Multi-angle/multi-spectral/multi-pixel remote sensing of 3D convectively-driven clouds with MISR and MODIS

A Progress Report for ROSES/TASNPP

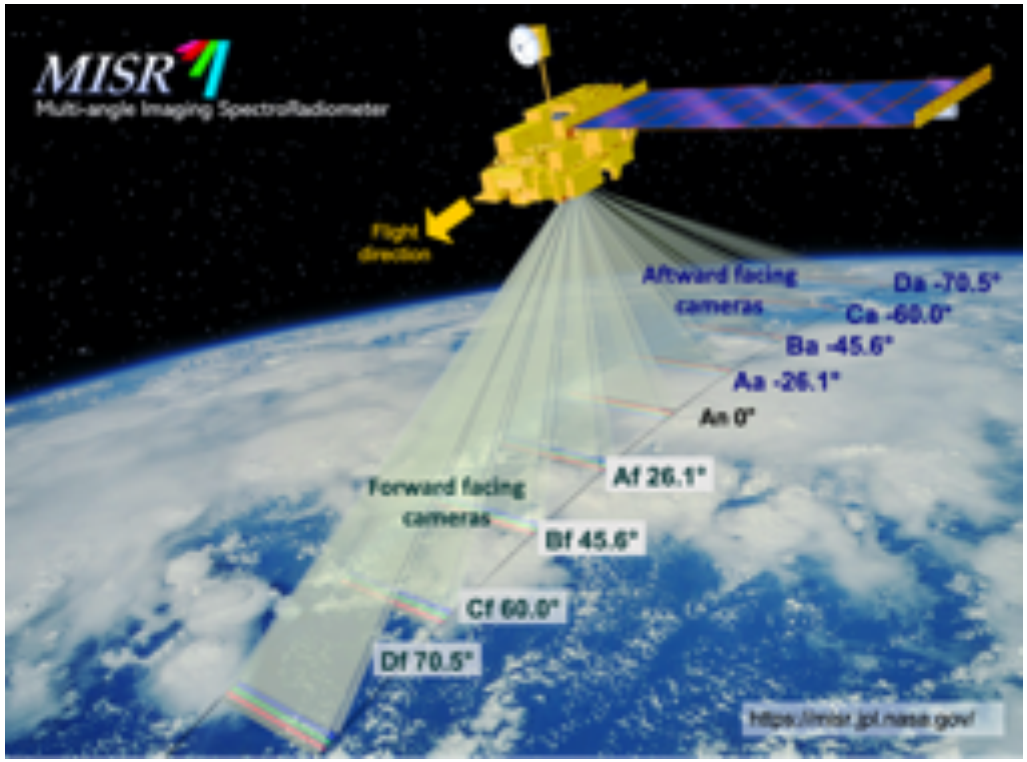
Anthony B. Davis (PI), Linda Forster, Marcin J. Kurowski, and David J. Diner (JPL);

Aviad Levis (Caltech); Jesse Loveridge (UI–UC); Yoav Y. Schechner (Technion);
Bernhard Mayer (LMU)

Jet Propulsion Laboratory
California Institute of Technology

Multi-angle Imaging Spectro-Radiometer (MISR) with MODIS, on Terra

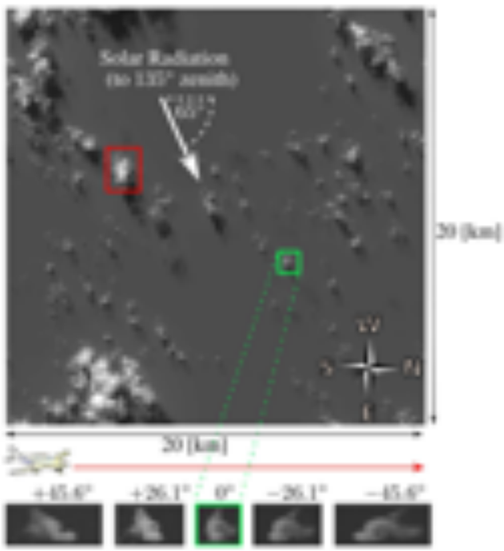
L2 aerosol products:
R.A. Kahn
(now at NASA-GSFC),
D.J. Diner,
J.V. Martonchik,
O.V. Kalashnikova,
M.J. Garay,
M.L. Witek,
et al.

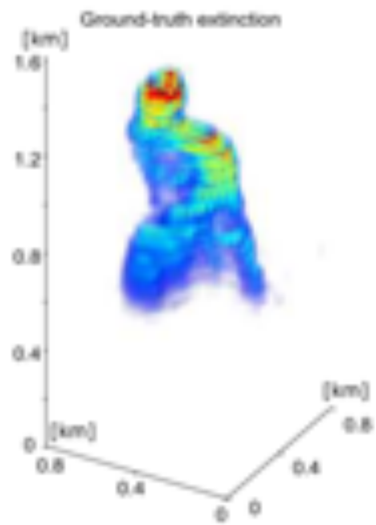


L2 cloud products:
R. Davies
(now at U of Auckland),
D.J. Diner,
V.M. Jovanovic,
C.M. Moroney,
M.J. Garay,
K.J. Mueller,
et al.

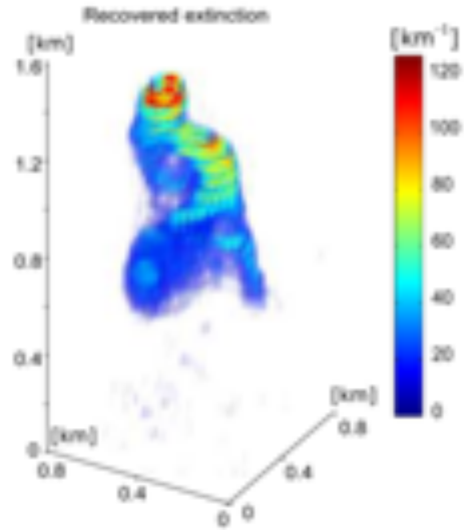
- push-broom acquisition, ~400 km swath
- 4 spectral channels, all VNIR
- 9 views, 275 m pixels (always in red-channel used here)
- ≈7 minutes from most forward to most aft-word

