Jet Propulsion Laboratory
California Institute of Technology

Reconstruction of Convective Clouds using AirMSPI or MISR/Terra Data and 3D Radiative Transfer: A Progress Report

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… also cloud tomography team at the Technion (Haifa, Israel):
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Asia Oceania Geosciences Society 15th Annual Meeting (AOGS2018),Special Session AS51 on "Frontiers and Challenges in the Applications of Radiative Transfer",Honolulu, Hi, 3-8 June, 2018

Outline

- **Multi-angle/multi-pixel algorithms for 3D cloud reconstruction**
  - Technion approach (3D optical tomography)
    - Now with microphysical characterization
  - Columbia approach (outer cloud shape only)
    - Recent evolution at JPL
  - Columbia/GISS→SRON approach (3D optical tomography)
    - PhD thesis of Will Martin (adjoint 3D RT-based, pure theory)
    - JQSRT paper by Martin, Cairns, and Bal
    - Will Smith postdoc at SRON (numerical implementation & demo)
    - JQSRT paper by Martin and Hasekamp
- **Conclusions/outlooks**
  - (distributed across approaches)

Progress at Technion

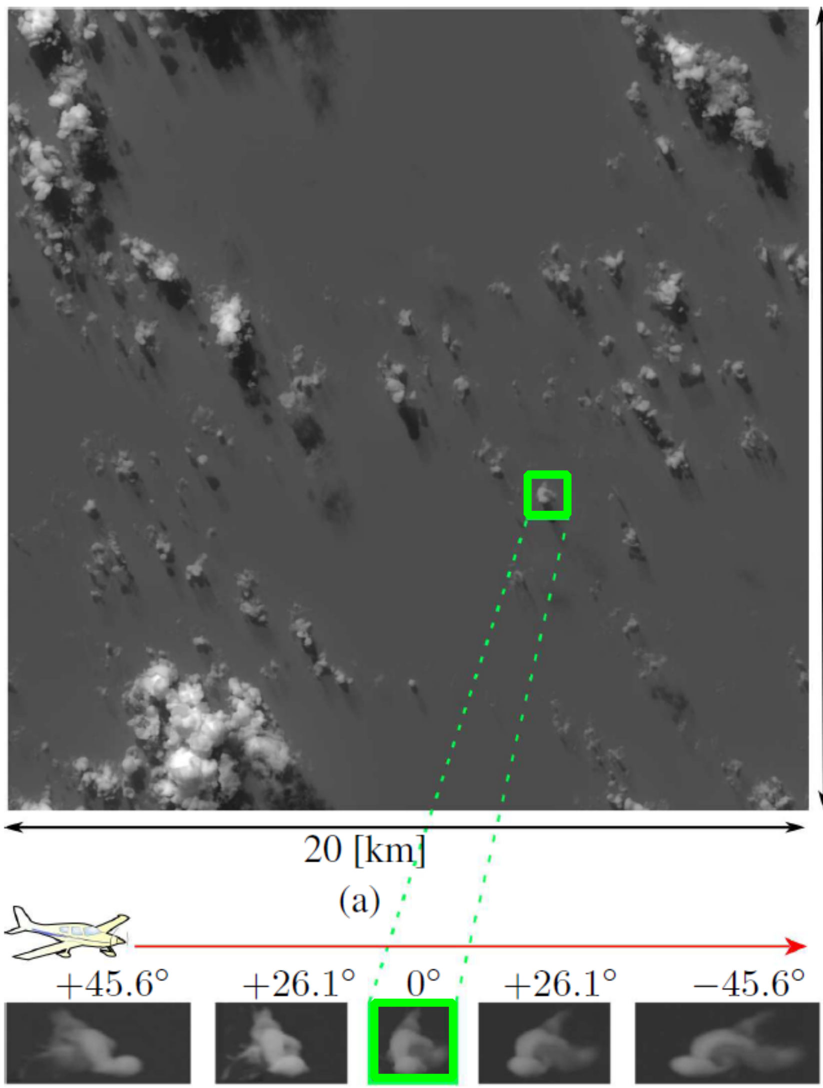
A. Levis, A. Aides, Y. Y. Schechner, and A. B. Davis, AIRBORNE THREE-DIMENSIONAL CLOUD TOMOGRAPHY. In *Proceedings of the IEEE International Conference on Computer Vision 2015 (ICCV15)*, pp. 3379-3387 (2015).

A. Levis, Y. Y. Schechner, and A. B. Davis, MULTIPLE-SCATTERING MICROPHYSICS TOMOGRAPHY. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR17)*, pp. 5797-5806 (2017).

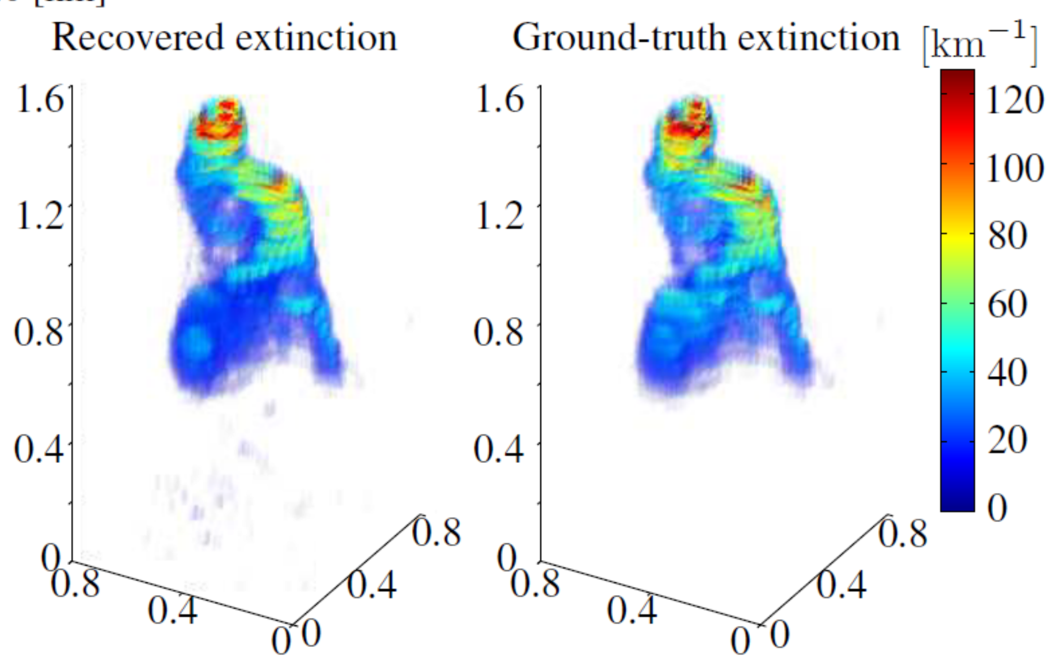
A. Levis, PhD Thesis, Technion, Haifa, Israel (in preparation).

Synthetic Data

LES+SHDOM generated cloud field



- 9 view angles: ±70.5°,±60.0°,±45.6°,±26.1°,0°
- Pixel resolution: 20 m
- SHDOM + photon & quantization noise
- Unknown extinction grid: (46,656 unknowns)



Synthetic Data

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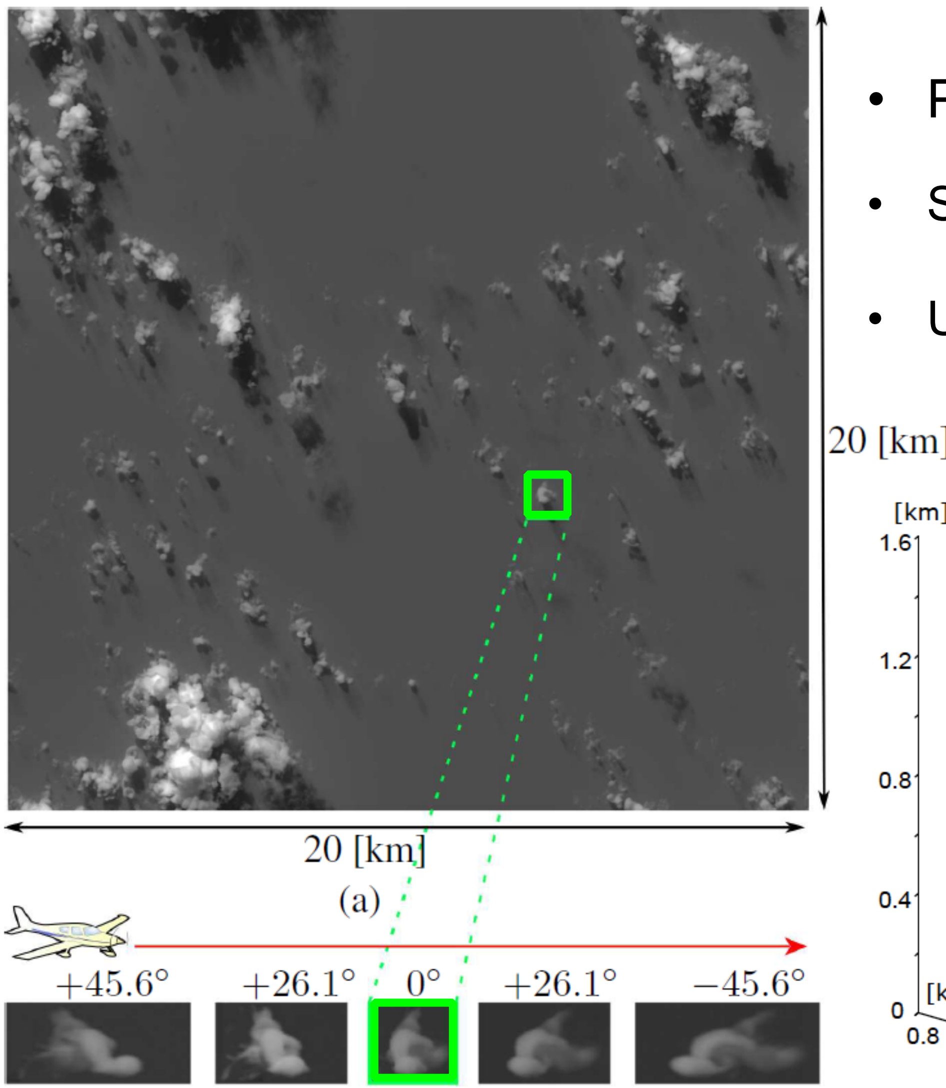

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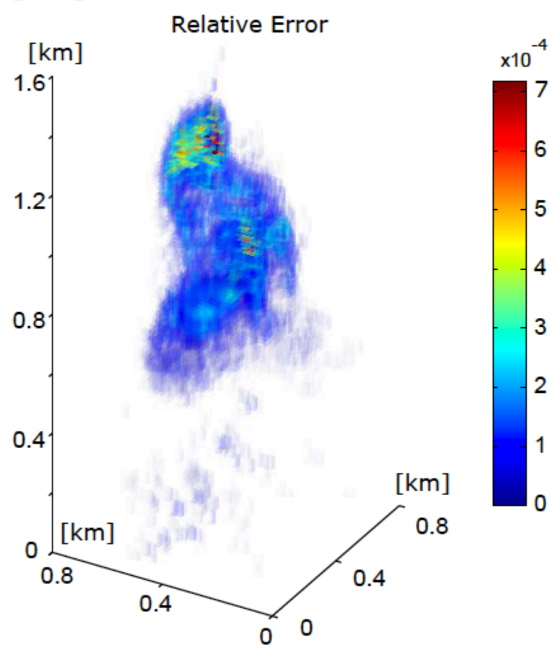
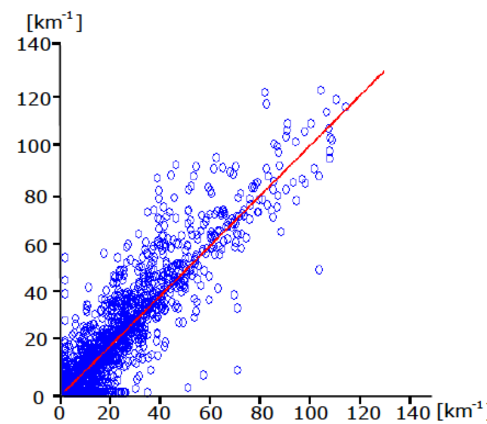


