end{aligned}$$

S.-T. Depth Reconstruction

Spatio-Temporal Depth Data Reconstruction:

- Problem Formulation
  - Dictionary
  - Weight matrix design: Constrained on the bands {LHL, HLL, HHL, LHH, HLH, HHH}
- Alternating Direction Method of Multipliers (ADMM)
  - Auxiliary variables
  - Augmented Lagrangian

$$\begin{aligned}\mathcal{L}(\boldsymbol{x}, \boldsymbol{r}, \boldsymbol{u}_1, \boldsymbol{u}_2, \boldsymbol{w}, \boldsymbol{q}_1, \boldsymbol{q}_2) = & \frac{1}{2}\|\boldsymbol{b} - \boldsymbol{S}\boldsymbol{r}\|_2^2 + \lambda\|\boldsymbol{W}\boldsymbol{u}_1\|_1 + \beta\|\boldsymbol{u}_2\|_1 \\ & - \boldsymbol{w}^T(\boldsymbol{r} - \boldsymbol{x}) - \boldsymbol{q}_1^T(\boldsymbol{u}_1 - \boldsymbol{B}\boldsymbol{x}) - \boldsymbol{q}_2^T(\boldsymbol{u}_2 - \boldsymbol{D}\boldsymbol{x}) \\ & + \frac{\rho}{2}\|\boldsymbol{r} - \boldsymbol{x}\|_2^2 + \frac{\gamma_1}{2}\|\boldsymbol{u}_1 - \boldsymbol{B}\boldsymbol{x}\|_2^2 + \frac{\gamma_2}{2}\|\boldsymbol{u}_2 - \boldsymbol{D}\boldsymbol{x}\|_2^2.\end{aligned}$$

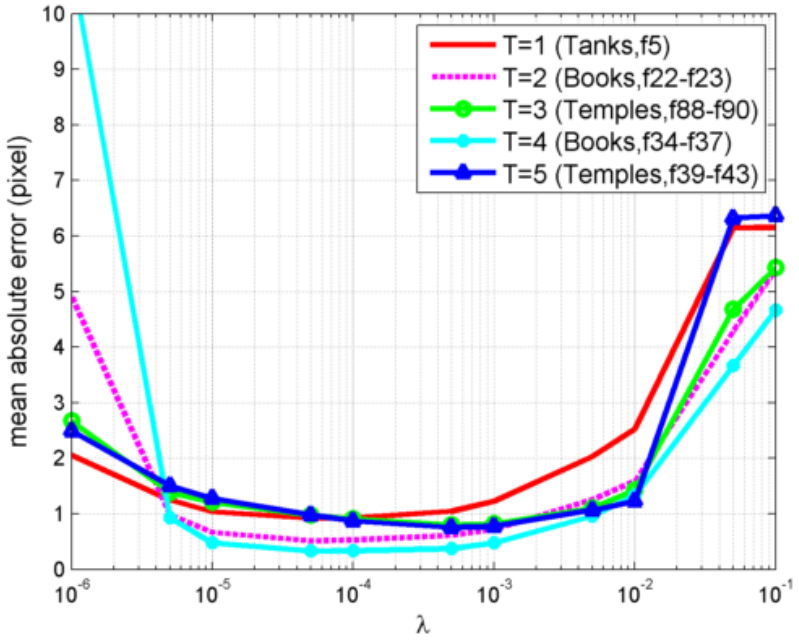
Split the problem into multiple sub-problems!!

