Diffuse Reflectance Imaging with Astronomical Applications

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Indirect Imaging with Diffuse Reflection

Diffuse surfaces generally blur together incident lighting from many directions

- To what extent can we use **diffuse objects** as **"cameras"**?
- How much **resolution** can we hope to achieve?

incident lighting recorded "directly" — incident lighting ill-posed?

Goal: Recover detailed incident illumination (or surface albedo) using photos measuring the reflectance of a diffuse object.

Theory of Reflection and its Inversion

Single-bounce light transport

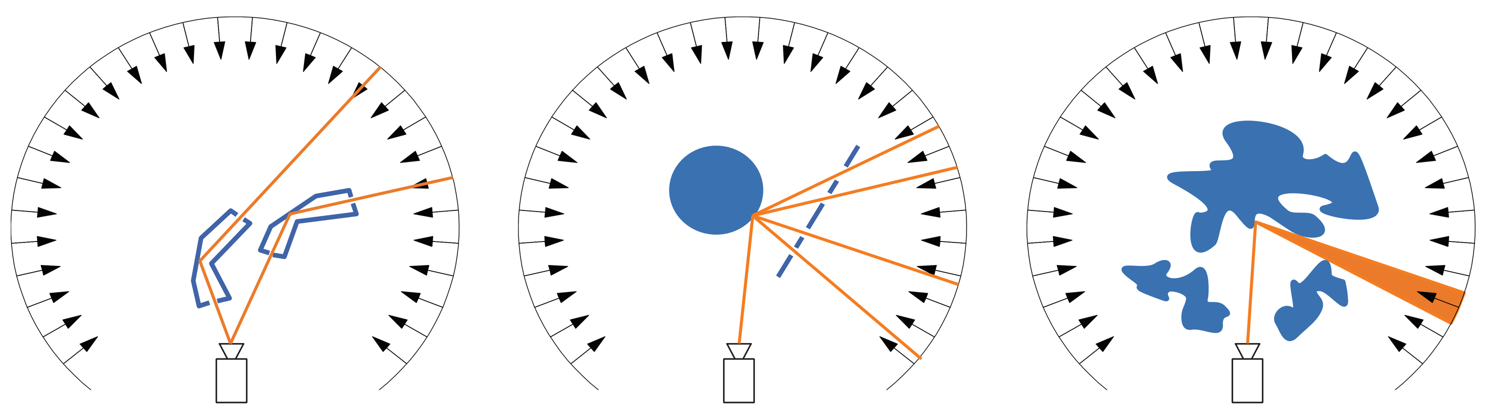
$$\underbrace{B(\mathbf{p},\vec{\omega}_o)}_{\text{reflected radiance}} = \int_\Omega \underbrace{\alpha(\mathbf{p})}_{\text{surface albedo}}\, \underbrace{L(\mathbf{p},\vec{\omega}_i)}_{\text{incoming radiance}}\, \underbrace{\rho(\vec{\omega}_i,\vec{\omega}_o)}_{\text{BRDF}}\, \underbrace{V(\mathbf{p},\vec{\omega}_i)}_{\textbf{visibility}}\, \underbrace{\max(\vec{\omega}_i\cdot\vec{n},0)}_{\text{clipped cosine}}\, d\vec{\omega}_i$$

Matrix formulation

$$\underbrace{p(\mathbf{y}|\mathbf{x})}_{\text{observed pixels}} = \mathcal{N}(\underbrace{\mathbf{A}}_{\text{transfer matrix}}\underbrace{\mathbf{x}}_{\text{distant lighting}}, \underbrace{\eta^2\mathbf{I}}_{\text{noise}})$$

- Reflectance ≈ spherical convolution of lighting and BRDF
- Images of convex Lambertian objects with distant lighting lie in a ~**9D** subspace [Basri and Jacobs, 2003] [Ramamoorthi and Hanrahan, 2001]

Key: Occlusion Geometry for Illumination Coding



double-pinholes — coded reflectance — natural complexity

"Sculpture design" for inverse rendering

- Occlusion creates high frequencies , improves conditioning
- In the extreme, scene geometry isolates individual rays

Bayesian Reconstruction Method

Standard MAP estimation

- Gaussian prior [Wiener 1949]

$$p(\mathbf{x}) = \mathcal{N}(\mathbf{0}, \boldsymbol{\Sigma}_\mathbf{x})$$

$$p(\mathbf{x}|\mathbf{y}) = \mathcal{N}(\boldsymbol{\Sigma}(\tfrac{1}{\eta^2}\mathbf{A}^T\mathbf{y}), \boldsymbol{\Sigma})$$
$$\boldsymbol{\Sigma} = (\boldsymbol{\Sigma}_\mathbf{x}^{-1} + \tfrac{1}{\eta^2}\mathbf{A}^T\mathbf{A})^{-1}$$

