What do color changes reveal about an outdoor scene?

Kalyan Sunkavalli

Fabiano Romeiro

Wojciech Matusik*

Todd Zickler

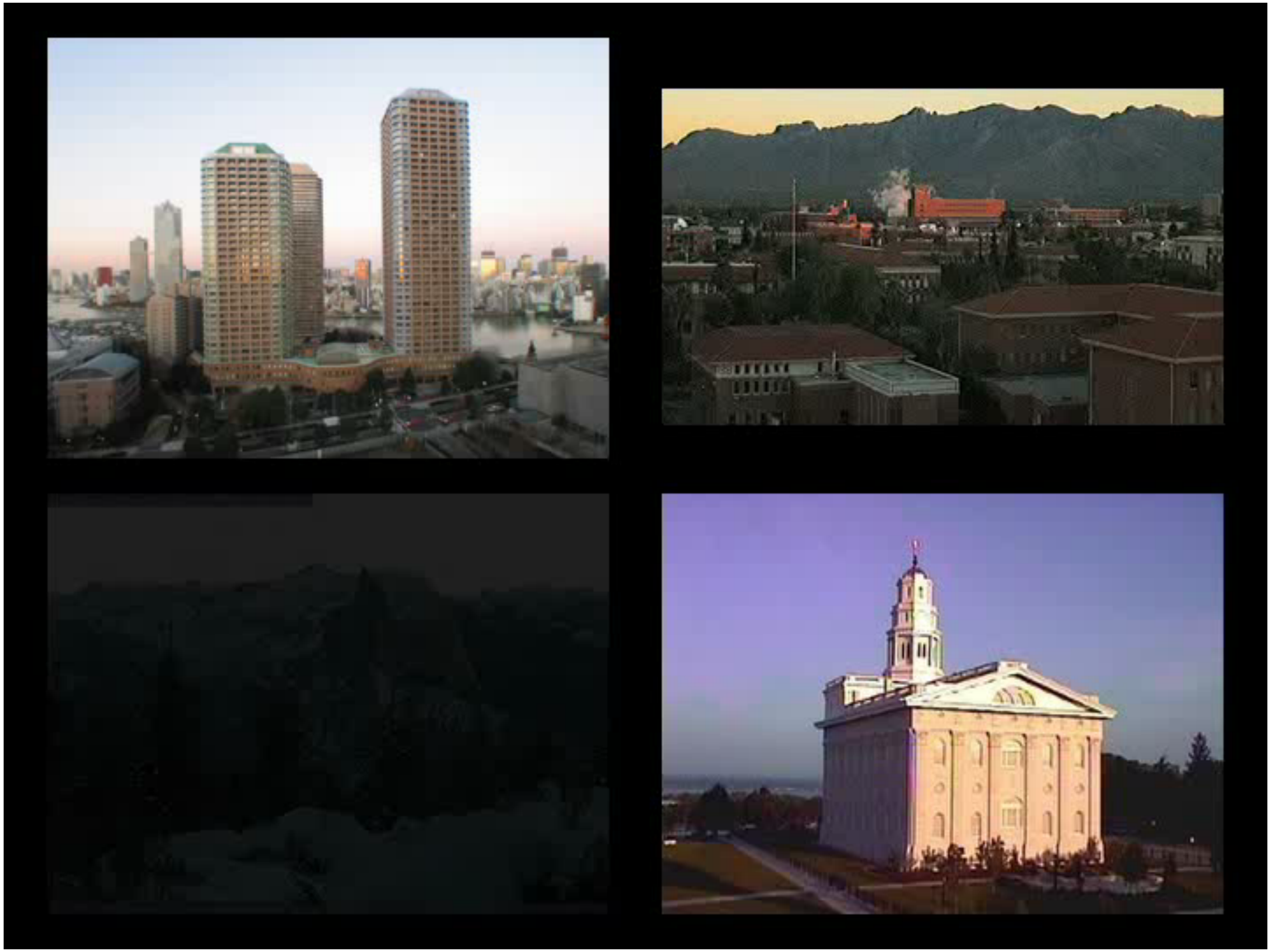
Hanspeter Pfister

Harvard University

* Adobe Systems

IEEE Conference on Computer Vision and Pattern Recognition 2008

Outdoor time-lapse



Time-lapse in Computer Vision

Coherence in time-lapse

- Most previous work makes use of only the **temporal structure** in time-lapse.