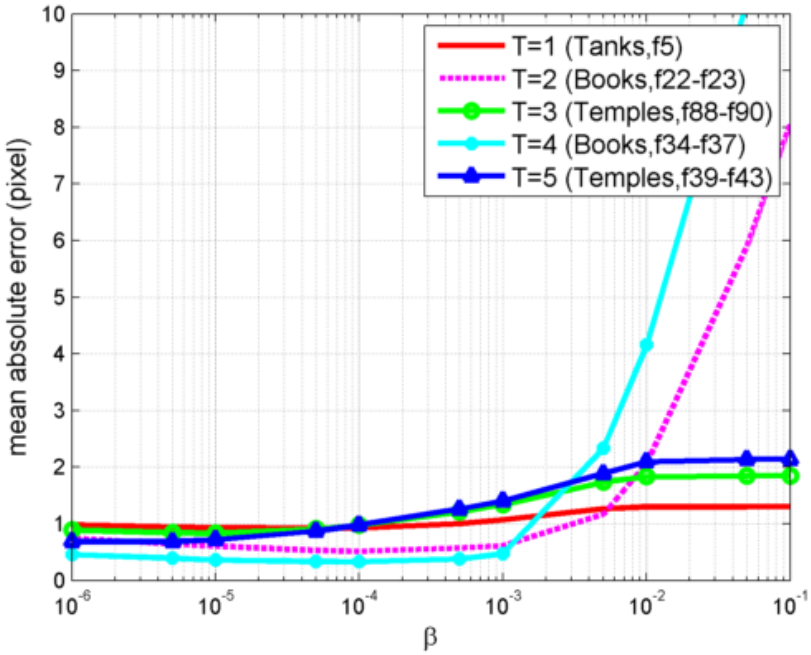
S.-T. Depth Reconstruction

Spatio-Temporal Depth Data Reconstruction:

- Problem Formulation
- Alternating Direction Method of Multipliers (ADMM)
- Parameter selection: External parameters: $\lambda = 10^{-4}, \beta = 5 \times 10^{-5}$

We set sampling rate to 10%, and we plot curves with another parameter fixed.





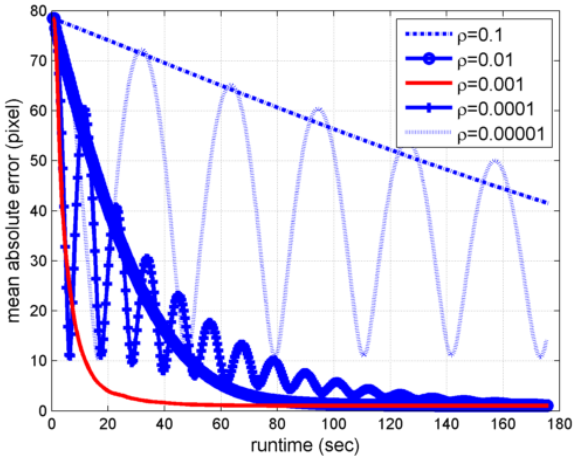
S.-T. Depth Reconstruction

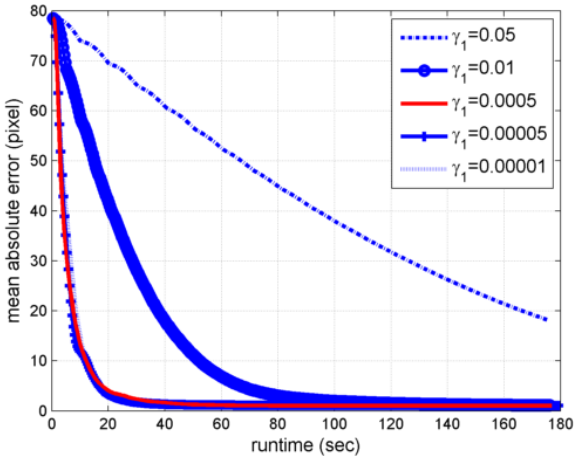
Spatio-Temporal Depth Data Reconstruction:

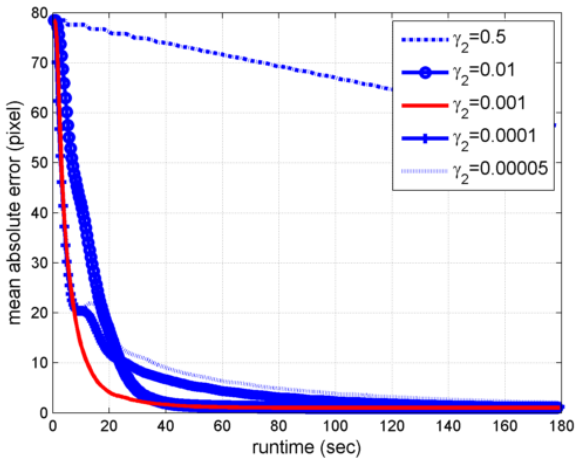
- Problem Formulation
- Alternating Direction Method of Multipliers (ADMM)
- Parameter selection: External parameters: $\lambda = 10^{-4}, \beta = 5 \times 10^{-5}$

  Internal parameters: $\rho = 10^{-3}, \gamma_1 = 5 \times 10^{-4}, \gamma_2 = 10^{-3}$

We set sampling rate to 10%, and we sweep parameters with other parameters fixed.





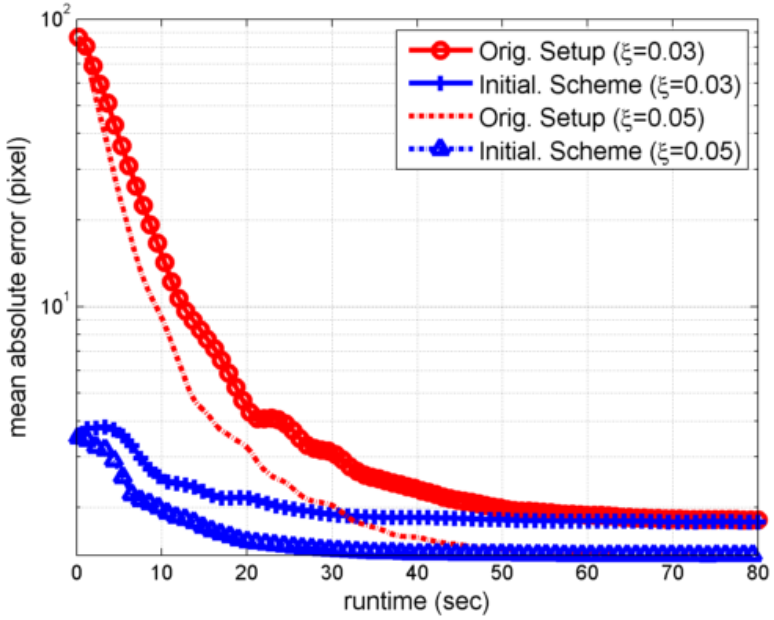


S.-T. Depth Reconstruction

Spatio-Temporal Depth Data Reconstruction:

- Problem Formulation
- Alternating Direction Method of Multipliers (ADMM)
- Parameter selection: External parameters: $\lambda = 10^{-4}, \beta = 5 \times 10^{-5}$
  Internal parameters: $\rho = 10^{-3}, \gamma_1 = 5 \times 10^{-4}, \gamma_2 = 10^{-3}$
- Further speed-up using temporal information: more than **2x** faster

We test “tanks” sequence with the 21st and 22nd frames.



S.-T. Depth Reconstruction

Performance comparisons:

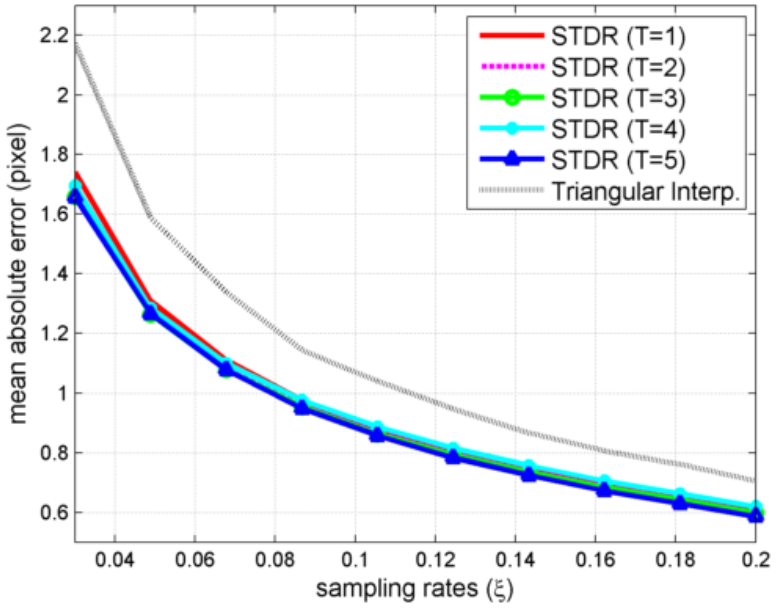
- Better performance in terms of PSNR, MAE and % Bad.
- We set T=5.

Sequence Name		Tanks (100 frames)				Books (41 frames)				Temples (100 frames)			
Sampling Rates	Methods	PSNR (dB)	MAE (pixels)	% Bad Pel. τ=1	% Bad Pel. τ=2	PSNR (dB)	MAE (pixels)	% Bad Pel. τ=1	% Bad Pel. τ=2	PSNR (dB)	MAE (pixels)	% Bad Pel. τ=1	% Bad Pel. τ=2
5%	Proposed	**34.5264**	**1.2601**	12.42	**8.66**	**40.4820**	**0.6101**	8.24	4.87	**31.3678**	**1.1994**	**9.45**	**6.05**
	Tri. Interp.	32.1065	1.4015	**12.28**	9.51	29.9535	0.7956	**5.68**	**4.34**	29.7601	1.6862	10.05	7.42
	Hawe [14]	31.1715	1.9065	21.26	13.85	28.3973	1.3913	13.84	8.58	29.5656	1.6928	18.22	11.28
10%	Proposed	**36.3440**	**0.8831**	**8.37**	**5.99**	**42.3340**	**0.3968**	4.44	**2.65**	**32.9085**	**0.8442**	**6.14**	**3.89**
	Tri. Interp.	34.6588	0.9899	9.02	6.98	33.8628	0.4859	**3.85**	2.96	31.5373	1.1595	6.93	5.01
	Hawe [14]	34.0886	1.1358	12.63	7.76	29.9567	0.9242	7.36	4.39	31.5382	1.0048	10.34	5.22
15%	Proposed	**37.3684**	**0.7072**	**6.56**	**4.79**	**43.5286**	**0.3056**	**3.02**	**1.90**	**34.1938**	**0.6459**	**4.52**	**2.91**
	Tri. Interp.	35.9236	0.8079	7.35	5.71	35.8252	0.3857	3.03	2.35	32.6726	0.9115	5.37	3.86
	Hawe [14]	35.5027	0.8340	8.89	5.32	31.3346	0.6926	4.93	2.94	32.8860	0.7231	6.79	3.02
20%	Proposed	**38.1133**	**0.5900**	**5.39**	3.98	**44.3916**	**0.2473**	**2.21**	**1.47**	**35.3459**	**0.5091**	**3.50**	2.26
	Tri. Interp.	36.9418	0.6896	6.23	4.86	37.3015	0.3245	2.49	1.96	33.5109	0.7595	4.42	3.17
	Hawe [14]	36.5424	0.6608	6.69	**3.97**	37.6195	0.3272	3.51	1.99	33.8765	0.5668	4.78	**2.03**

S.-T. Depth Reconstruction

Performance comparisons:

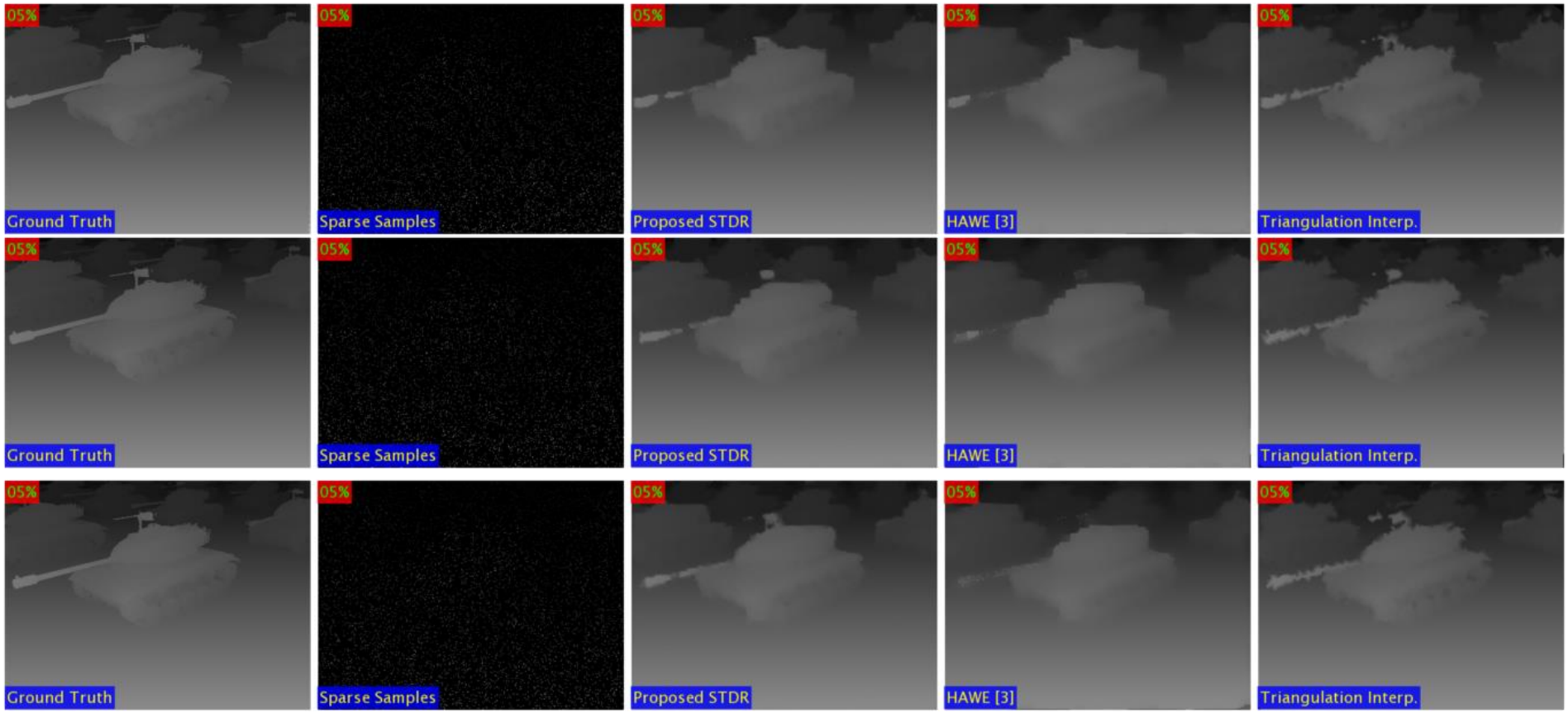
- Better performance in terms of PSNR, MAE and % Bad.
- We set T=5.
- Robust performance to varying spatio-temporal volume size, T.