3D cloud tomography: Demonstrated





Ground truth

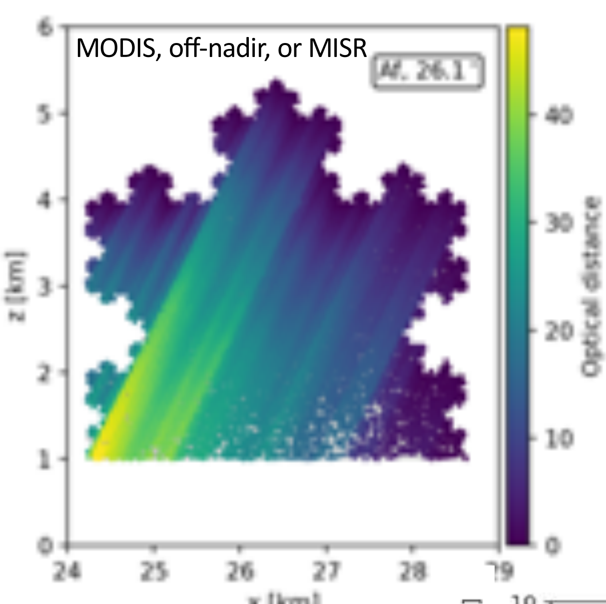


Reconstruction

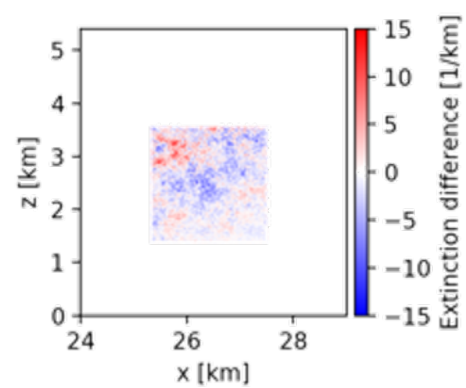
- Levis et al. (2015): red channel, 9 views, 20-m (≈AirMSPI) resolution
  - 46,656 unknowns & 315,018 unknowns, 2-step iteration scheme (1st linearized) using SHDOM
- Levis et al. (2017): VNIR multi-spectral
  - basic (profile-only) microphysics (r_e,v_e) **w/o SWIR (à la MODIS) nor polarization (à la MSPI)**
- Levis et al. (2020): VNIR multi-spectral/multi-polarimetric
  - potential for a full 3D microphysics (N_e, r_e, v_e) retrieval using polarization [I,Q,U]

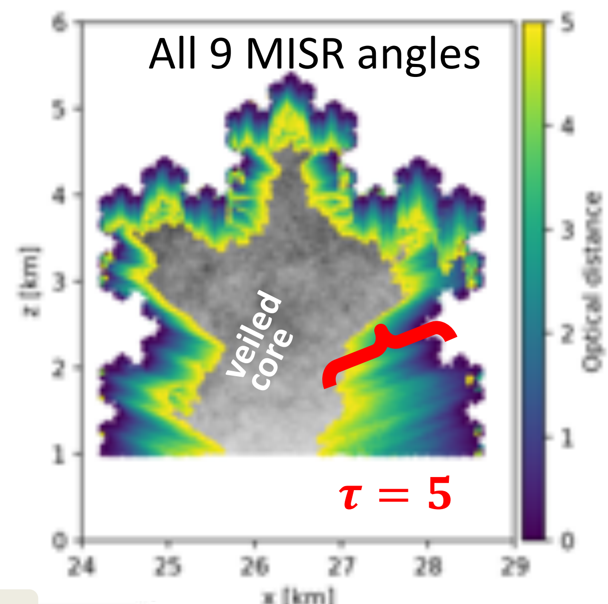
The "veiled core" of opaque clouds

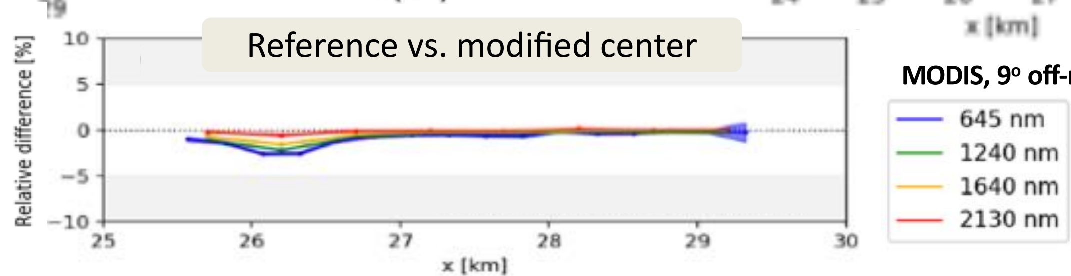
- **Problem:** ≈20 m pixels from airborne sensors
  → ≈250 & 500 m pixels from space (MISR + MODIS)
  → SHDOM issues: opaque, internally variable pixels



Optical distance
$\tau = \int_0^s \beta_{ext}(s')ds'$,
s: line of sight







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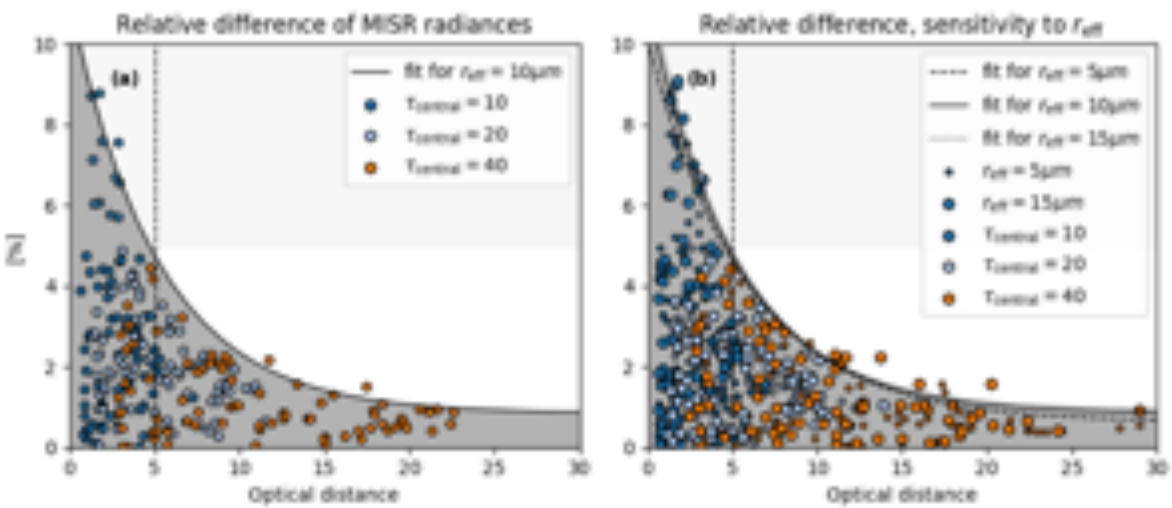
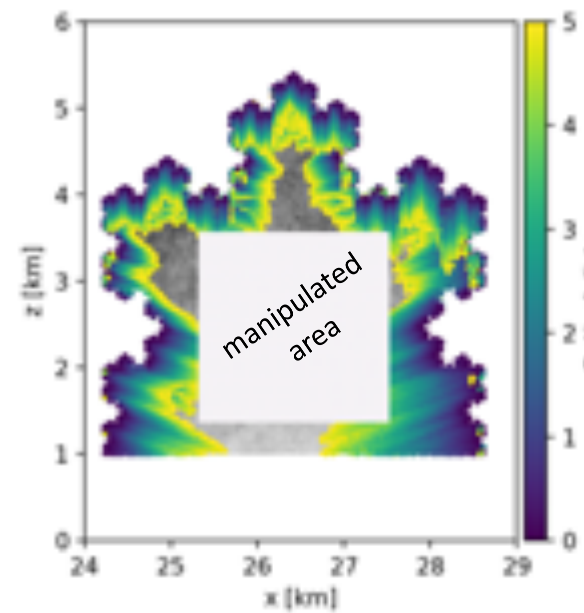




L. Forster, A. B. Davis, B. Mayer, and D. J. Diner (2020), Toward Convective Cloud Tomography from Space using MISR and MODIS: Locating the “Veiled Core” in Opaque Convective Clouds, *J. Atmos. Sci.* (in press). http://arxiv.org/abs/1910.00077