- Outdoor time-lapse also has a **colorimetric structure**.

overcast sky

clear sky

sunset

Outline

1. A physics-based model.

2. A method to fit the model to data.

3. Applications of the model.

Outline

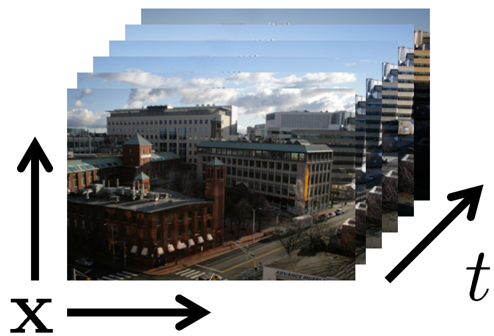
1. **A physics-based model.**

2. A method to fit the model to data.

3. Applications of the model.

A model for outdoor time-lapse

- Assumption 1 : **Static scene**

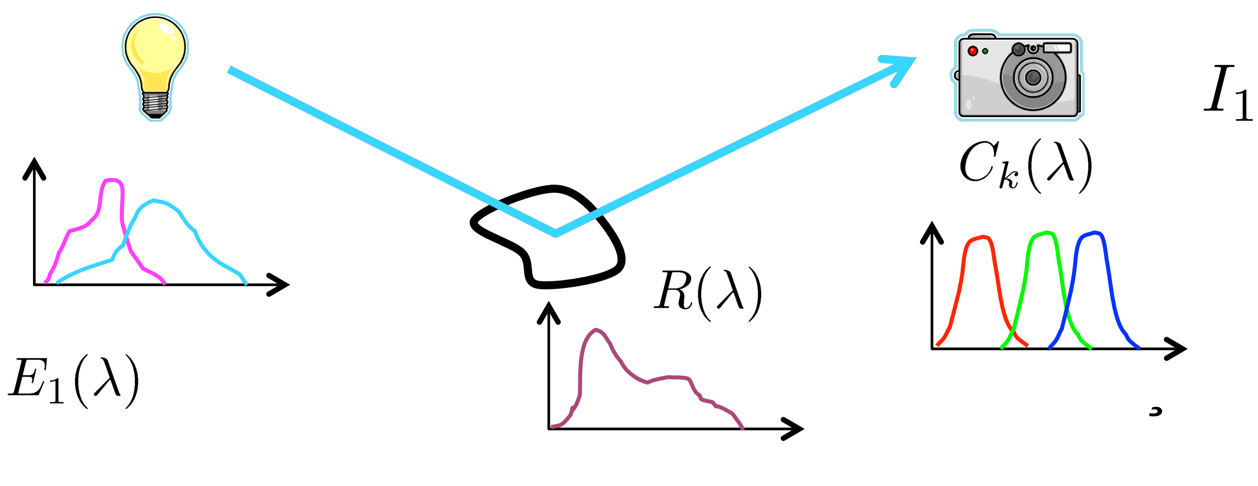


$$= \mathbf{I}(\mathbf{x}, t)$$

A model for outdoor time-lapse

- Assumption 2 : **Linear Transforms for Re-illumination**

$$\underbrace{\mathbf{I}(\mathbf{x},t)}_{\text{observed pixel values}} = \underbrace{\mathbf{M}(t)}_{\text{color transform}}\underbrace{\rho(\mathbf{x})}_{\text{scene color under canonical lighting}}$$



A model for outdoor time-lapse

- Assumption 3 : **Ambient sky and direct sun illumination**

$$\mathbf{I}(\mathbf{x}, t) = \mathbf{M}(t)\rho(\mathbf{x})$$

$$\Rightarrow \mathbf{I}(\mathbf{x}, t) = \alpha(\mathbf{x}, t)\underbrace{\mathbf{M}^{sky}(t)}_{\text{sky illumination}}\rho(\mathbf{x}) + \beta(\mathbf{x}, t)\underbrace{\mathbf{M}^{sun}(t)}_{\text{sun illumination}}\rho(\mathbf{x})$$

mixing weights

A model for outdoor time-lapse

- Assumption 4 : **2-d subspace for daylight spectra**

$$\mathbf{I}(\mathbf{x},t) = \mathbf{M}(t)\rho(\mathbf{x})$$

$$\Rightarrow \mathbf{I}(\mathbf{x},t) = \alpha(\mathbf{x},t)\mathbf{M}^{sky}(t)\rho(\mathbf{x}) + \beta(\mathbf{x},t)\mathbf{M}^{sun}(t)\rho(\mathbf{x})$$

$$e_1^{sky}(t)\mathbf{M}_1 + e_2^{sky}(t)\mathbf{M}_2 \qquad e_1^{sun}(t)\mathbf{M}_1 + e_2^{sun}(t)\mathbf{M}_2$$