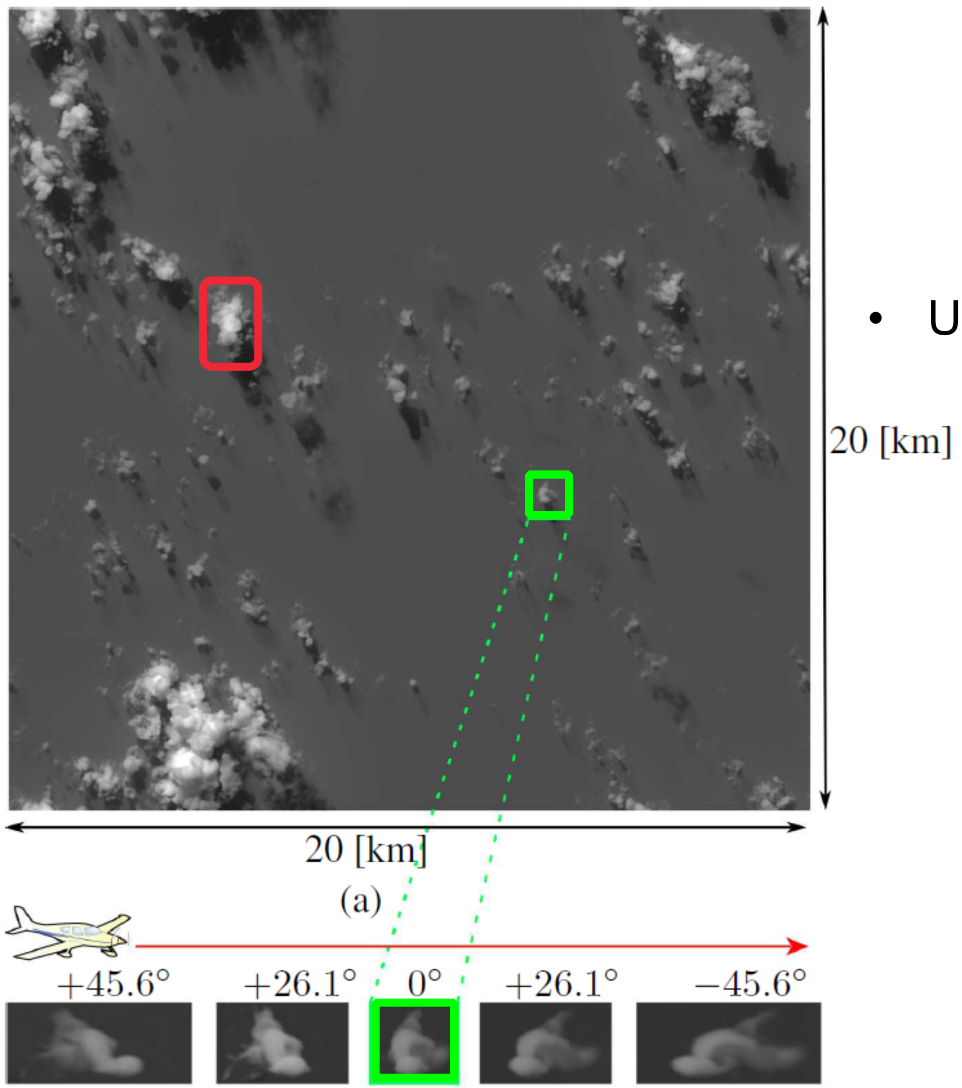
Correlation (R^2):
0.94

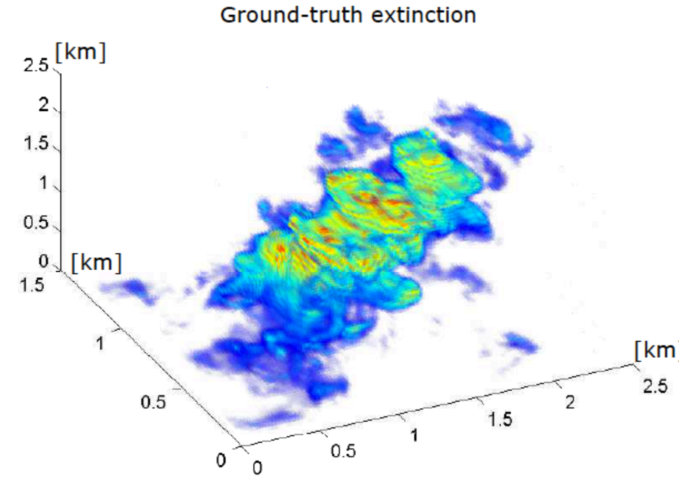


Errors: 5% on total mass; ±33% on local extinction.

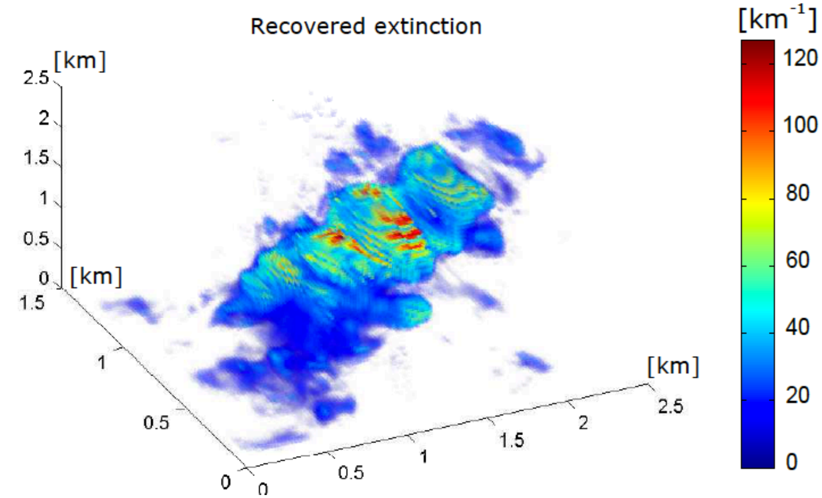
Synthetic Data

LES+SHDOM generated cloud field





- Unknown extinction grid: 66x111x43 (315,018 unknowns)



Errors:
30% on total mass;
±70% on local extinction.

Correlation (R^2): 0.76

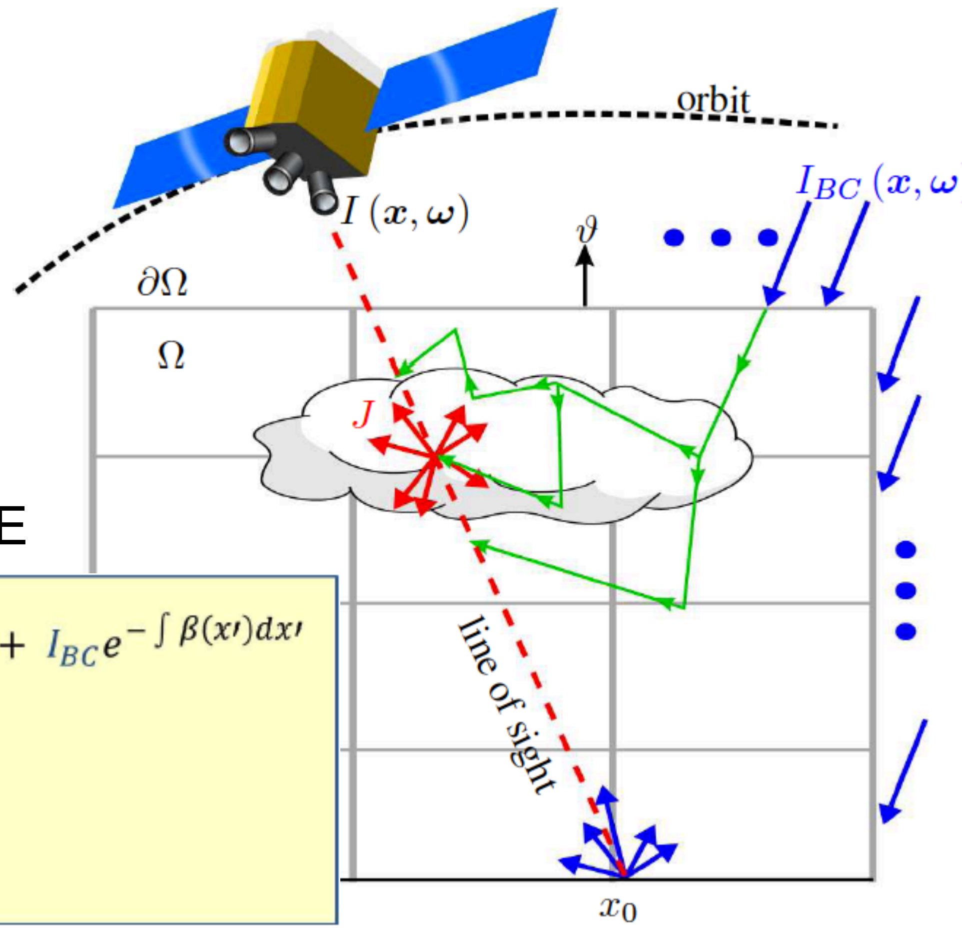
Fine-scale cloud tomography

Two-level iterative solution

🡇 "Formal" solution of 3D RTE

$$I(x,\omega) = \int J(x',\omega)\beta(x')\, e^{-\int \beta(r)dr} dx' + I_{BC} e^{-\int \beta(x')dx'}$$

$$J(x,\omega) = \frac{\varpi}{4\pi} \int_{S^2} p(x, \omega \cdot \omega') I(x,\omega') d\omega'$$