Cloud image formation in VNIR+SWIR: A story of two diffusions

Diffusion process #1:

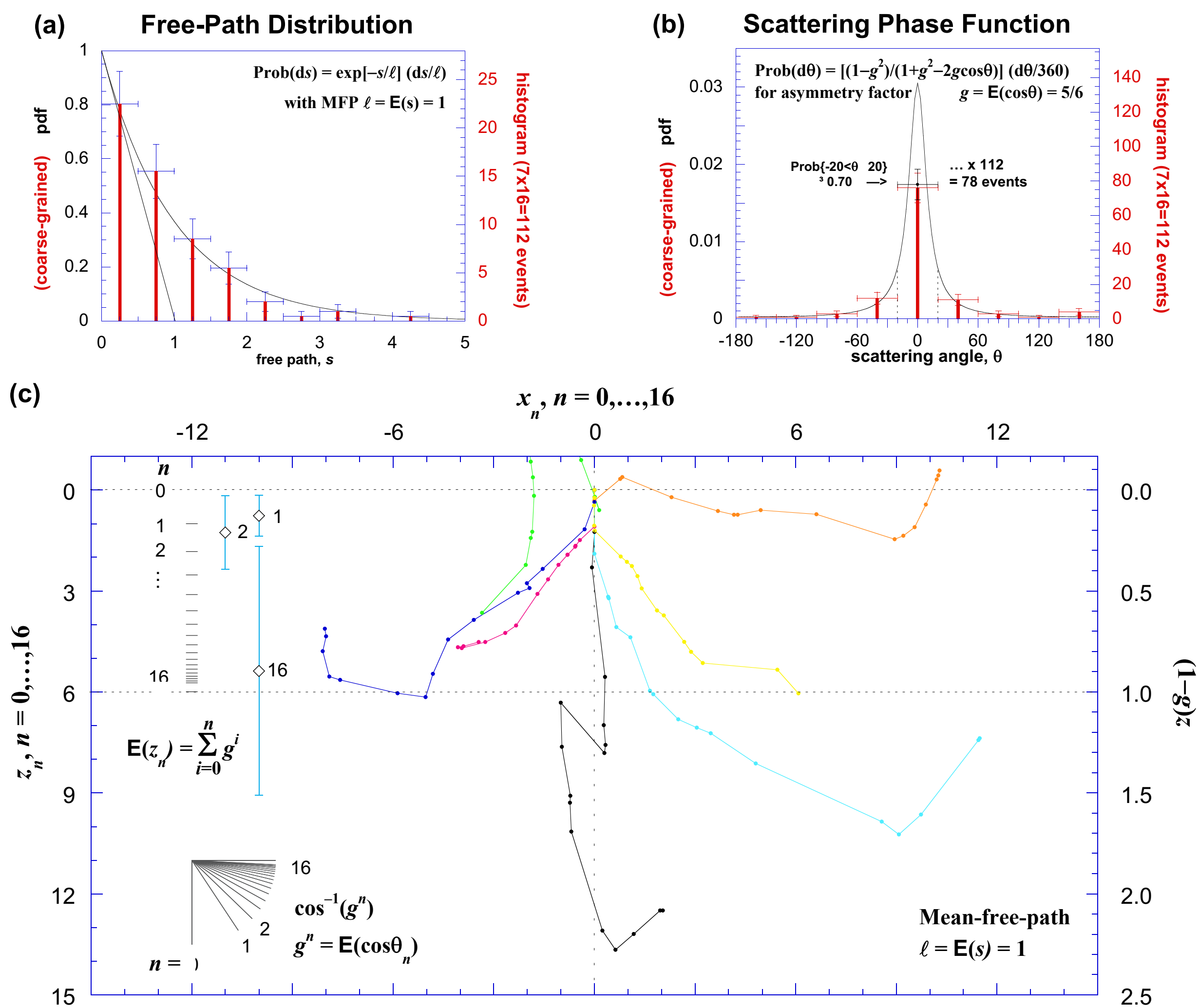
- random walk is on the sphere (*direction* space)
- in the *outer* shell
- gradual loss of *directional* memory

Characteristic time:

$N^* = 1/\ln(1/g) \approx (1/g-1)^{-1}$

$N^* \approx 6$ for $g \approx 0.85$

... explains empirical (≈5) threshold for definition of veiled core in optical distance



Cloud image formation in VNIR+SWIR: A story of two diffusions

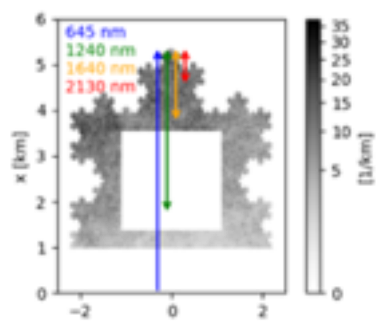
Diffusion process #2:

- random walk is in 3D *physical* space
- in the *veiled* core
- gradual loss of *positional* memory

Characteristic scale:

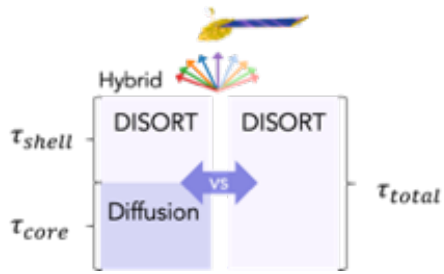
diffusion scale L_d

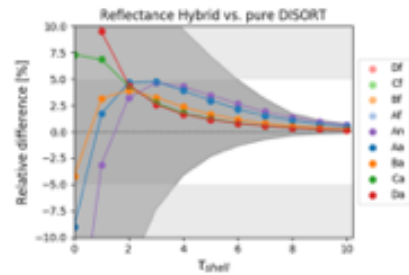
L_d x (mean extinction) = $[3(1-\omega)(1-\omega g)]^{-1/2}$