[Judd et al. 1964, Sastri and Das 1968, …, Hernández-Andrés et al. 2000]

A model for outdoor time-lapse

- Assumption 4 : **2-d subspace for daylight spectra**

$$\mathbf{I}(\mathbf{x},t) = \mathbf{M}(t)\rho(\mathbf{x})$$

$$\Rightarrow \mathbf{I}(\mathbf{x},t) = \alpha(\mathbf{x},t)\underbrace{\mathbf{M}^{sky}(t)}_{e_1^{sky}(t)\mathbf{M}_1 + e_2^{sky}(t)\mathbf{M}_2}\rho(\mathbf{x}) + \beta(\mathbf{x},t)\underbrace{\mathbf{M}^{sun}(t)}_{e_1^{sun}(t)\mathbf{M}_1 + e_2^{sun}(t)\mathbf{M}_2}\rho(\mathbf{x})$$

$$\mathbf{I}(\mathbf{x},t) = \alpha(\mathbf{x},t)\left(\sum_{i=1}^{2} e_i^{sky}(t)\mathbf{M}_i\right)\rho(\mathbf{x}) + \beta(\mathbf{x},t)\left(\sum_{i=1}^{2} e_i^{sun}(t)\mathbf{M}_i\right)\rho(\mathbf{x})$$

A model for outdoor time-lapse

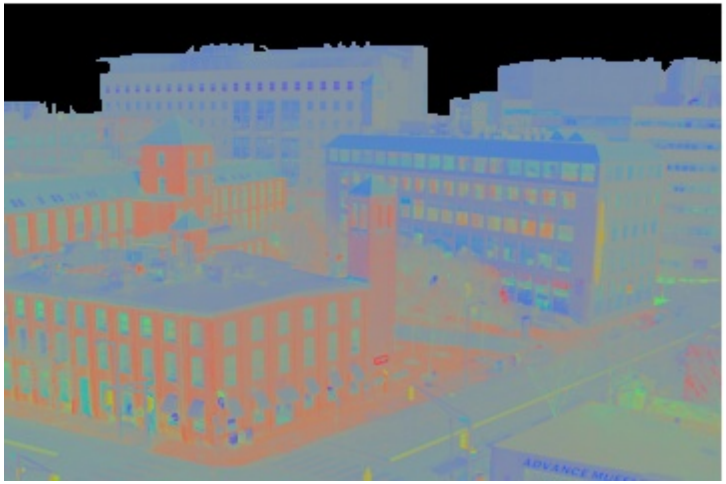
$$\mathbf{I}(\mathbf{x},t) = \alpha(\mathbf{x},t)\left(\sum_{i=1}^{2} \underline{e_i^{sky}(t)}\mathbf{M}_i\right)\rho(\mathbf{x}) + \beta(\mathbf{x},t)\left(\sum_{i=1}^{2} \underline{e_i^{sun}(t)}\mathbf{M}_i\right)\rho(\mathbf{x})$$

illumination coefficients

A model for outdoor time-lapse

$$\mathbf{I}(\mathbf{x},t) = \alpha(\mathbf{x},t)\left(\sum_{i=1}^{2} e_i^{sky}(t)\mathbf{M}_i\right)\underline{\rho(\mathbf{x})} + \beta(\mathbf{x},t)\left(\sum_{i=1}^{2} e_i^{sun}(t)\mathbf{M}_i\right)\underline{\rho(\mathbf{x})}$$

scene color under canonical lighting (normalized)



A model for outdoor time-lapse

$$\mathbf{I}(\mathbf{x},t) = \alpha(\mathbf{x},t)\left(\sum_{i=1}^{2} e_i^{sky}(t)\mathbf{M}_i\right)\rho(\mathbf{x}) + \beta(\mathbf{x},t)\left(\sum_{i=1}^{2} e_i^{sun}(t)\mathbf{M}_i\right)\rho(\mathbf{x})$$

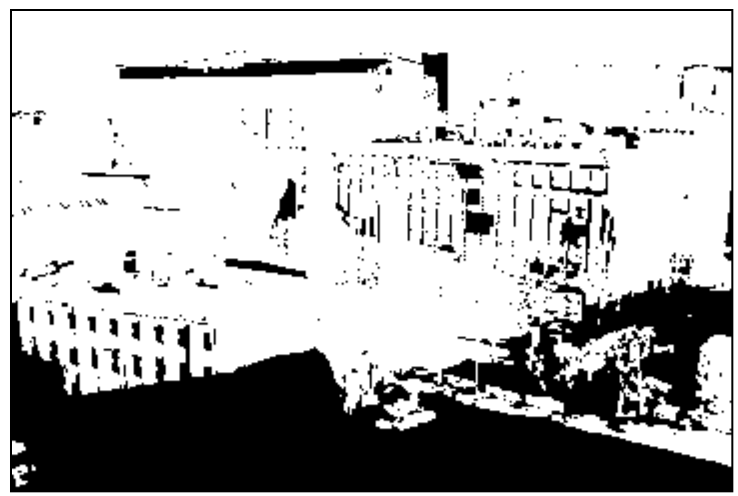
$$\mathbf{V}(\mathbf{x},t)\cos(\omega^{sun}t + \Phi(\mathbf{x}))$$