- Sparse derivative prior [Levin et al. 2007]

$$g(z) = |z|^{0.8}$$

Reconstructing the stable component of **time-varying lighting**

- Marginalize out temporal variations

$$p(\mathbf{y}|\mathbf{x},\mathbf{t}_1,\ldots,\mathbf{t}_D) = \mathcal{N}\left(\begin{bmatrix}\mathbf{A}_1(\mathbf{x}+\mathbf{t}_1)\\ \vdots \\ \mathbf{A}_D(\mathbf{x}+\mathbf{t}_D)\end{bmatrix}, \eta^2\mathbf{I}\right)$$
$$p(\mathbf{t}_i) = \mathcal{N}(\mathbf{0}, \boldsymbol{\Sigma}_\mathbf{t})$$

temporal binning with Gaussian prior

$$p(\mathbf{y}|\mathbf{x}) = \mathcal{N}\left(\begin{bmatrix}\mathbf{A}_1\\ \vdots \\ \mathbf{A}_D\end{bmatrix}\mathbf{x}, \begin{bmatrix}\mathbf{A}_1\boldsymbol{\Sigma}_\mathbf{t}\mathbf{A}_1^T & & \mathbf{0}\\ & \ddots & \\ \mathbf{0} & & \mathbf{A}_D\boldsymbol{\Sigma}_\mathbf{t}\mathbf{A}_D^T\end{bmatrix} + \eta^2\mathbf{I}\right)$$

temporal variations as correlated noise

(1) Rim Reflectance Imaging

Exploit visibility differences very close to **occlusion boundary**

- **Single shot** is enough
- Requires high resolution, compact lighting
- Novel approach (to our knowledge)

(2) Time-Varying Imaging

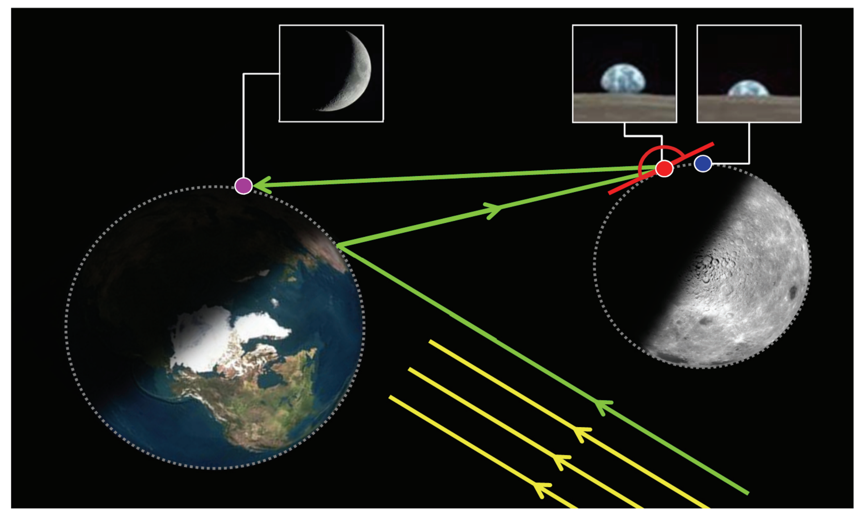
Exploit variation over time in the occlusion geometry

- **Single pixel** is enough
- Requires many shots, natural variation
- Classical astronomy ("light curves")