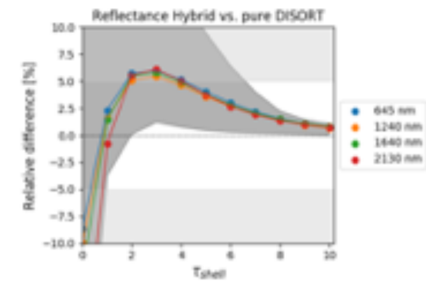


→ veiled core grows with absorption in MODIS-SWIR

Hybrid RT: Implementation in 1D

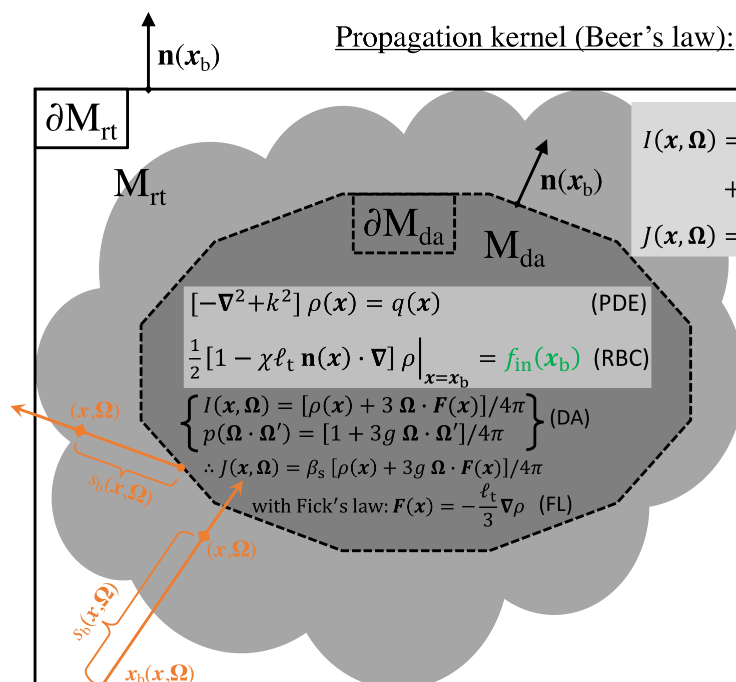






Hybrid RT: Possible Implementation in 3D

Propagation kernel (Beer's law): $T(\boldsymbol{x},\boldsymbol{\Omega};s) = \exp[-\int_0^s \beta(\underbrace{\boldsymbol{x}-\boldsymbol{\Omega}s'}_{\boldsymbol{x}_{s'}})\mathrm{d}s']$ (BL)



$$I(\boldsymbol{x},\boldsymbol{\Omega}) = \int_0^{s_b(\boldsymbol{x},\boldsymbol{\Omega})} [J(\boldsymbol{x}_s,\boldsymbol{\Omega}) + Q(\boldsymbol{x}_s,\boldsymbol{\Omega})]\,T(\boldsymbol{x},\boldsymbol{\Omega};s)\mathrm{d}s + I_b(\boldsymbol{x}_b,\boldsymbol{\Omega})\,T(\boldsymbol{x},\boldsymbol{\Omega};s_b(\boldsymbol{x},\boldsymbol{\Omega})) \quad \text{(RTE)}$$

$$J(\boldsymbol{x},\boldsymbol{\Omega}) = \beta_s(\boldsymbol{x})\int_{4\pi} p(\boldsymbol{\Omega}\cdot\boldsymbol{\Omega}')\,I(\boldsymbol{x},\boldsymbol{\Omega}')\mathrm{d}\Omega' \quad \text{(SF)}$$

Boundary condition at $\boldsymbol{x}_b(\boldsymbol{x},\boldsymbol{\Omega}) \in \partial M_{rt}$

$$I_b(\boldsymbol{x}_b,\boldsymbol{\Omega}) = 0, \text{ for } \mathbf{n}(\boldsymbol{x}_b)\cdot\boldsymbol{\Omega} < 0 \quad \text{(iBC)}$$

Two-way couplings at $\boldsymbol{x}_b(\boldsymbol{x},\boldsymbol{\Omega}) \in \partial M_{da}$

RT → DA:

$$f_{in}(\boldsymbol{x}_b) = \int_{\mathbf{n}(\boldsymbol{x}_b)\cdot\boldsymbol{\Omega}<0} |\mathbf{n}(\boldsymbol{x}_b)\cdot\boldsymbol{\Omega}|\,I(\boldsymbol{x}_b,\boldsymbol{\Omega})\mathrm{d}\Omega$$

DA → RT:

$$\begin{cases} I_b(\boldsymbol{x}_b,\boldsymbol{\Omega}) = f_{out}(\boldsymbol{x}_b)\dfrac{\mathbf{n}(\boldsymbol{x}_b)\cdot\boldsymbol{\Omega}}{\pi}, \text{ if } \mathbf{n}(\boldsymbol{x}_b)\cdot\boldsymbol{\Omega} > 0, \\ \text{where } f_{out}(\boldsymbol{x}_b) = \dfrac{1}{2}[1+\chi\ell_t\,\mathbf{n}(\boldsymbol{x})\cdot\nabla]\,\rho\big|_{\boldsymbol{x}=\boldsymbol{x}_b} \end{cases}$$

Tomography initialization: Outer cloud shape … *quickly!*

Progress in 3D Tomographic Cloud Reconstruction, Part 2*: Efficient determination of outer shapes of convective clouds from MISR data using radiosity

<u>*Anthony B. Davis*</u>, JPL / Caltech, Pasadena, Ca, USA
Guillaume Bal, University of Chicago, Chicago, Il, USA
Céline Cornet, Laboratoire d'Optique Atmosphérique, Lille, France

*** Part 1 is Linda Forster's oral presentation on Wednesday PM.**

Objective & Results

Tomographic reconstruction of 3D convective clouds is a large and challenging inverse problem that can benefit from a reasonably good initial guess. In this study, we use synthetic and real MISR data to demonstrate a robust and highly efficient determination of the effective outer shape of a 3D cloud, one slice at a time. Although time will tell, we believe this will constitute a viable initial guess for the full 3D cloud tomography.

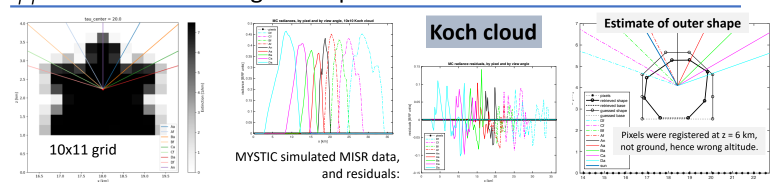
In our methodology, the outer boundary of a 2D slice from a 3D cloud along any convenient direction (say N-S) is represented as an irregular *n*-sided off-grid polygon with the lowest facet (i.e., cloud base) being constrained to remain horizontal. Radiance emerging from each facet (except the base) is modeled with a radiosity-type angular distribution inspired by asymptotic radiative transfer theory; this function has at most two free parameters. In total, $2n-1+2(n-1) = 4n-3$ parameters need to be determined by fit to the MISR data. We found that $n = 8$ is a reasonable balance for a wide range of cloud sizes, in view of the coarse nature of the cloud boundary model. Thus, a nonlinear minimization problem is solved to estimate the 29 parameters per 2D slice, 15 of which will be used in the subsequent full 3D cloud tomographic reconstruction to construct an initial guess. This preliminary fitting problem also calls for an initial guess that we distill out of cloud masks for the nadir and most oblique views.

Two-parameter (a_i,t_i) radiosity model:

$I(\mathbf{\Omega}_0, \mathbf{\Omega}_v, \boldsymbol{n}_i; a_i, t_i) = a_i \times (\mathbf{\Omega}_v \cdot \boldsymbol{n}_i) \times \max(-\mathbf{\Omega}_0 \cdot \boldsymbol{n}_i, t_i)$

where:
- $\mathbf{\Omega}_0$ is solar incidence direction;
- $\mathbf{\Omega}_v$ is viewing direction;
- $\boldsymbol{n}_i$ is the outward normal of the i^{th} facet;
- $a_i > 0$ is an albedo-like parameter;
- $t_i > 0$ is a diffuse Lambertian background.