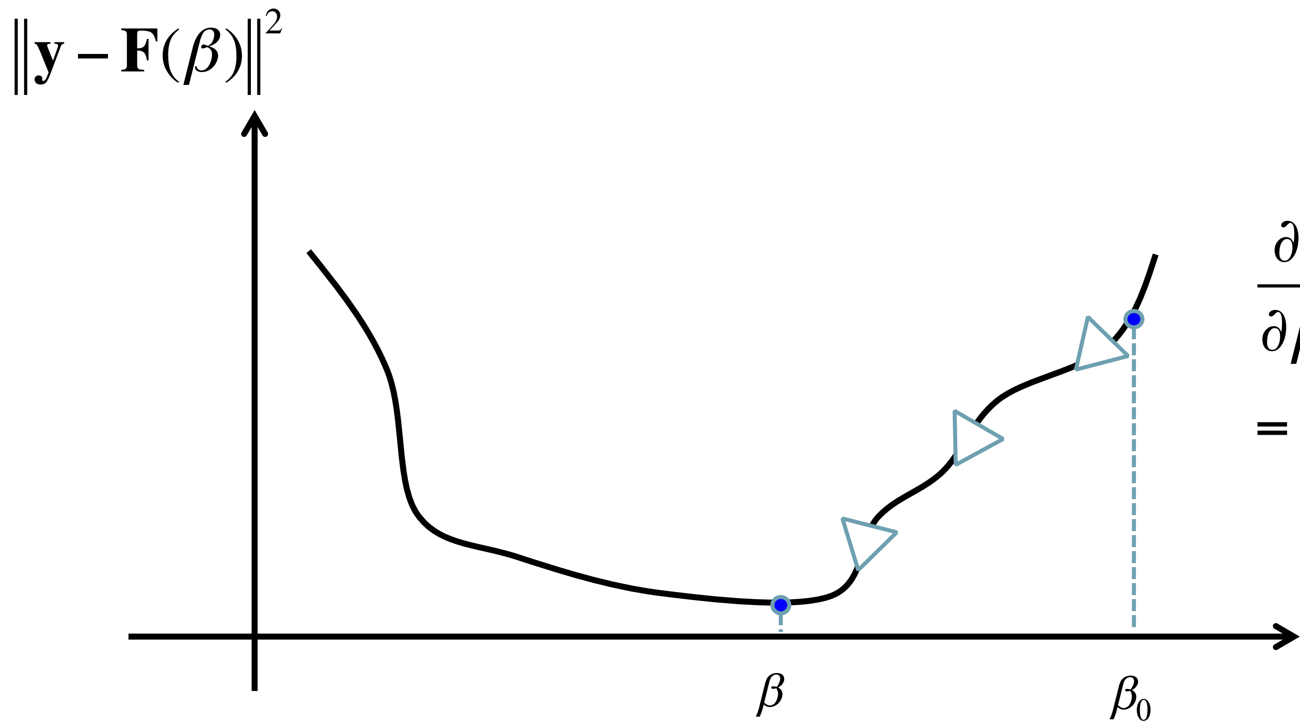


🡅 "Ancillary" integral RTE (solved with SHDOM)

Iterative multi-angle/multi-pixel algorithm

$$\beta_0 \longrightarrow \beta = \underset{\beta}{\operatorname{argmin}} \left\| \mathbf{y} - \mathbf{F}(\beta) \right\|^2$$

$$\begin{cases} \mathbf{F}(\beta) = I[\beta, J(\beta)] \text{ (formal solution)} \\ J(\beta) = \text{SHDOM}(\beta) \text{ (Picard iteration)} \end{cases}$$



$$\frac{\partial}{\partial \beta} \mathbf{F}(\beta, \text{SHDOM}(\beta))$$

$$= ???$$

Iterative multi-angle/multi-pixel algorithm

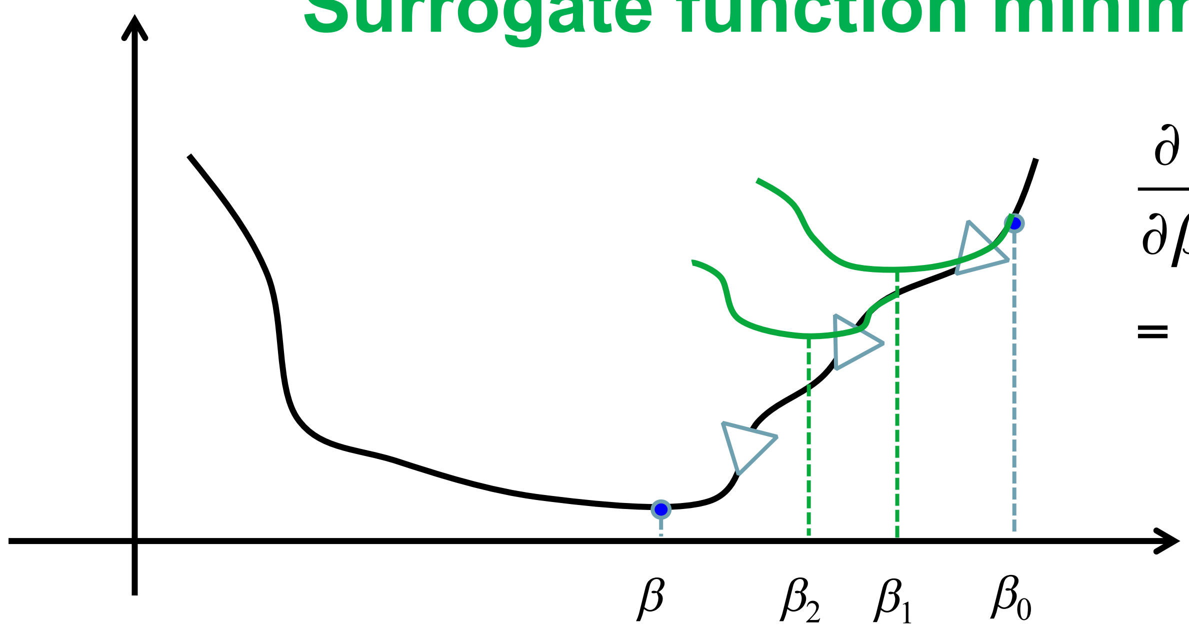
β_0 → $$\beta = \underset{\beta}{\operatorname{argmin}} \left\| \mathbf{y} - \mathbf{F}(\beta) \right\|^2$$

↑ ↓

$$\beta_{n+1} = \underset{\beta}{\operatorname{argmin}} \left\| \mathbf{y} - \mathbf{F}(\beta \mid J_n) \right\|^2$$

$$\mathbf{F}(\beta \mid J_n) = I[\beta, J(\beta_n)] \text{ (formal solution)}$$

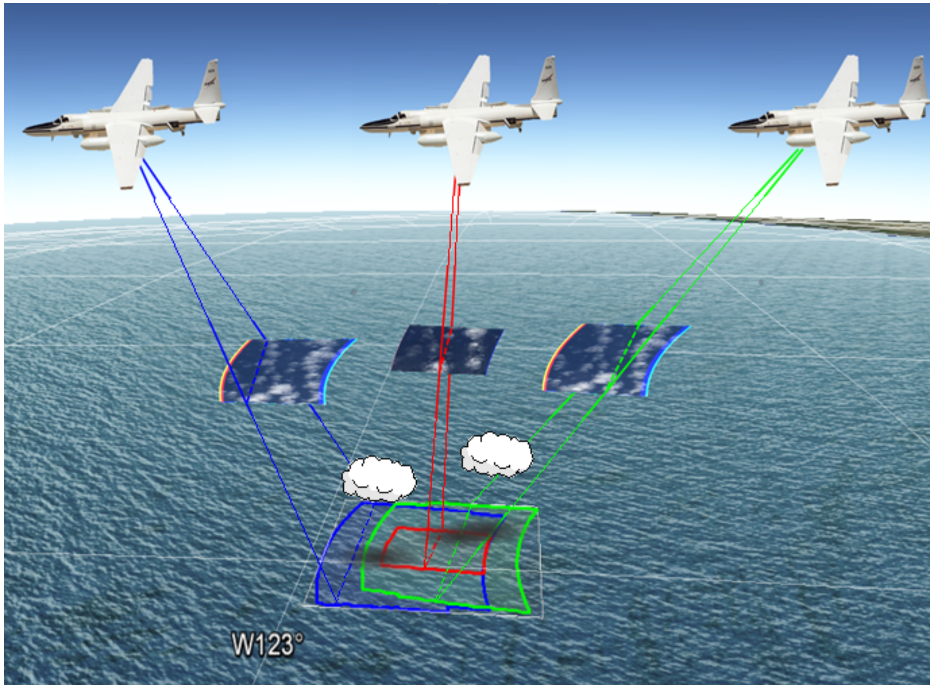
Surrogate function minimization

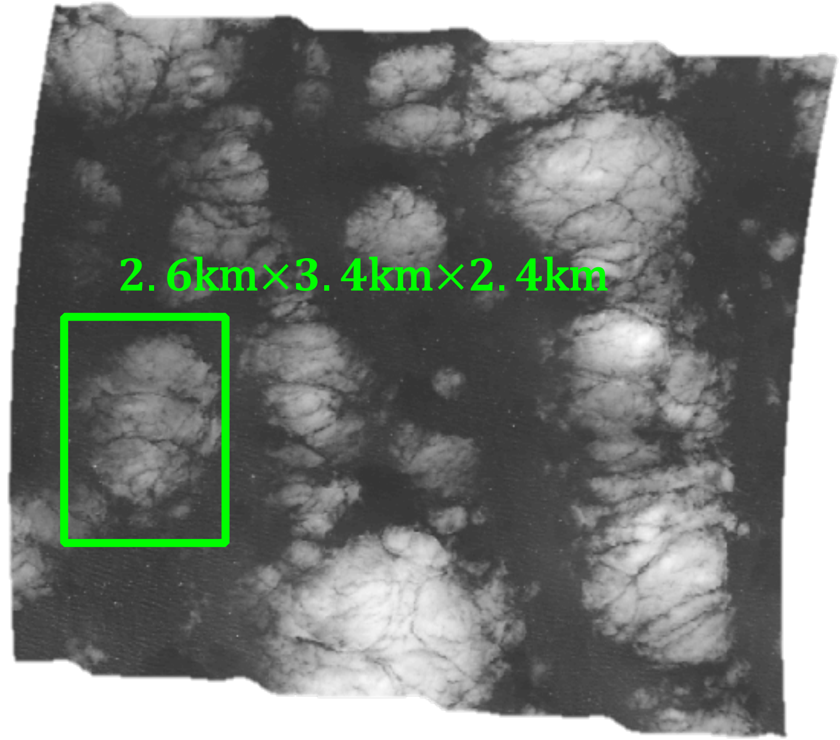


$$\frac{\partial}{\partial \beta} \mathbf{F}(\beta \mid J_n)$$

$=$ ✓

AirMSPI Data

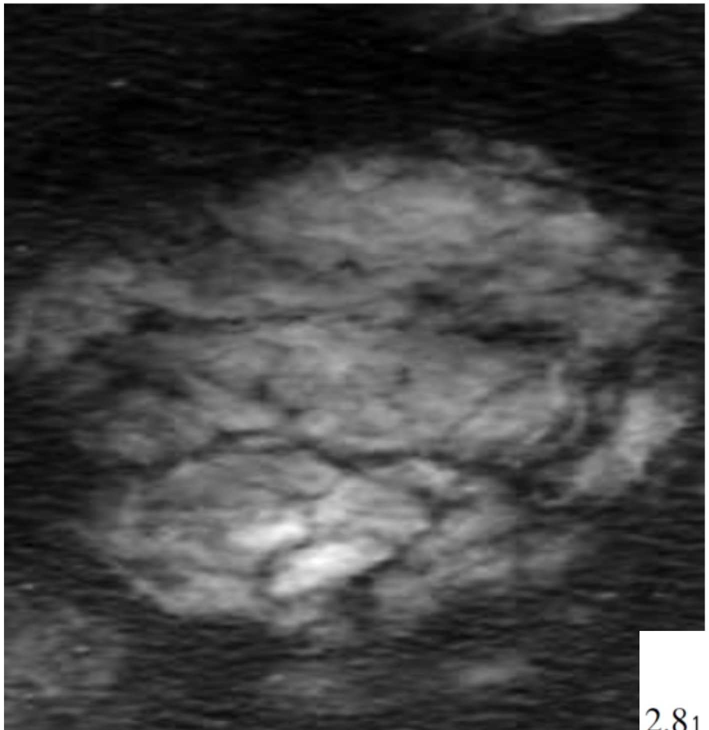




- 9 view angles: ±66.0°, ±58.9°, ±47.7°, ±29.0°, and 0°
- Pixel resolution: 10 m
- Extinction grid: 86,688 unknowns (at 60 m resolution)