Moon as a Mirror - Feasibility Study

Observing Earth via its reflection in the moon

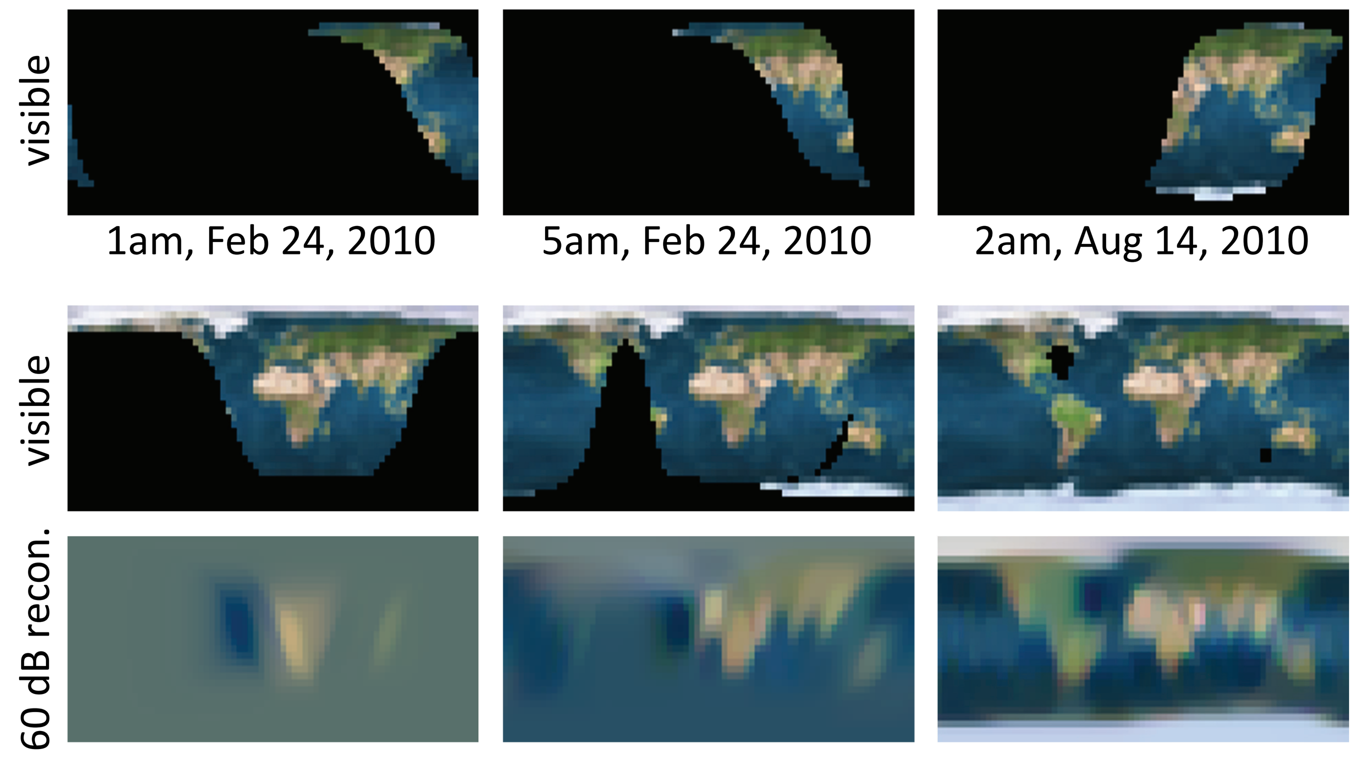
- BBSO **earthshine** project measures albedo over time [Qiu et al. 2003] [Pallé et al. 2003]
- Can we resolve more than a single pixel?



Simulation: Rim reflectance imaging

std. optics (0.4″) — adaptive optics (0.07″)

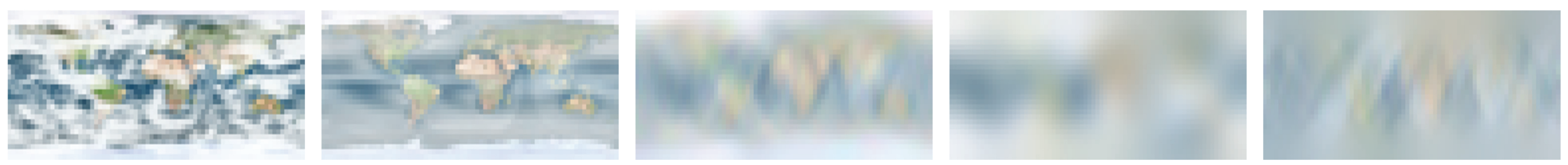
Simulation: Time-varying imaging



1am, Feb 24, 2010 — 5am, Feb 24, 2010 — 2am, Aug 14, 2010

1 night (107 obs.) — 1 month (412 obs.) — 1 year (963 obs.)

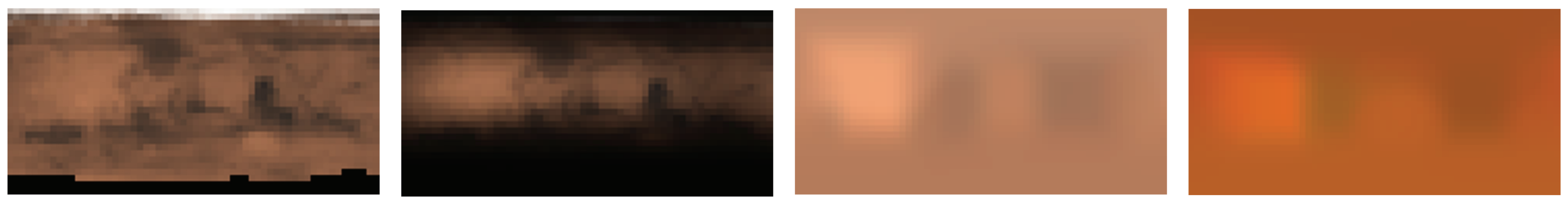
Simulation: Time-varying imaging with clouds



earth with clouds — mean clouds — ideal baseline — basic recon. — covariant recon.

Martian Surface from Single-Pixel Data

Real data: 234 historical photometry measurements [Irvine et al. 1968ab]



ground truth visible — relative contribution — recon. from simulation — recon. from real data (hVB)