A model for outdoor time-lapse

$$\mathbf{I}(\mathbf{x},t) = \alpha(\mathbf{x},t)\left(\sum_{i=1}^{2} e_i^{sky}(t)\mathbf{M}_i\right)\rho(\mathbf{x}) + \beta(\mathbf{x},t)\left(\sum_{i=1}^{2} e_i^{sun}(t)\mathbf{M}_i\right)\rho(\mathbf{x})$$

$$\mathbf{V}(\mathbf{x},t)\cos(\omega^{sun}t + \Phi(\mathbf{x}))$$

shadows



A model for outdoor time-lapse

$$\mathbf{I}(\mathbf{x},t) = \alpha(\mathbf{x},t)\left(\sum_{i=1}^{2} e_i^{sky}(t)\mathbf{M}_i\right)\rho(\mathbf{x}) + \beta(\mathbf{x},t)\left(\sum_{i=1}^{2} e_i^{sun}(t)\mathbf{M}_i\right)\rho(\mathbf{x})$$

$$\mathbf{V}(\mathbf{x},t)\,\underbrace{\cos(\omega^{sun}t + \Phi(\mathbf{x}))}_{\textit{shading}}$$

A model for outdoor time-lapse

$$\mathbf{I}(\mathbf{x},t) = \alpha(\mathbf{x},t)\left(\sum_{i=1}^{2} e_i^{sky}(t)\mathbf{M}_i\right)\rho(\mathbf{x}) + \beta(\mathbf{x},t)\left(\sum_{i=1}^{2} e_i^{sun}(t)\mathbf{M}_i\right)\rho(\mathbf{x})$$

$$\mathbf{V}(\mathbf{x},t)\cos(\omega^{sun}t + \Phi(\mathbf{x}))$$

1-d projection of normals onto solar plane

Outline

1. A physics-based model.

2. **A method to fit the model to data.**

3. Applications of the model.

Fitting the model

$\mathbf{M}_i$	e_i^{sky}, e_i^{sun}	$\rho(\mathbf{x})$	$\mathbf{V}(\mathbf{x}, t)$	$a(\mathbf{x}), b(\mathbf{x})$	$\Phi(\mathbf{x})$	$\omega^{sky}, \omega^{sun}$
illum. bases	*illum. coeffs.*	*albedo*	*shadows*	*brightness*	*normals*	*angular velocity*