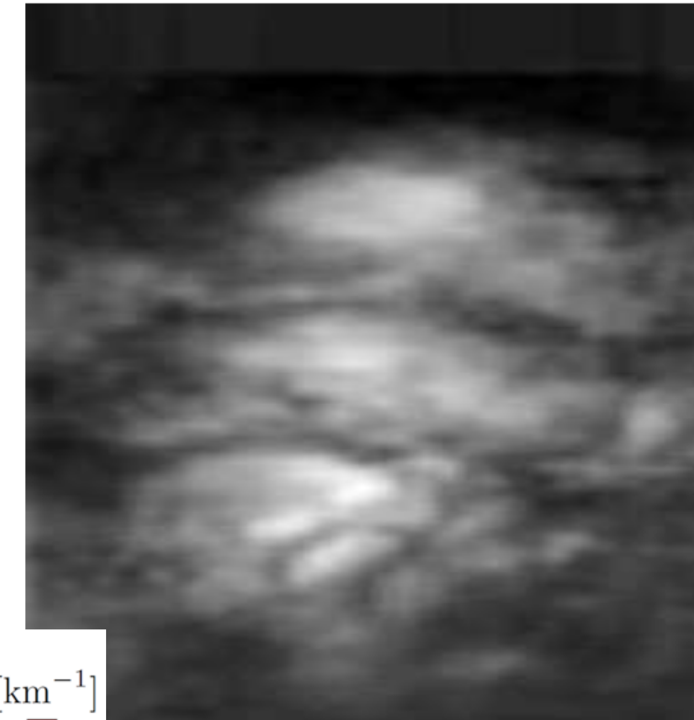
Radiance Domain Comparison

AirMSPI's nadir

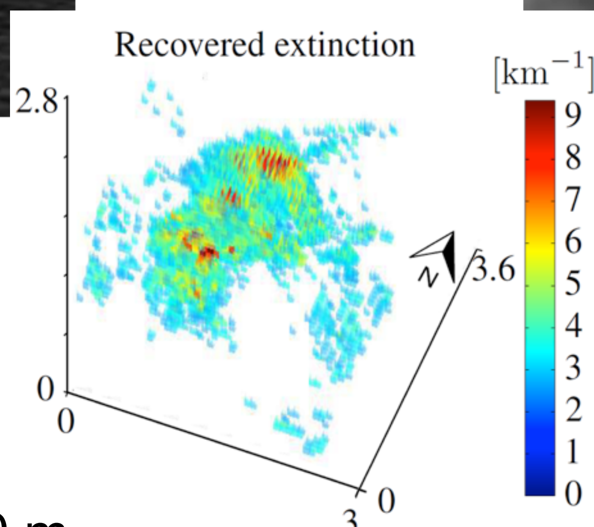


10 m resolution

SHDOM rendered nadir

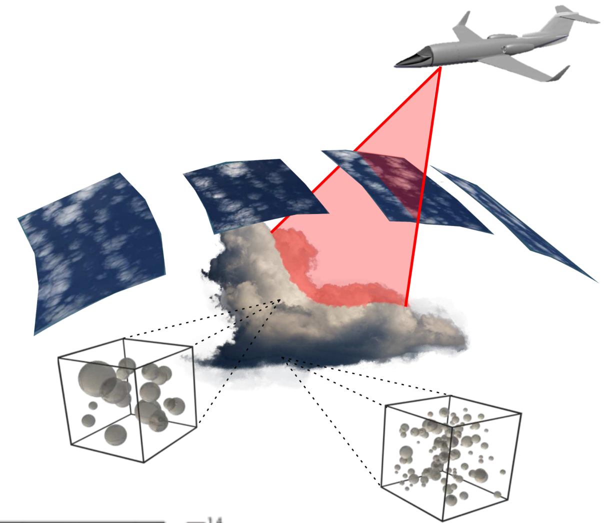


60 m resolution



- Cloud base at ~1.5 km
- Mean-free-path of ~100 m

… now relax the cloud microphysics (r_e,v_e):



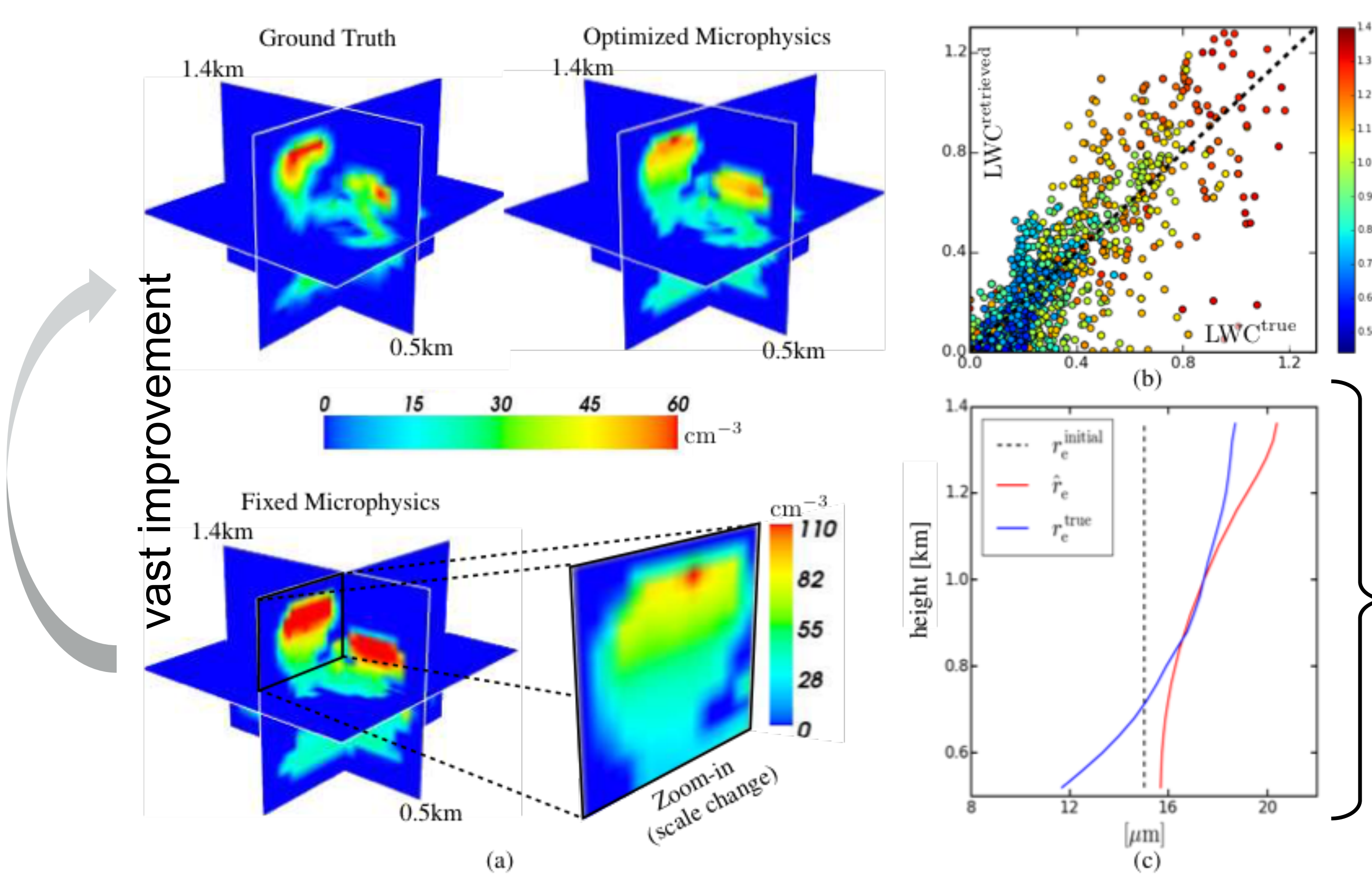
linearization of microphysics in the surrogate forward model

$$\frac{\partial n(r|\boldsymbol{\nu})}{\partial N} = C r^{(v_e^{-1}-3)} \exp\left(-\frac{r}{r_e v_e}\right),$$

$$\frac{\partial n(r|\boldsymbol{\nu})}{\partial r_e} = \frac{r + 2 r_e v_e - r_e}{r_e^2 v_e} n(r|\boldsymbol{\nu}),$$

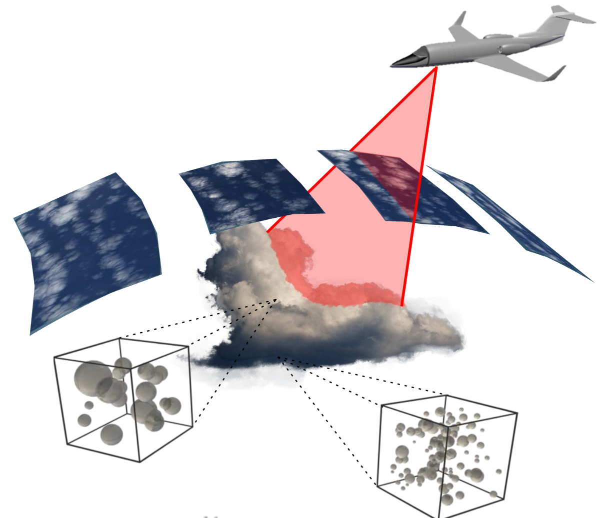
$$\frac{\partial n(r|\boldsymbol{\nu})}{\partial v_e} = \frac{\psi(\frac{1}{v_e}-2) - \log\frac{r}{r_e v_e} - 1 + 2 v_e + r r_e^{-1}}{v_e^2} n(r|\boldsymbol{\nu}).$$

Here $\psi = \mathrm{d}\log\Gamma(x)/\mathrm{d}x$ is the *digamma* function.



microphysical variability is constrained to the vertical, and regularized (required to be smooth)

… now relax the cloud microphysics (r_e, v_e):



linearization of microphysics in the surrogate forward model

$$\begin{cases} \dfrac{\partial n(r|\boldsymbol{\nu})}{\partial N} = C r^{(v_e^{-1}-3)} \exp\left(-\dfrac{r}{r_e v_e}\right), \\ \dfrac{\partial n(r|\boldsymbol{\nu})}{\partial r_e} = \dfrac{r+2r_e v_e - r_e}{r_e^2 v_e} n(r|\boldsymbol{\nu}), \\ \dfrac{\partial n(r|\boldsymbol{\nu})}{\partial v_e} = \dfrac{\psi(\frac{1}{v_e}-2) - \log\frac{r}{r_e v_e} - 1 + 2v_e + r r_e^{-1}}{v_e^2} n(r|\boldsymbol{\nu}). \end{cases}$$