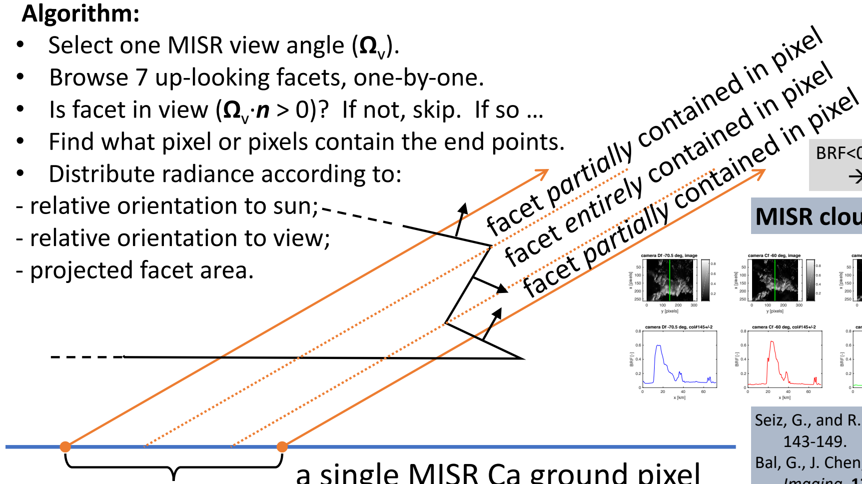
For a non-illuminated facet ($\mathbf{\Omega}_0 \cdot \boldsymbol{n}_i > 0$) or a grazing sun ($-\mathbf{\Omega}_0 \cdot \boldsymbol{n}_i < t_i$), $a_i t_i$ combines into a single free parameter.

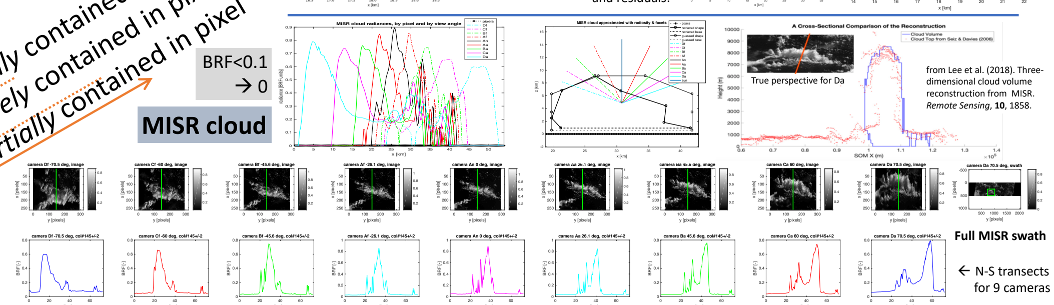


Algorithm:

- Select one MISR view angle ($\mathbf{\Omega}_v$).
- Browse 7 up-looking facets, one-by-one.
- Is facet in view ($\mathbf{\Omega}_v \cdot \boldsymbol{n} > 0$)? If not, skip. If so …
- Find what pixel or pixels contain the end points.
- Distribute radiance according to:

- relative orientation to sun;
- relative orientation to view;
- projected facet area.

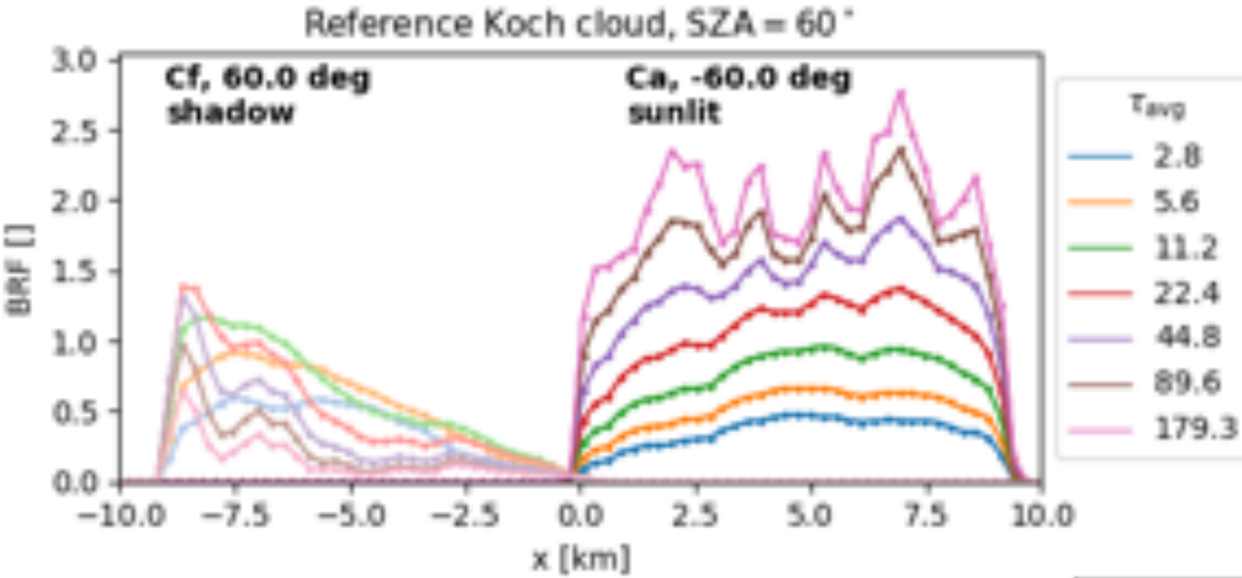




Seiz, G., and R. Davies (2006). Reconstruction of cloud geometry from multi-view satellite images. *Remote Sens. Environ.*, **100**, 143-149.

Bal, G., J. Chen, and A. B. Davis (2018). Reconstruction of cloud geometry from high-resolution multi-angle images. *Inv. Prob. Imaging*, **12**, 261-280.

Tomography initialization: Mean extinction … *quickly!*



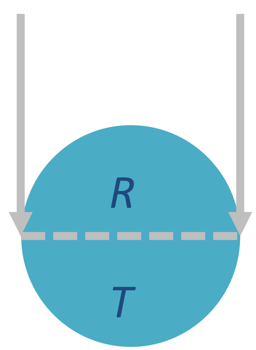
$(1-g)*\tau_{avr}$	$\tau_{central}$
0.42	5
0.84	10
1.68	20
3.36	40
6.72	80
13.4	160
26.9	320

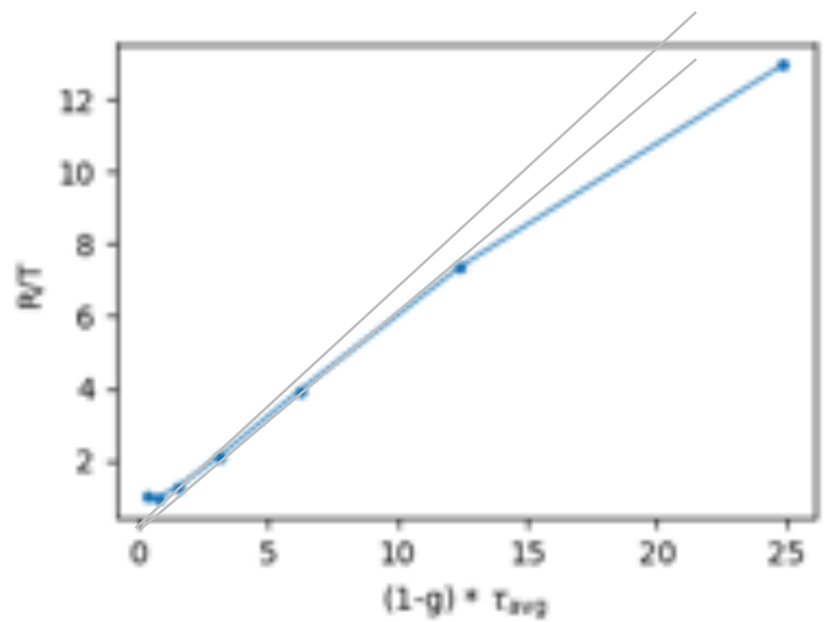
Exact diffusion theory:

$$R/T = (1-g)\tau_{diam}/2\chi$$

1D: segments (χ = 1)
2D: circles ($\chi = \pi/4$)
3D: slabs/cylinders/spheres (χ = 2/3)