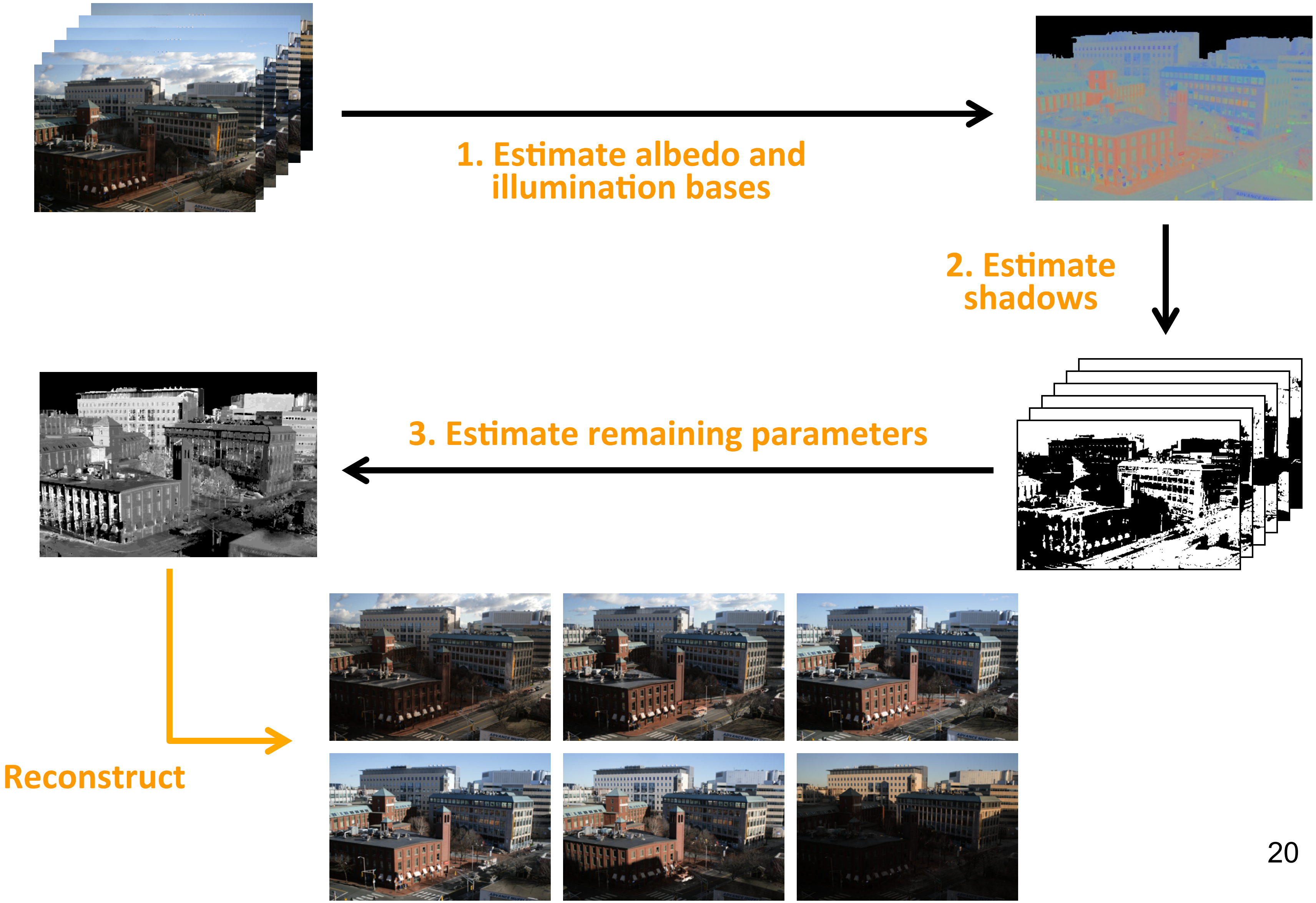
over-constrained system

320 X 240 images, 100 frames

23,040,000 measurements

8,141,220 parameters

Fitting the model



Fitting results

original reconstruction

240 x 360 images, 120 frames, ~5 mins. interval

Fitting results

original **error x 3**

240 x 360 images, 120 frames, ~5 mins. interval, 7.36% RMS error

Outline

1. A physics-based model.

2. A method to fit the model to data.

3. **Applications of the model.**

Application I : Color Constancy

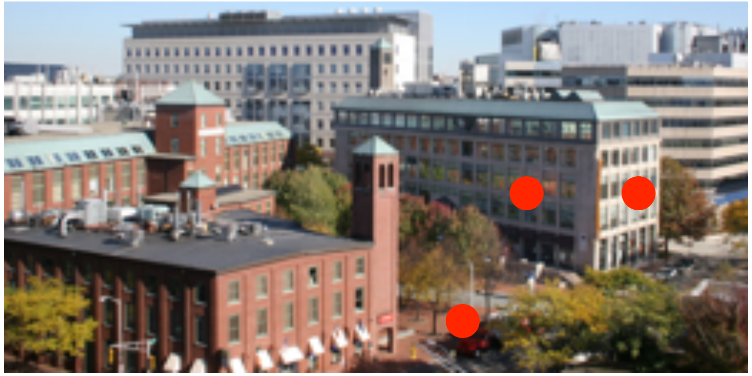
[D'Zmura and Lennie 1986, Forsyth 1990, Funt et al. 1991, Finlayson and Funt 1994, Brainard and Freeman 1997, Barnard et al. 1997, Finlayson et al. 2001, Ebner 2004,…]