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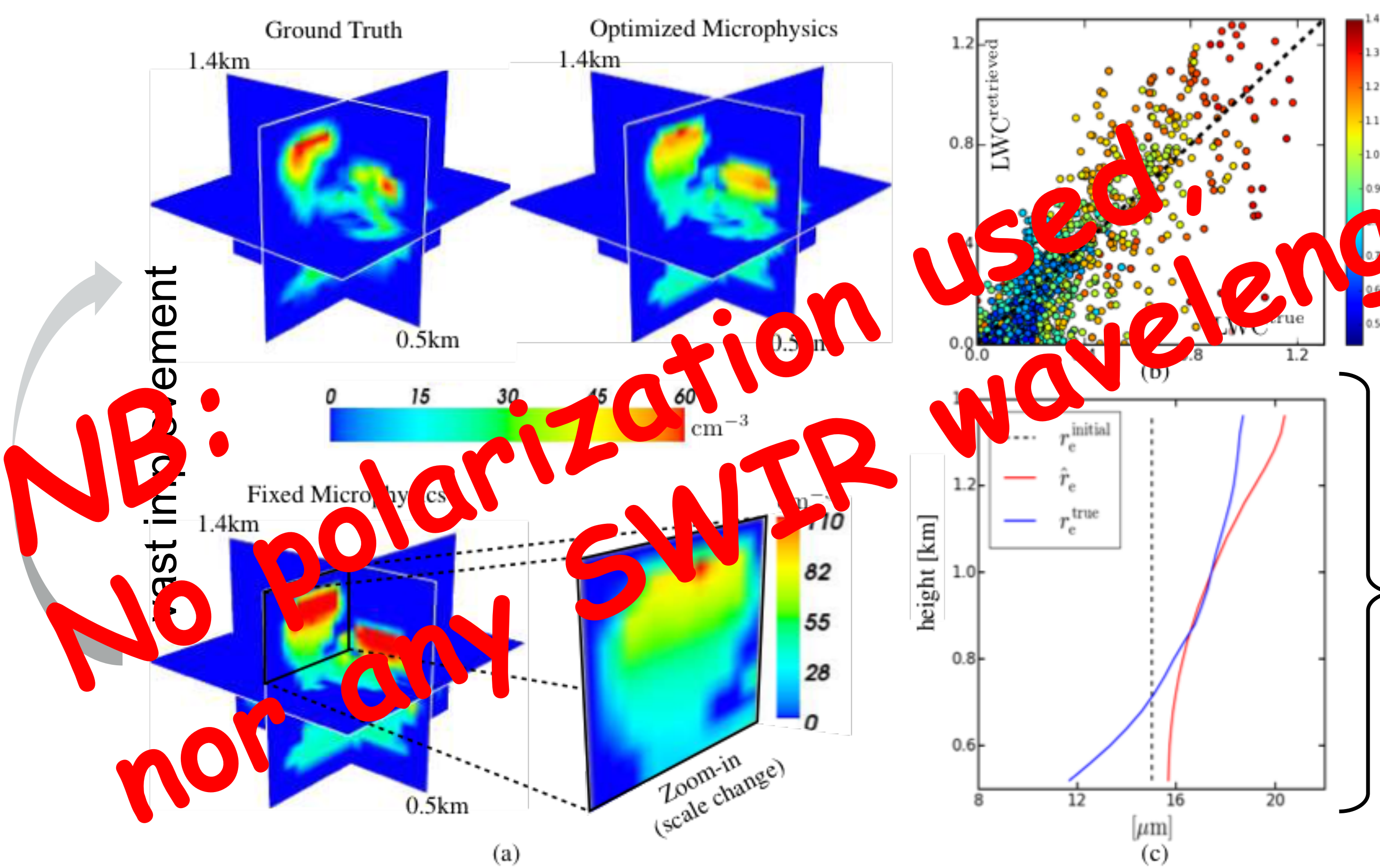


microphysical variability is constrained to the vertical, and regularized (required to be smooth)

NB: No polarization used, nor any SWIR wavelengths!

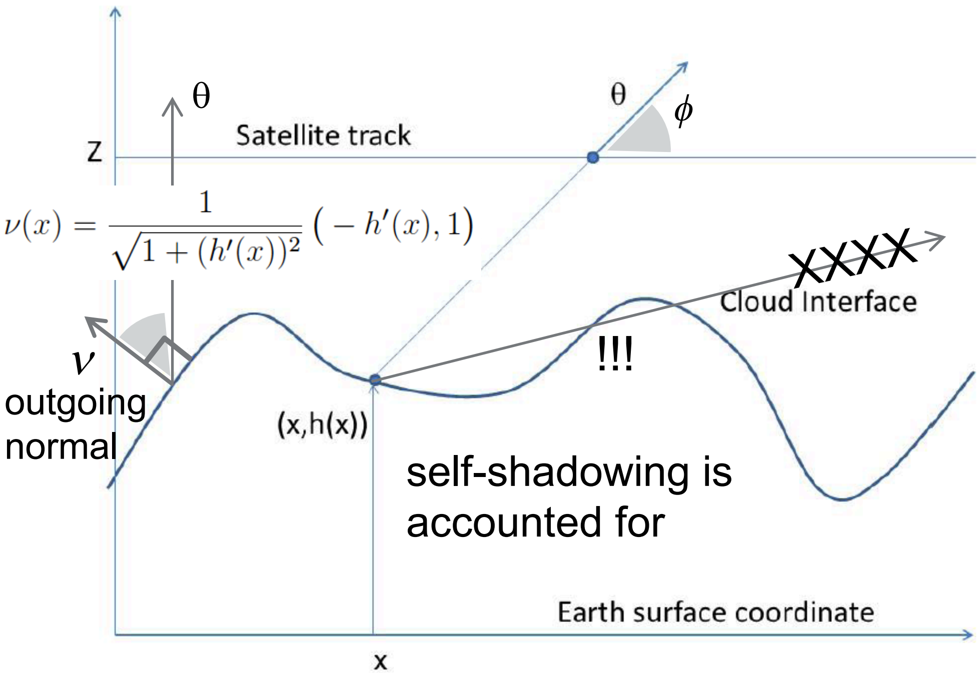
Conclusions/outlook

- **Accurate and <u>practical</u> 3D RT-based cloud tomography (multi-angle/multi-pixel reconstruction) demonstrated** on
  – Synthetic data (known truth ➔ rigorous error quantification)
    - Large-Eddy Simulation clouds, then Monte Carlo 3D RT
  – Real-world data from AirMSPI
    - Now: seeking relevant validation data in field campaign collections
- **Initialization**
  – Previously: no cloud!
  – Currently: “space carving”
  – Next: see “Columbia” approach, and beyond?
- **Regularization**
  – Previously: none!
  – Currently: only for microphysical profile
  – Next: enforce fractal cloud structure?

Progress at Columbia

G. Bal, J. Chen, and A. B. Davis, Reconstruction of cloud geometry from high-resolution multi-angle images, *Inverse Problems in Imaging* (2018, in press).

Problem:
Retrieve External Cloud Shape



Super-simple (radiosity-like) 2D RT:

$$\theta \cdot \nabla u(x, z, \theta) = 0$$

Forward model:

$$u(x, h(x), \theta) = \underbrace{\alpha(x)}_{\text{local outgoing flux}} \underbrace{\beta(\overbrace{\phi - \arctan h'(x)}^{\cos^{-1}(\theta(\phi)\cdot\nu(x))})}_{\text{global angular distribution model}}$$

local outgoing flux — global angular distribution model

Main results

- **Analytical "Fréchet" derivatives:** $\frac{\delta u}{\delta \alpha}, \frac{\delta u}{\delta \beta}$
- **Insights**
  - Failure anticipated in 2 situations:
    1. $h''(x) = 0$, i.e., inflexion points (incl. flat surface!)
       - fixed by regularization of the cost function
    2. $H'(\theta \cdot v) \equiv 0$, i.e., Lambertian cloud-leaving radiance
- **Numerical experiments**
  - 3 unknown functions + a few unknown numbers
  - Increasing complexity …

Numerical experiments, 1

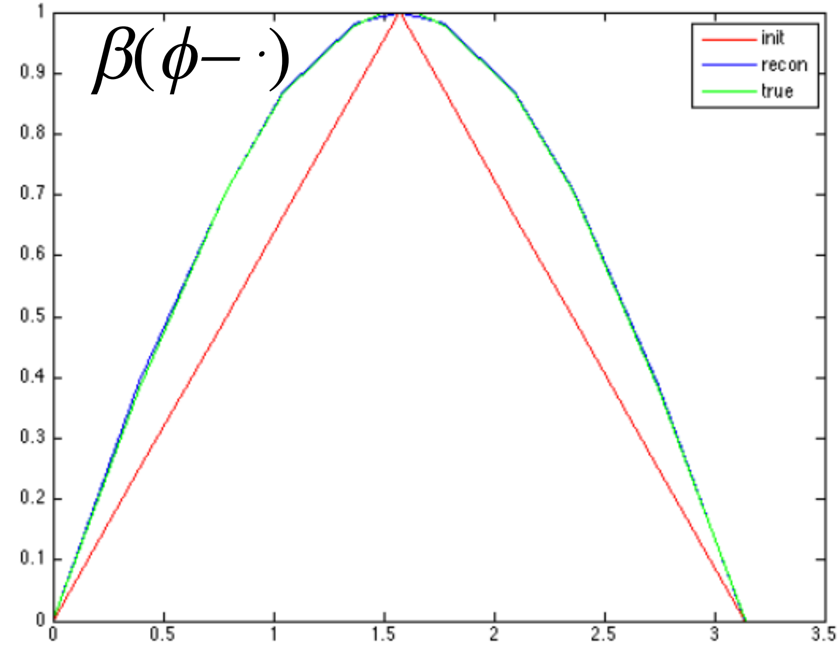
Data:

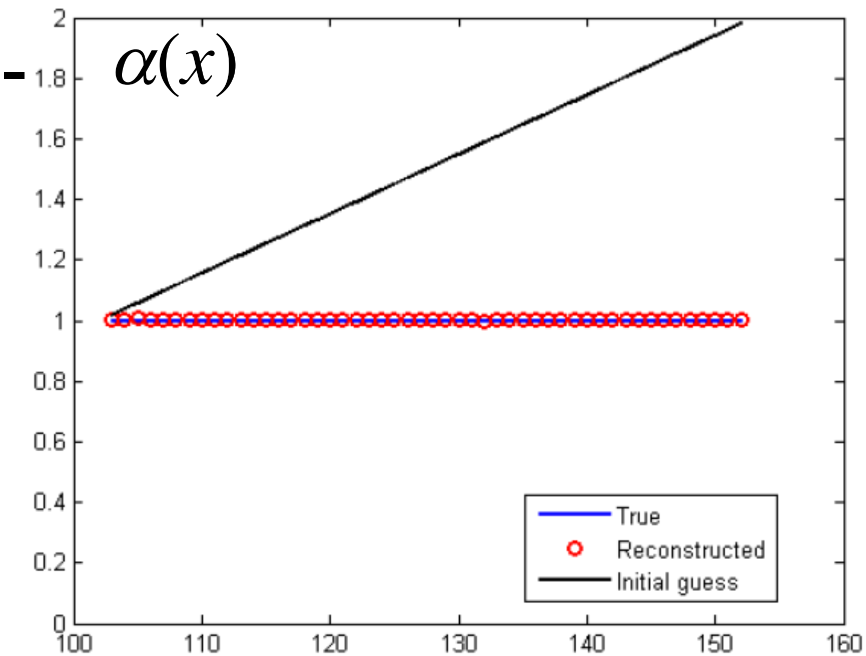
9 angles (MISR values)

51 grid points (pixels)

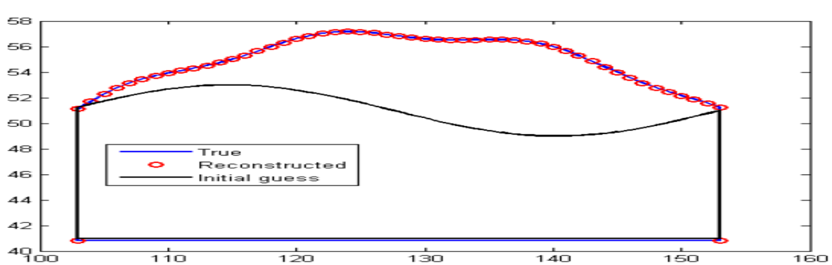
Easy case:

- Chandrasekhar *H* function-like angular model $\beta(\phi - \cdot)$
- Smooth boundary $h(x)$
- Uniform emittance $\alpha(x)$