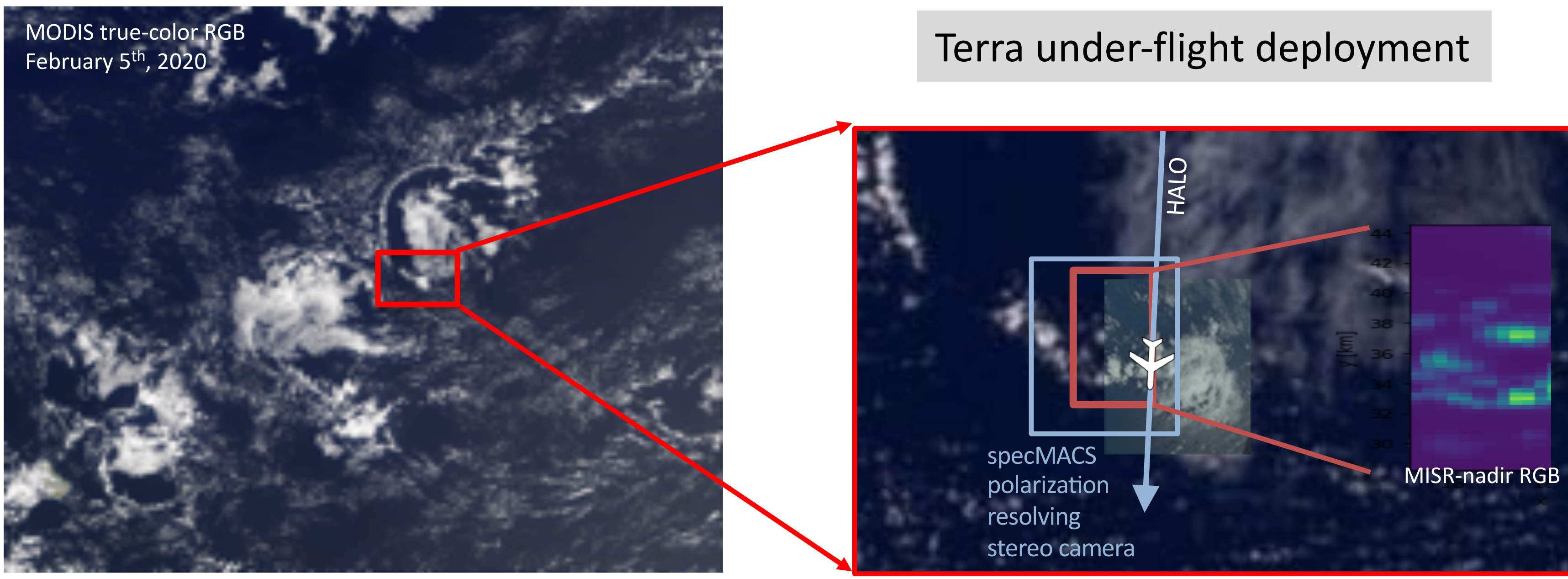
(χ is the “extrapolation” scale)





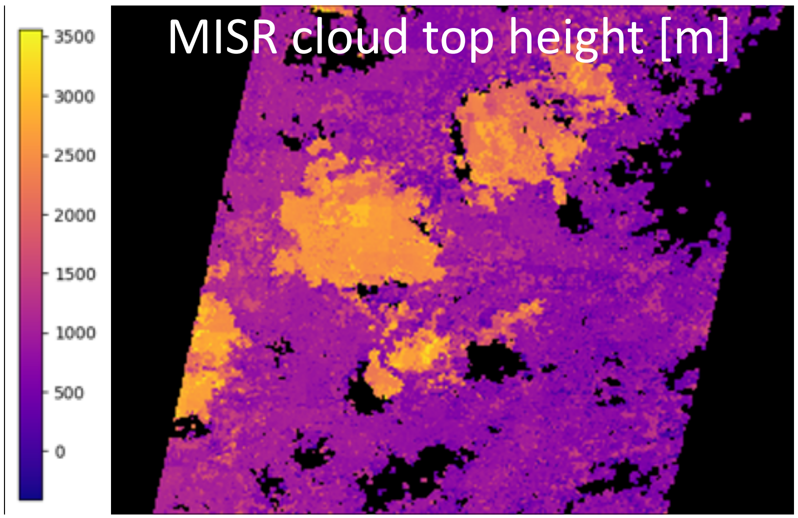
EUREC^{4}A (ElUcidating the Role of Clouds-Circulation Coupling in ClimAte) field campaign