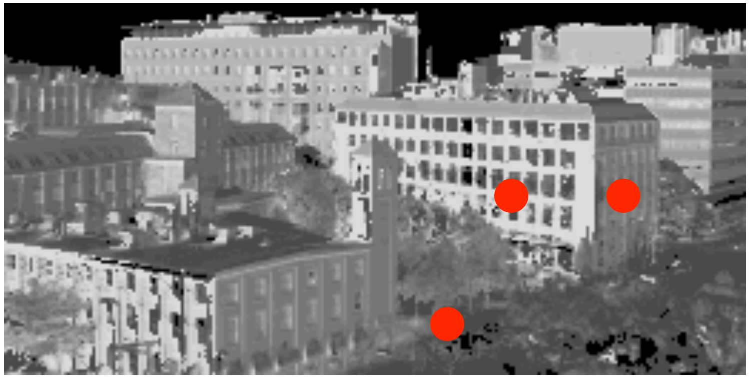
Application I : Color Constancy

original color corrected

Application II : Scene Reconstruction

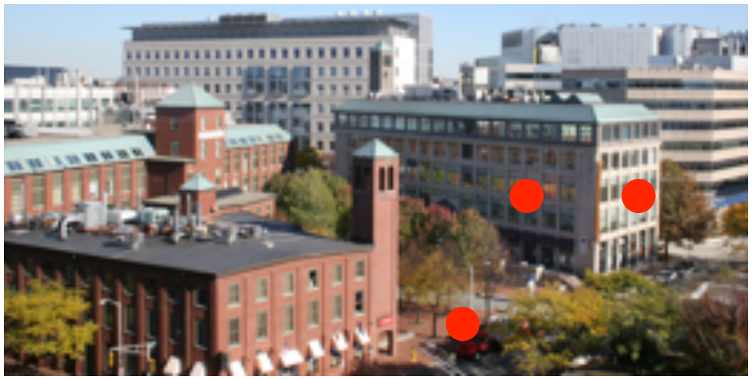
$\Phi(\mathbf{x})$

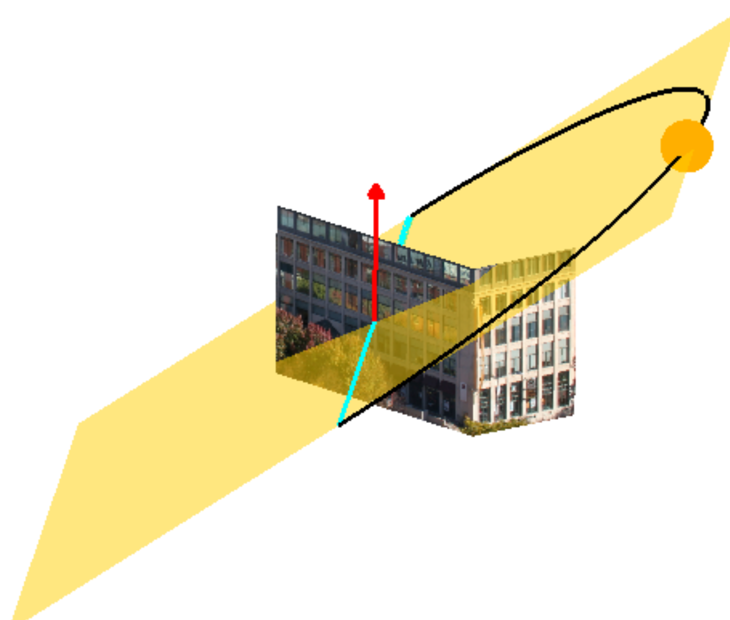




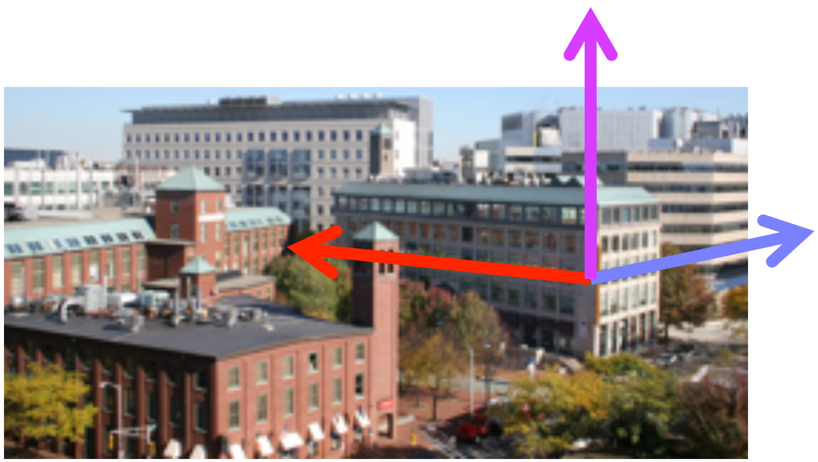
Application II : Scene Reconstruction

$\Phi(\mathbf{x})$