$h(x)$



Numerical experiments, 2

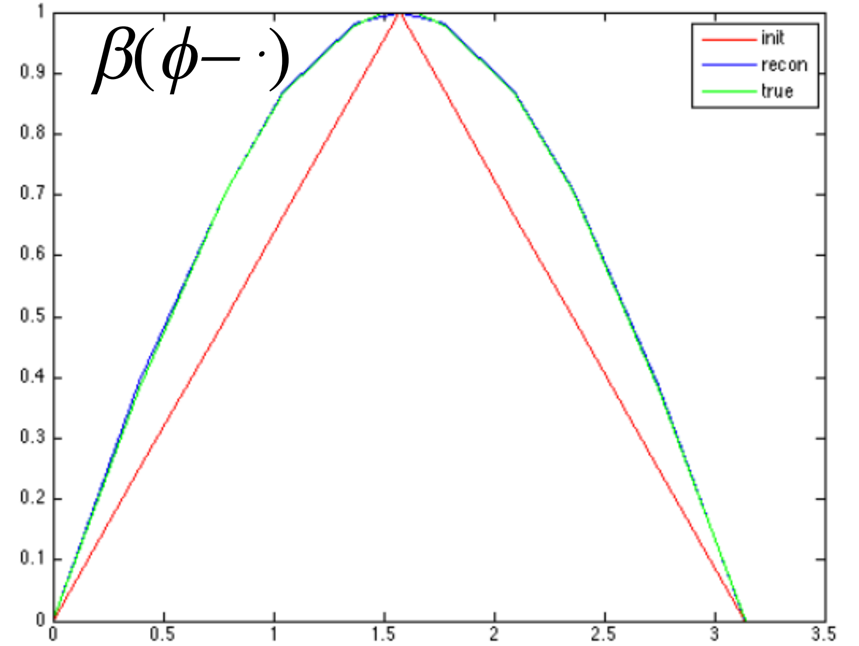
Data:

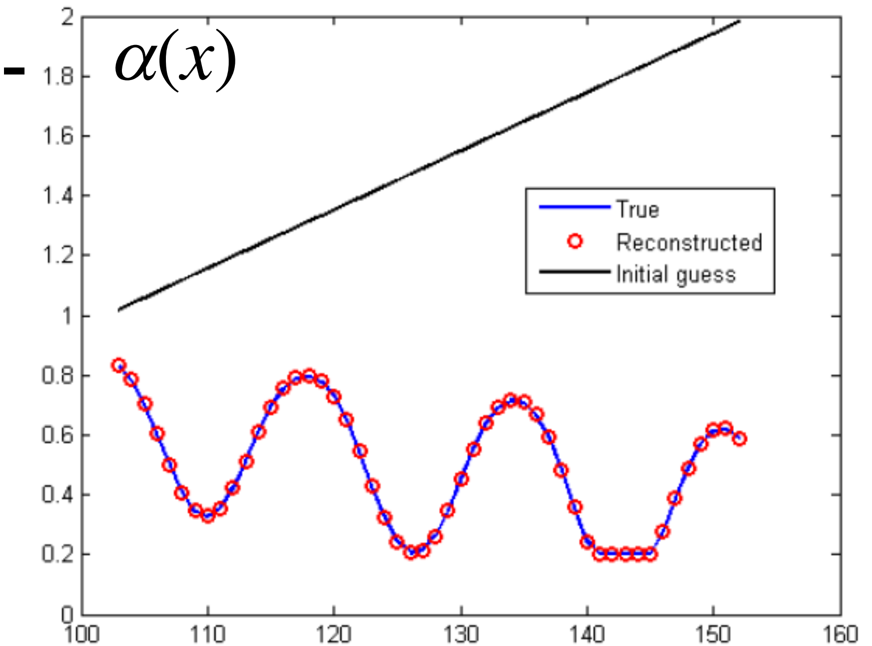
9 angles (MISR values)

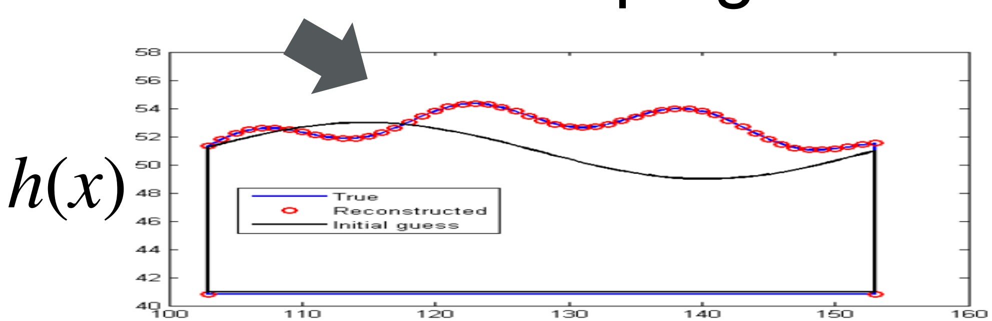
51 grid points (pixels)

Tougher case:

- Chandrasekhar *H* function-like angular model (same)
- More curvy boundary
- Solar-like escaping fluxes







Numerical experiments, 3

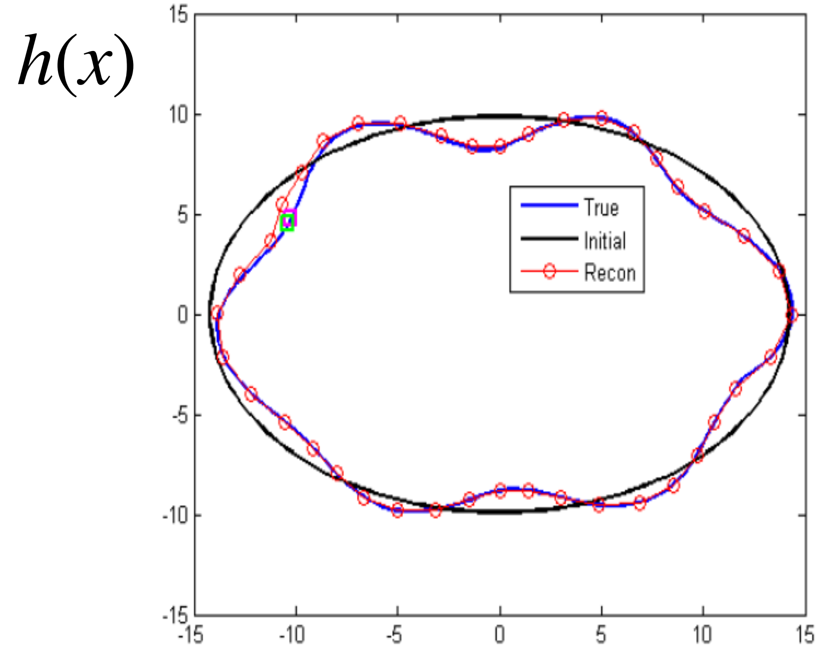
Data:

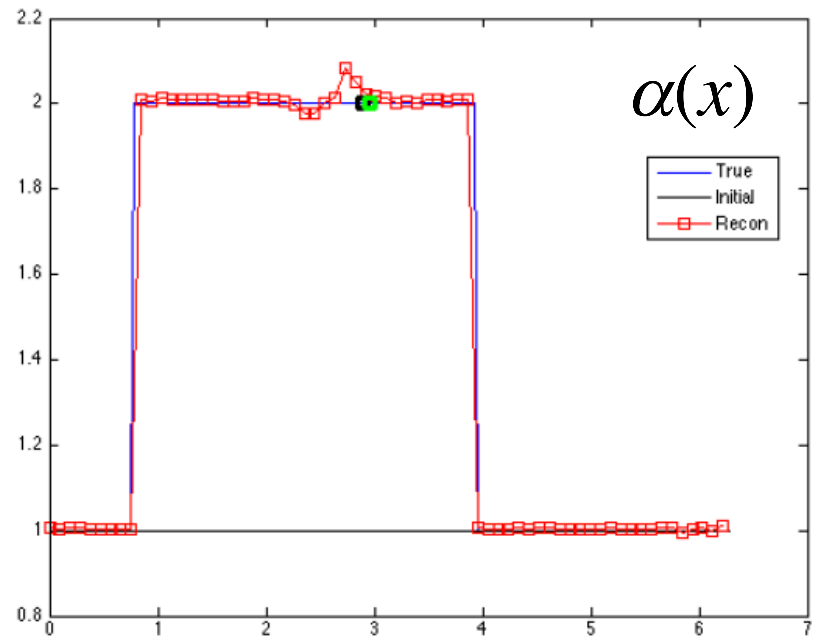
11 angles

201 points

Problematic case:

- Chandrasekhar *H* function-like angular model (same)
- Curvy boundary expressed in polar coordinates
- Step function fluxes





Summary/outlook

- **Outer cloud shape reconstruction demonstrated**
- ***However,* for the moment, the "inverse crime" is committed: data is obtained from forward model!**
  - **not even instrument noise was added**
- ***Worse,* the boundary is assumed to be smooth: hence, derivatives exist!**
  - **Real clouds are fractal-shaped. So, at best, a smooth approximation will be delivered at the scale of the pixels in the real-world observations.**
- **Present demo assumes *high spatial resolution***
  - **more like an airborne than space-based sensor**

Progress at JPL

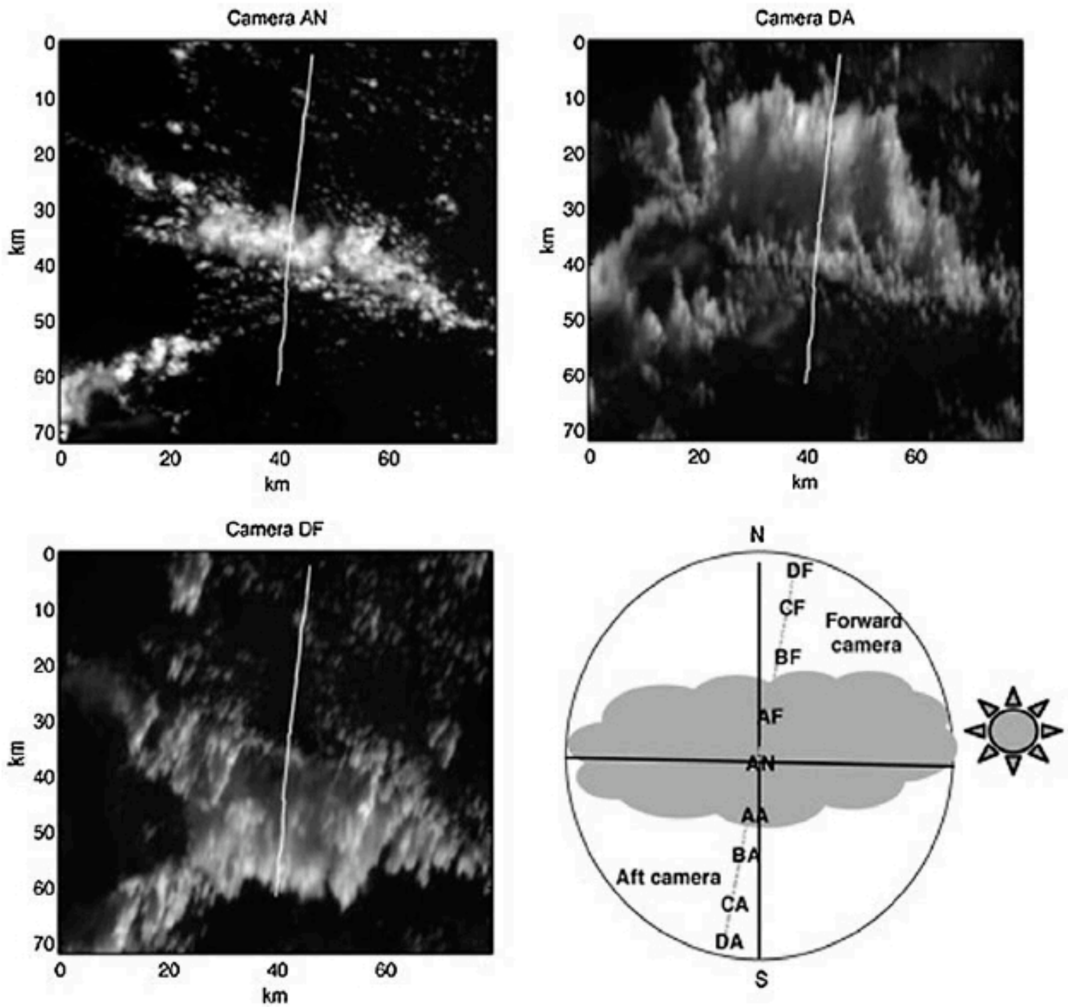
ROSES Terra-Aqua-Soumi/NPP proposal

Addressing cloud-related climate challenges with LES cloud- process models, data from MISR and MODIS, and novel re- construction techniques for 3D convective clouds

selected for funding. ☺

… for using fused MISR/Terra's multi-angle VIS (red channel, 275 m pixels) and MODIS/Terra's mono-angle SWIR (500 m pixels) to extend Technion cloud tomography methodology from airborne to space-based sensors.