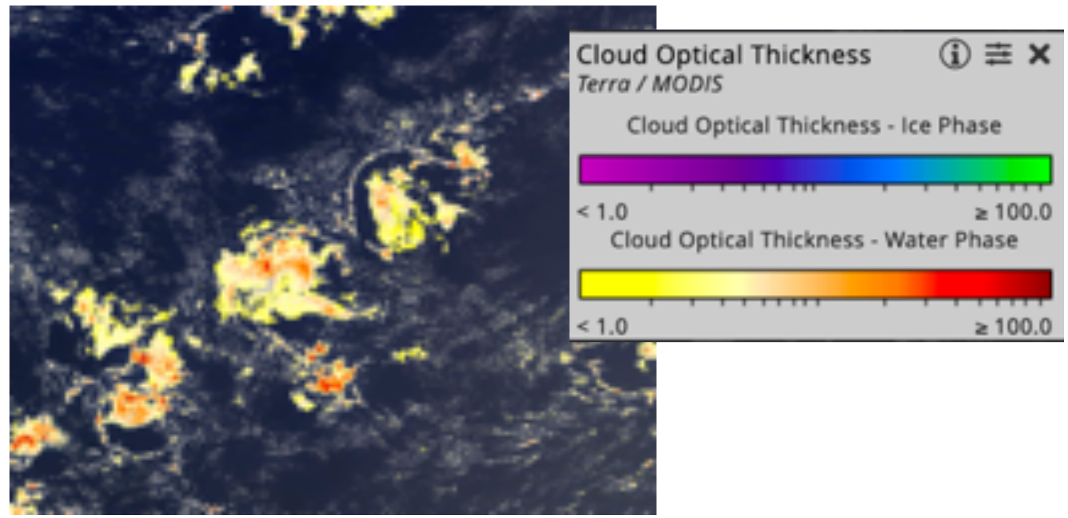
Barbados, 1/20-2/20, 2020

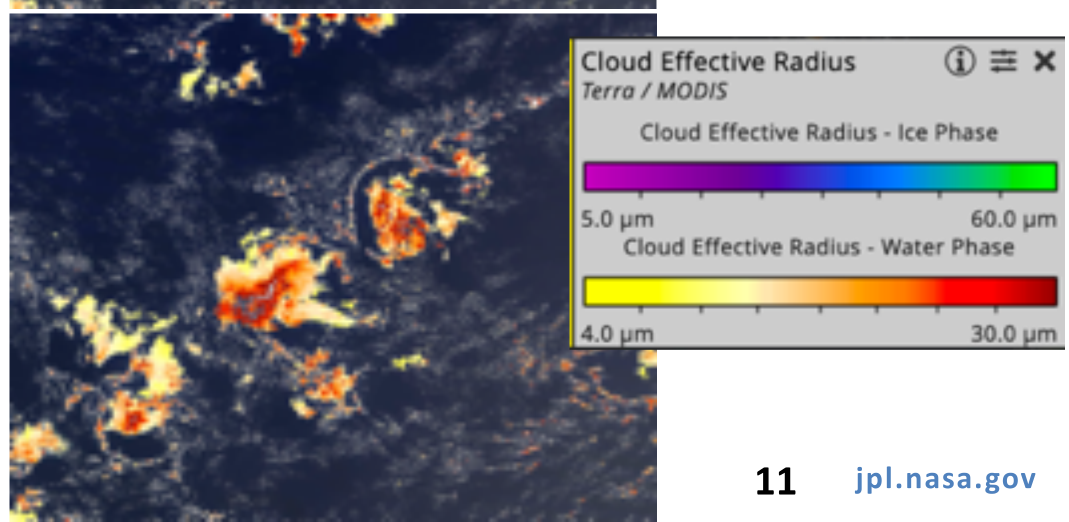


collaborator-participants at LMU: Linda Forster & Bernhard Mayer

EUREC^{4}A (ElUcidating the Role of Clouds-Circulation Coupling in ClimAte) field campaign



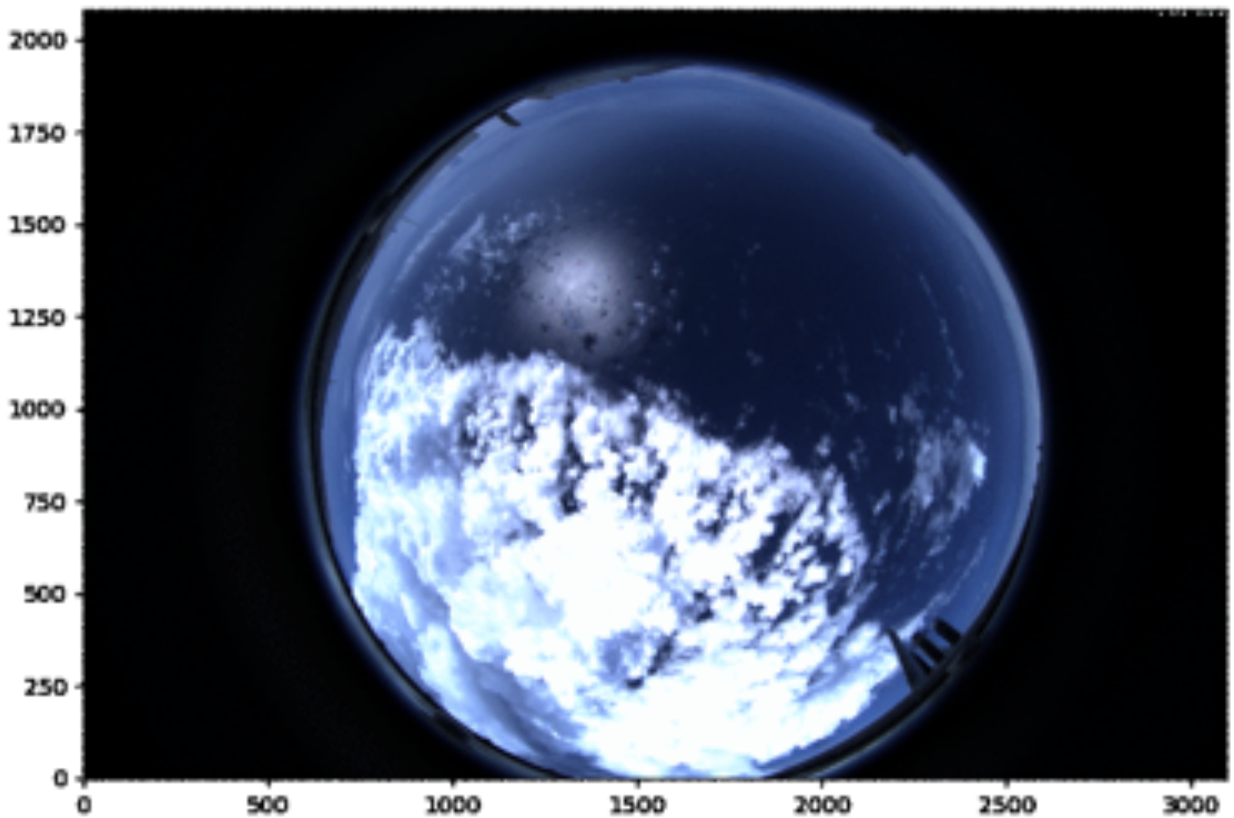




Apart from a hyperspectral imager, aircraft has lidar and radar.

→ **Opportunity to compare with operational MISR & MODIS cloud products**

Cloud, Aerosol and Monsoon Processes Philippines Experiment (CAMP^{2}Ex)



collaborator-participants at UI–UC: Jesse Loveridge & Larry di Girolamo

From 3D-TRACE to CloudCT, and beyond

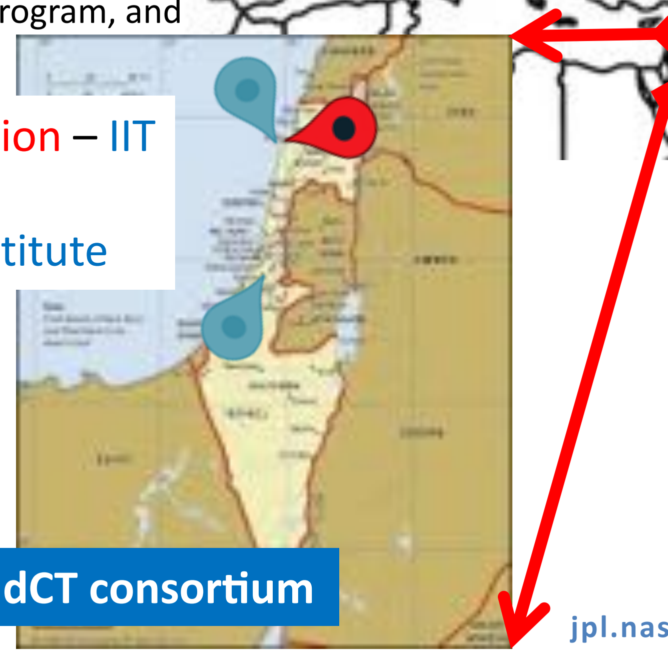
3D-TRACE: Three-Dimensional Tomographic Reconstruction of the Aerosol-Cloud Environment
… ESTO/AIST (~FY13), then ESD/RST (2013–2015) seed funds for JPL