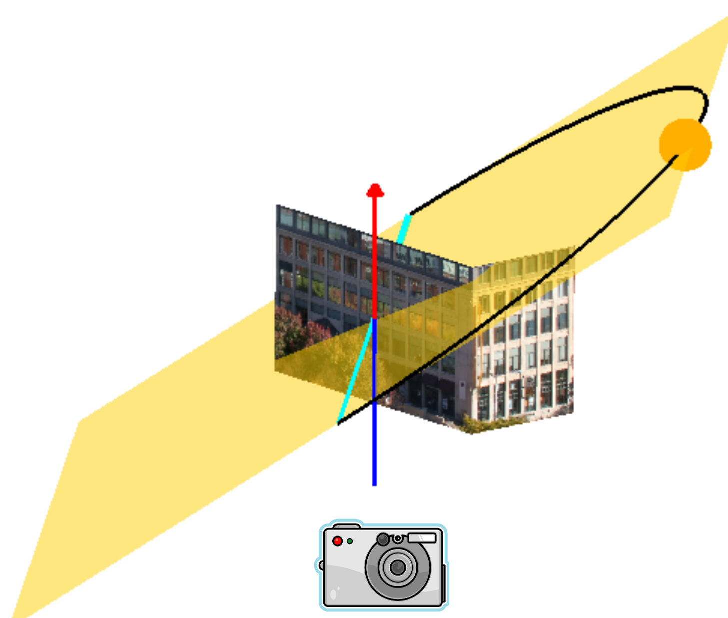




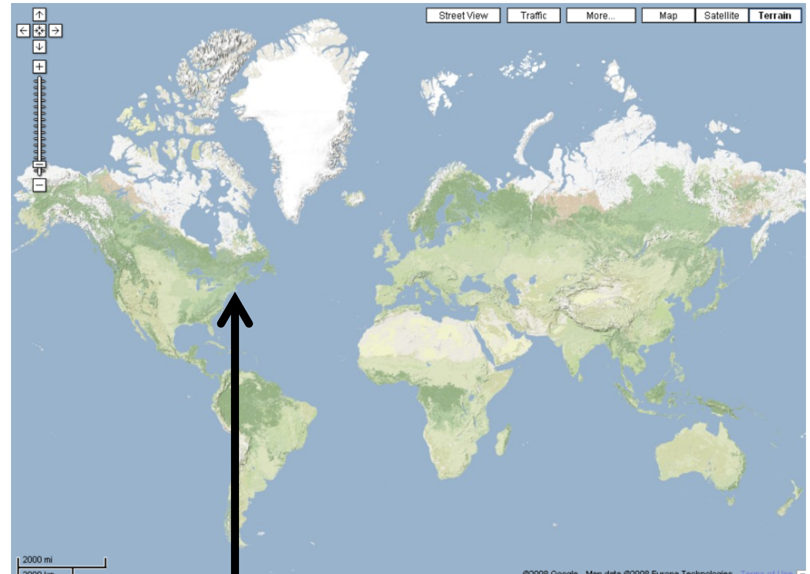
Application II : Scene Reconstruction

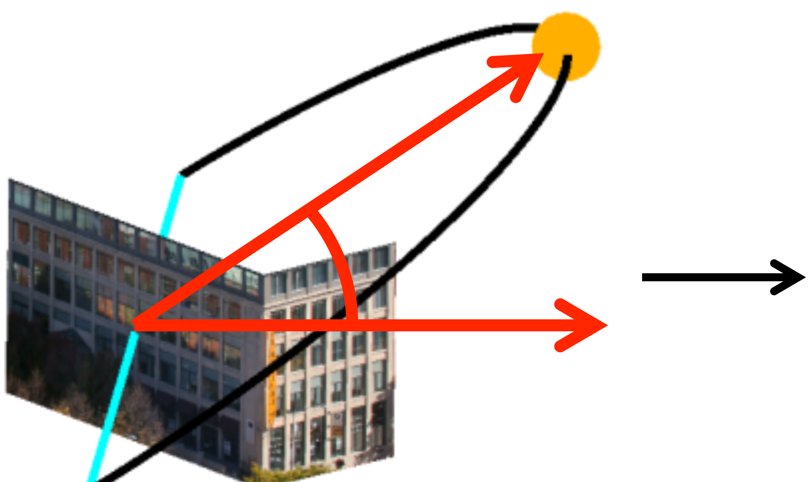


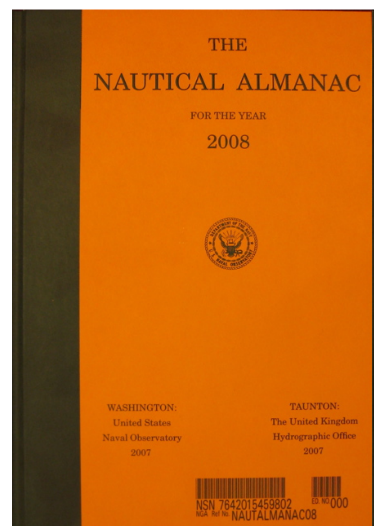
$\Phi(\mathbf{x})$



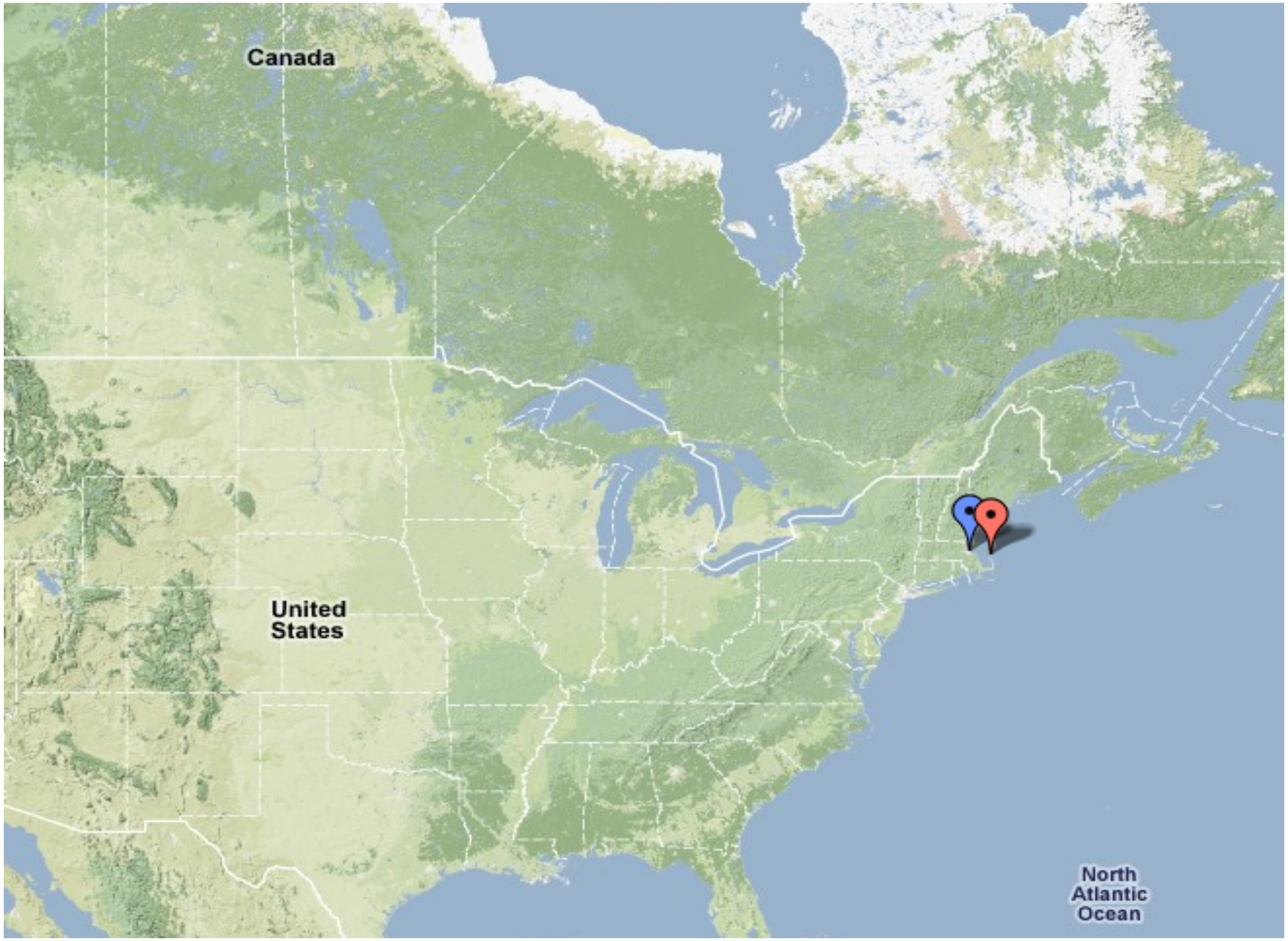
Application III : Geo-location







Application III : Geo-location



Summary

1. Outdoor time-lapse sequences are ubiquitous.

2. They are a rich source of scene information.

3. By using *both* temporal and colorimetric coherence we can access that scene information.

Future Work

1. Robust Fitting (mutual illumination, non-lambertian surfaces, foreground clutter).

2. Multiple viewpoints.

3. Estimating weather and atmospheric conditions.

Thank you!