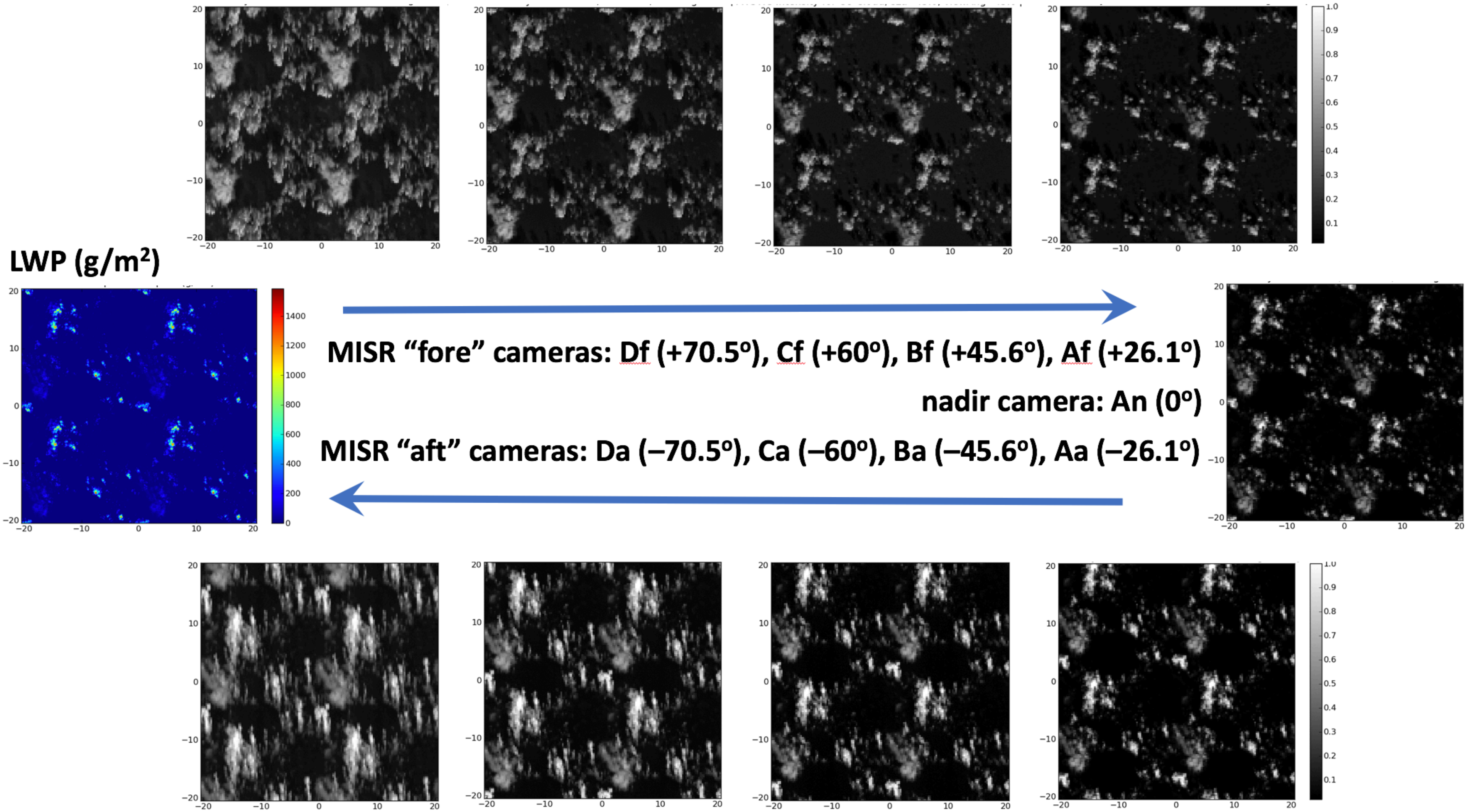
Targeted "case study" …



Seiz, G., and R. Davies, Reconstruction of cloud geometry from multi-view satellite images. *Remote Sens. Environ.*, **100**, 143-149 (2006).

Cornet, C., and R. Davies, Use of MISR measurements to study the radiative transfer of an isolated convective cloud: Implications for cloud optical thickness retrieval, *J. Geophys. Res.*, **113**, D04202 (2008).

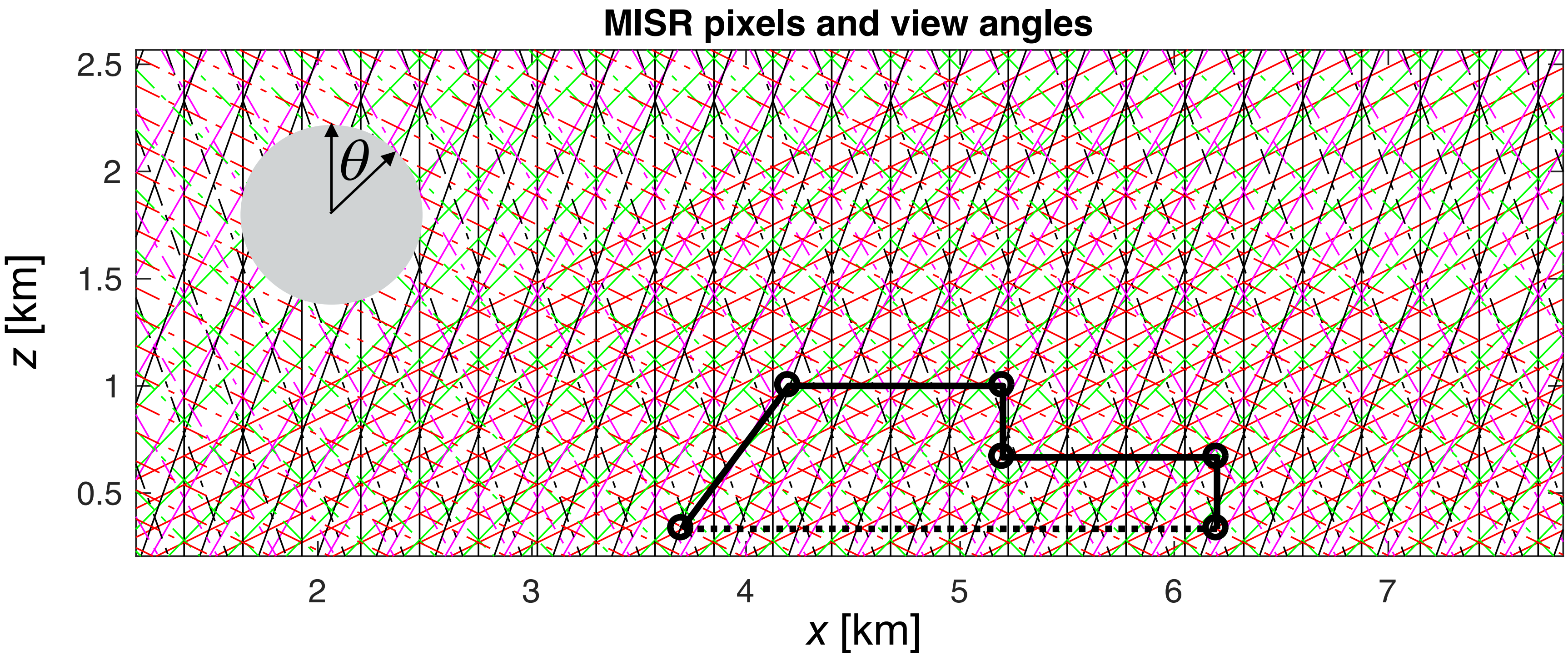
Error quantification based on LES cloud scenes:



Major challenges going from AirMSPI's fine-scale to coarser MISR+MODIS data:

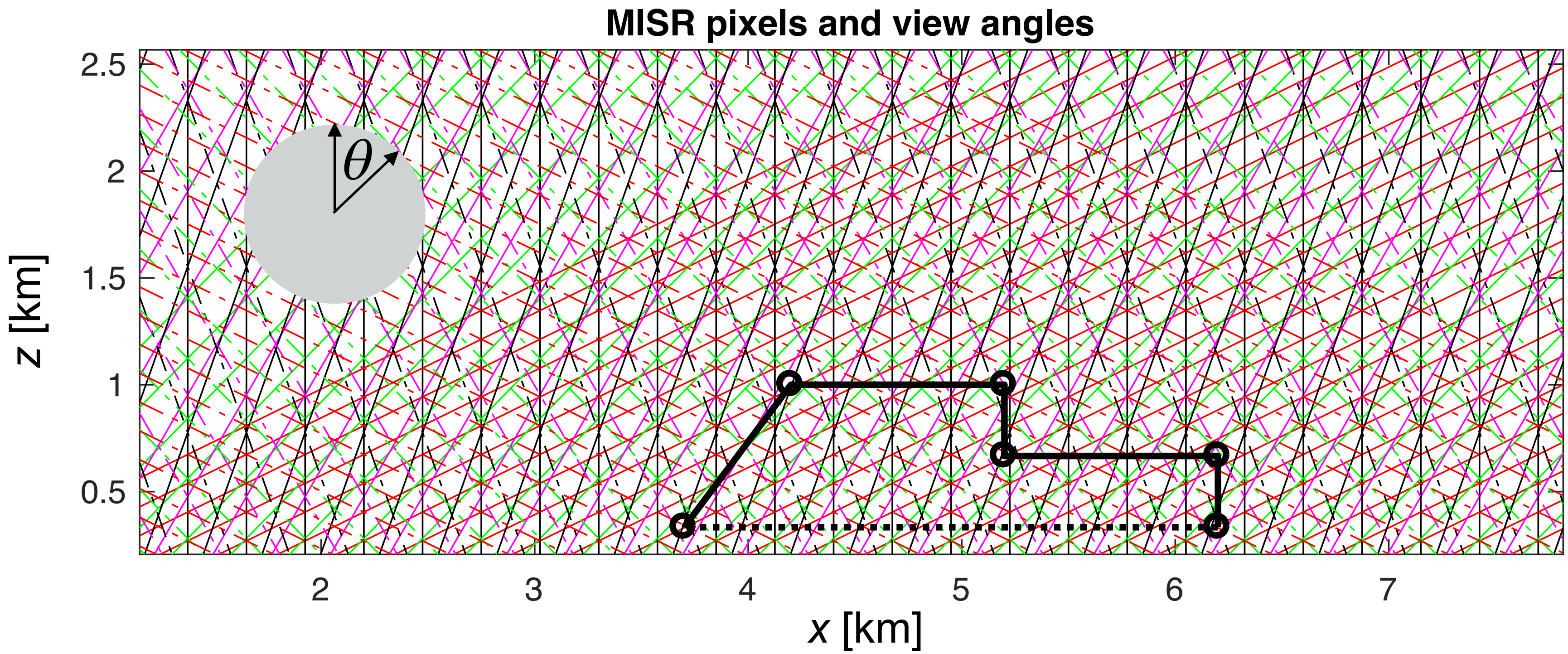
- **Forward modeling**
  - *Pixels—hence voxels—are much bigger.*
    - They are opaque: very bad for SHDOM!
    - They will have copious sub-pixel variability.
- **Inverse problem solution**
  - How to inform forward model about the "optically deep" zone, not worth computing in great detail?
  - How to harmonize reconstruction with "information value" of data? From there, how to bring the computational effort to the appropriate level?
- **ROSES/TASNPP proposal says …**
  - Implement Monte Carlo or hybrid 3D RT
  - Use some form of data-driven regularizaton

First, we revisit the outer shape reconstruction ("Columbia" approach), for the initial guess.