CloudCT: Cloud Computed Tomography … 14M€ ERC Horizon 2020 grant (~10 cubesat mission)

Wurzenberg: Zentrum für Telematik
Munich: Ludwig-Maximilians-Universität

University of Illinois – **Urbana Champaign**

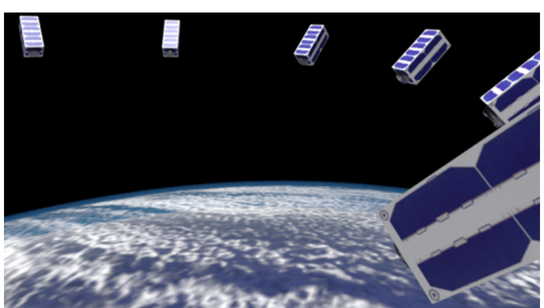
Support also acknowledged from:
JPL (RTD, CAP & JROC), ROSES (TASNPP & FINNEST), BSF, EC’s Marie Skłodowska–Curie Fellowship Program, and others …



Haifa: Technion – IIT

Pasadena:
- JPL
- Caltech

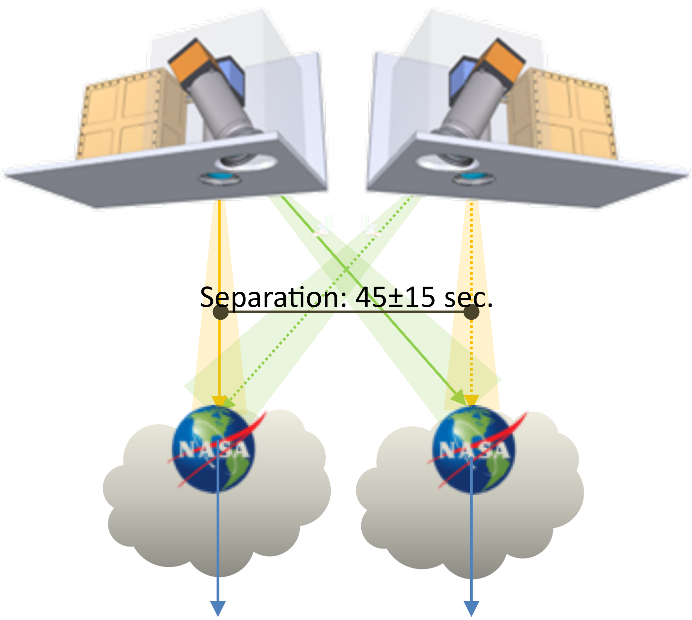
Rehovot: Weizmann Institute



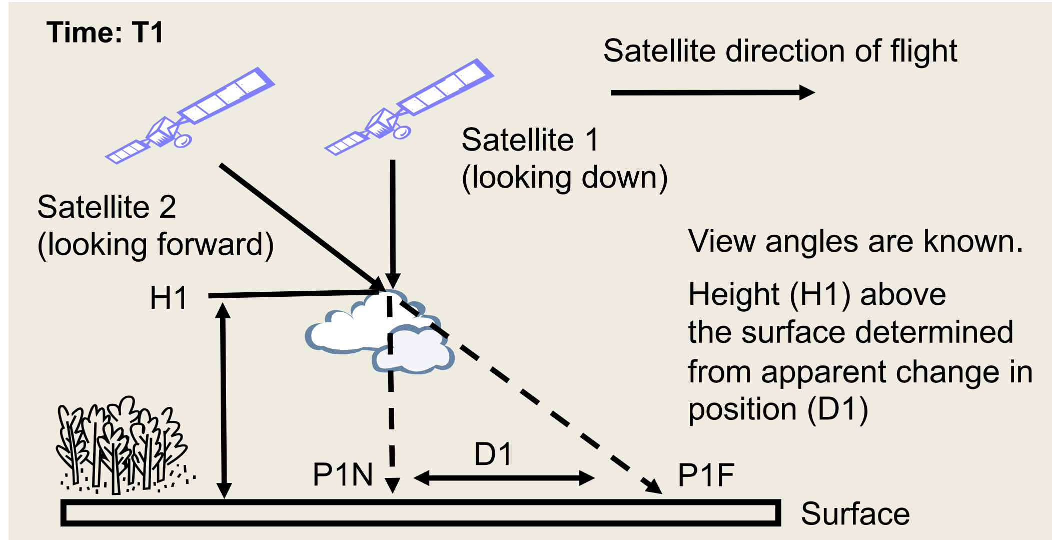
CloudCT consortium

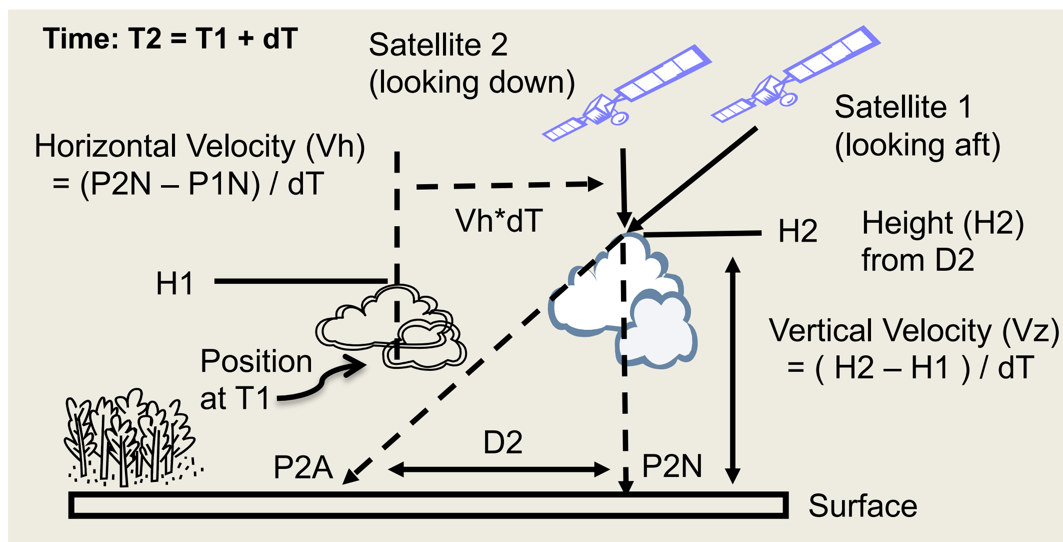
jpl.nasa.gov

Support of A/CCP mission formulation: Tandem StereoCam "delta t" concept



Same cloud feature is observed from 2 view angles (stereo/3D image) twice (cloud motion after 45 sec.).





Summary & Outlook

- 2 papers published:
  - Levis et al. (2020)
  - Forster et al. (2020)
- 2 papers in preparation:
  - Davis et al. (two diffusion processes)
  - Davis et al. (robust tomography initialization)
  - other projects in progress, for later publications
- 2 field campaigns for validation data
  - EUREC^{4}A
  - CAMP^{2}EX