S.-T. Depth Reconstruction

Visual comparisons:

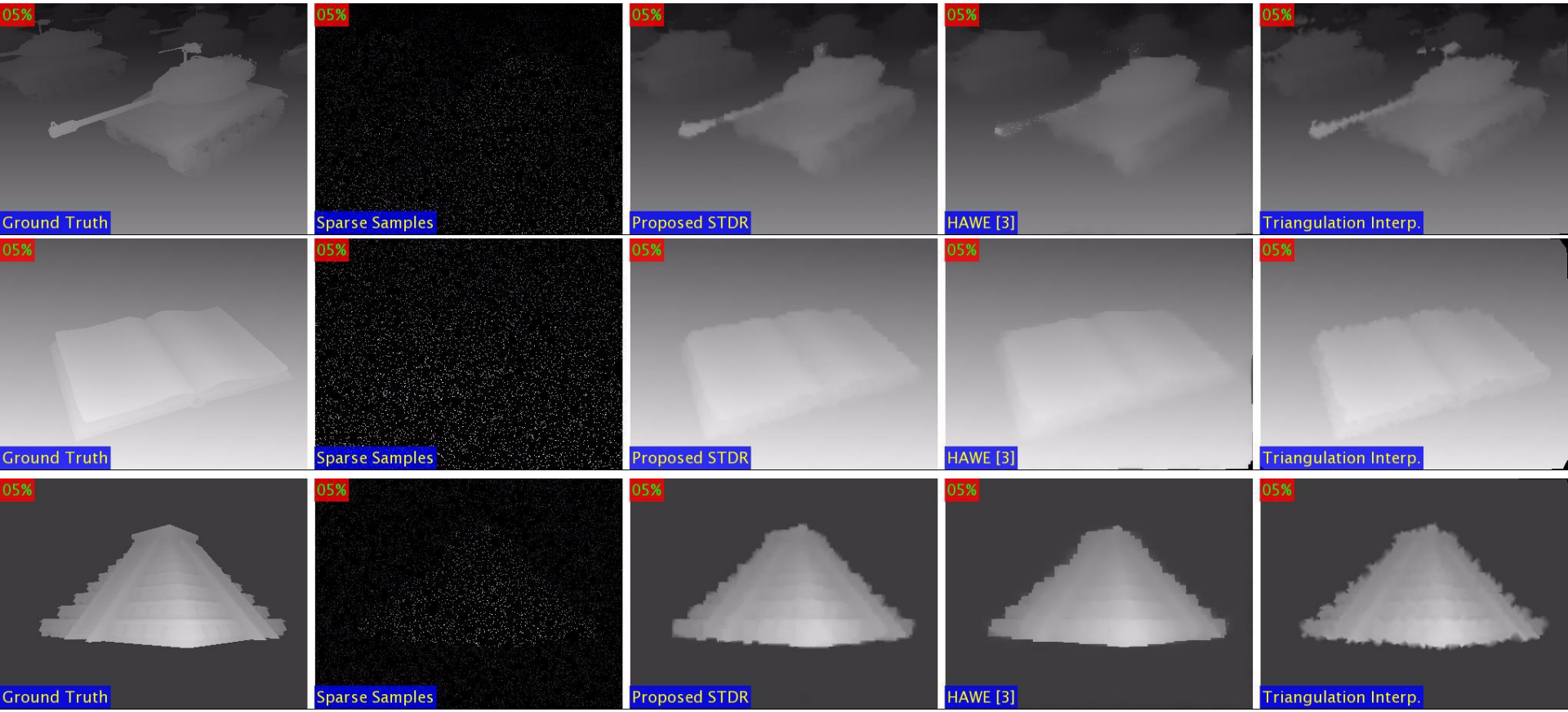
- Temporal Consistency - Frame No. 82, 83, and 84.



S.-T. Depth Reconstruction

Visual comparisons:

- Temporal Consistency - Frame No. 82, 83, and 84.
- Video sequences



Conclusions

- Problem Formulation for Spatio-Temporal Depth Data Reconstruction
  - 3-Dimensional Discrete Wavelet Transform
  - Weight Matrix Design

- Efficient Spatio-Temporal Depth Data Reconstruction Algorithm
  - Alternating Direction Method of Multipliers (ADMM)
  - Speed-up scheme using Temporal Information