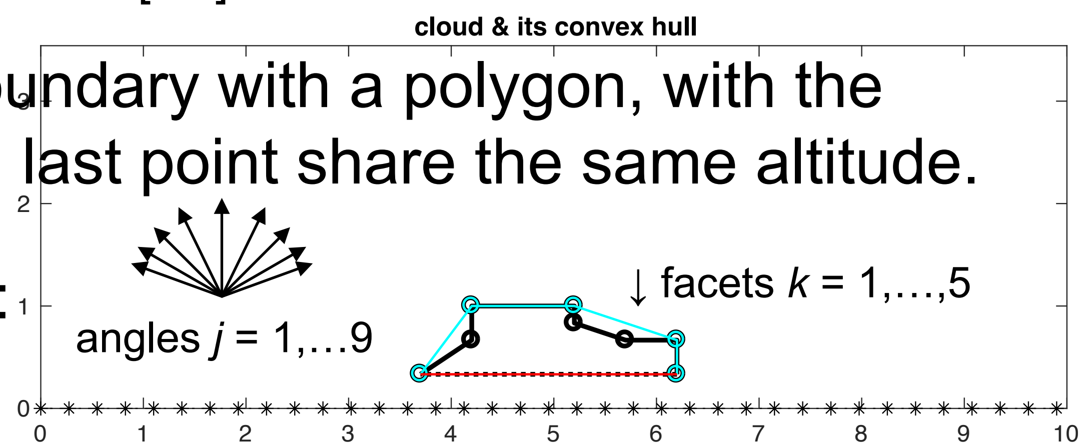
Represent outer cloud boundary with a polygon, with the constraint that the 1st and last point share the same altitude.

First, we revisit the outer shape reconstruction ("Columbia" approach), for the initial guess.



Represent outer cloud boundary with a polygon, with the constraint that the 1st and last point share the same altitude.

Start with *convex* shapes:



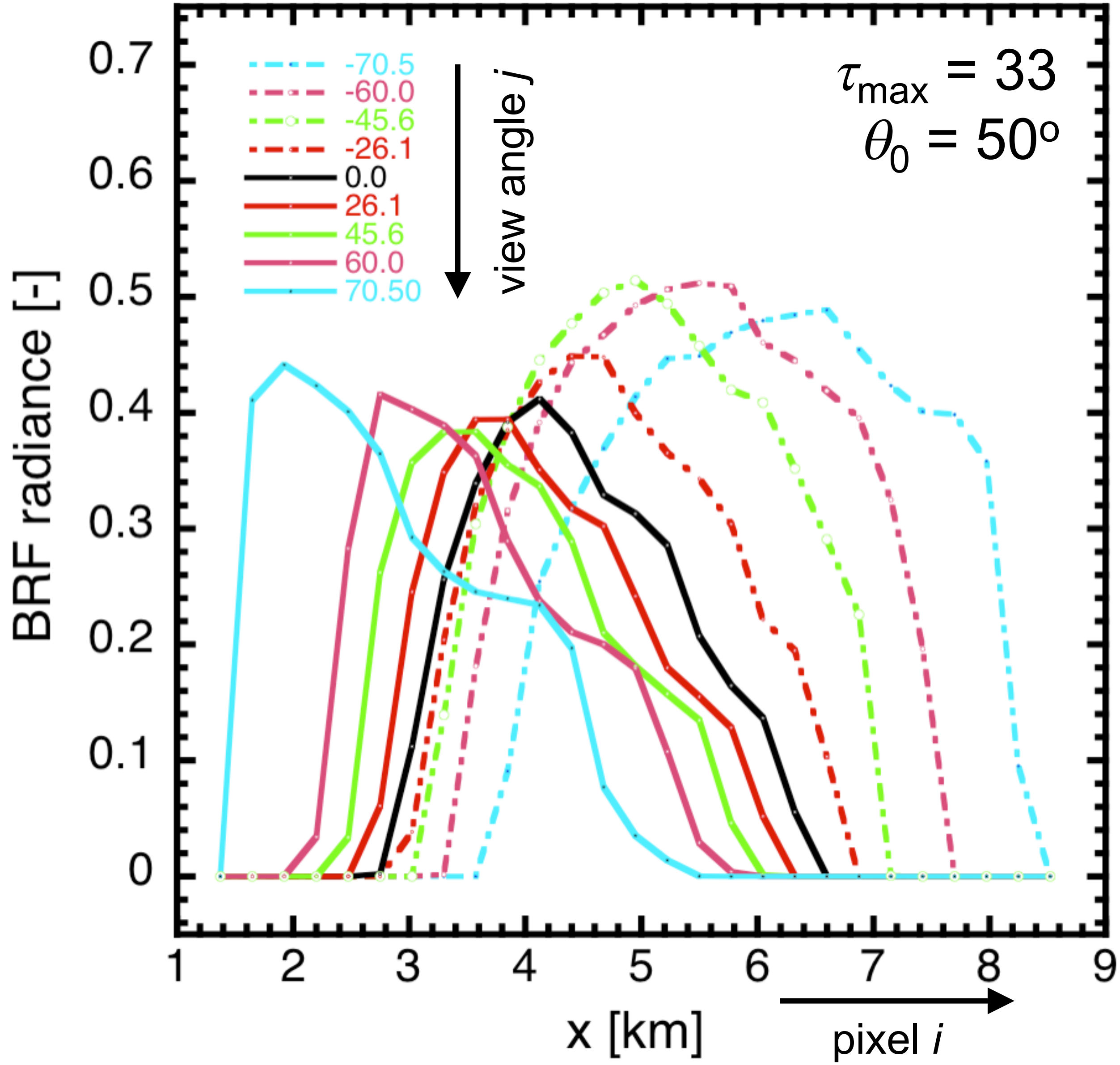
pixels *i* = 1, 37 →

… and upgrade the synthetic data model (that is, no more "inverse crime" committed).

Developed a custom forward 2D Monte Carlo code for convex polygon-shaped "clouds:"

* 9 MISR views simultaneously, via local estimation

* Triple Henyey-Greenstein phase function to mimic the famous "C1"



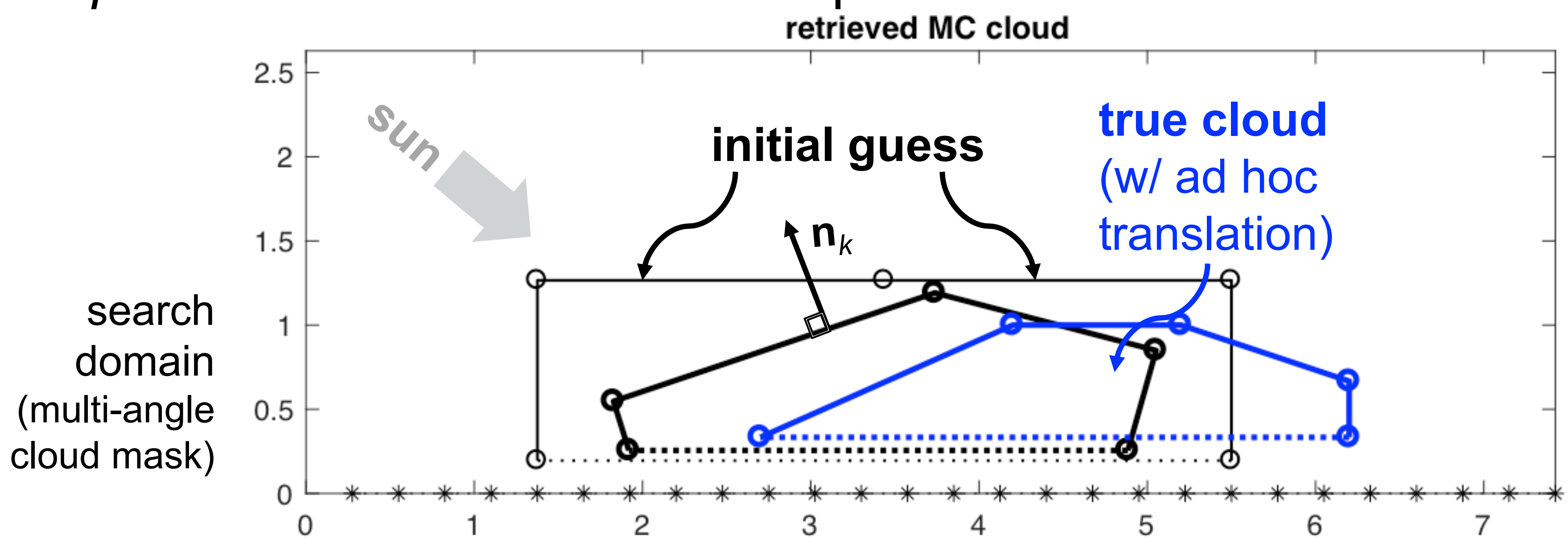
Use MatLab™'s Optimization Toolbox to fit Monte Carlo data with the simple forward radiosity model.

$\text{radiance}_{jk} = f_j * (\max\{\mathbf{n}_k{\cdot}\omega_j, \rho\}),\ j = 1,\ldots,9$ (10 parameters)

$$\text{rad}_j\_\text{pixel}_i = \sum_{\text{facet}_k \text{ in view}_j} \text{weight}_{ik} * \text{radiance}_{jk}$$

with $\sum_{\text{facet}_k \text{ in view}_j} \text{weight}_{ik} \leq 1$, for any pixel i (< at edge) and view j

→ *lsqnonlin* "out of the box" on 20 parameter inversion …



Summary/outlook

- **Outer cloud shape reconstructed … well enough for the present purposes ... and very fast.**
- **What purposes?**
  - 1st guess for full 3D tomographic cloud reconstruction
  - improvement of near-cloud retrievals affected by clouds
    - Aerosols
    - Trace gases
    - Surface fluxes
- **Next?**
  - 2D→3D (segments → facets/triangulation)
  - non-convex shapes
  - apply to MISR “test case”
  - write/submit paper to MISR special issue in Remote Sensing