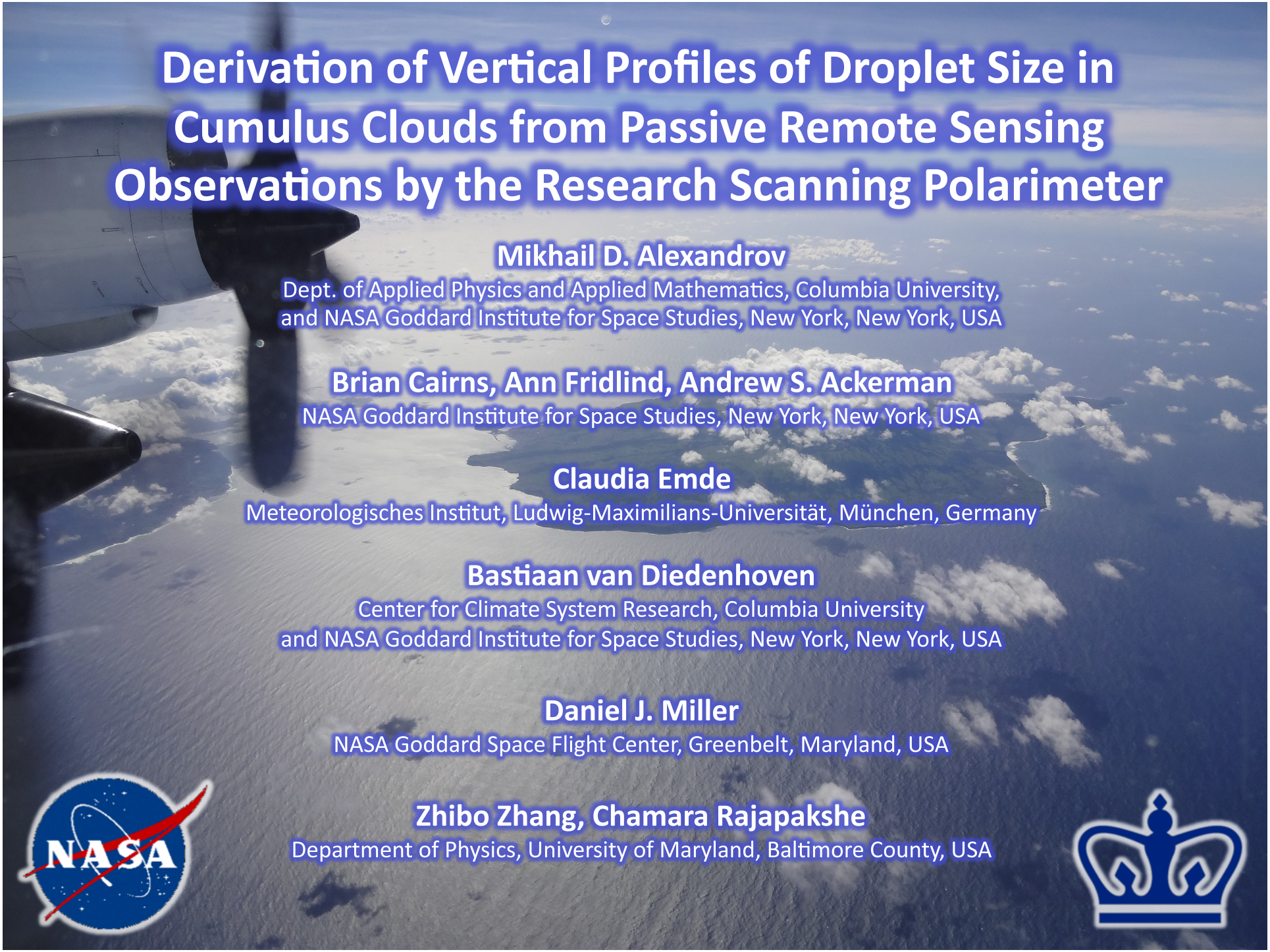


Derivation of Vertical Profiles of Droplet Size in Cumulus Clouds from Passive Remote Sensing Observations by the Research Scanning Polarimeter

Mikhail D. Alexandrov
Dept. of Applied Physics and Applied Mathematics, Columbia University,
and NASA Goddard Institute for Space Studies, New York, New York, USA

Brian Cairns, Ann Fridlind, Andrew S. Ackerman
NASA Goddard Institute for Space Studies, New York, New York, USA

Claudia Emde
Meteorologisches Institut, Ludwig-Maximilians-Universität, München, Germany

Bastiaan van Diedenhoven
Center for Climate System Research, Columbia University
and NASA Goddard Institute for Space Studies, New York, New York, USA

Daniel J. Miller
NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

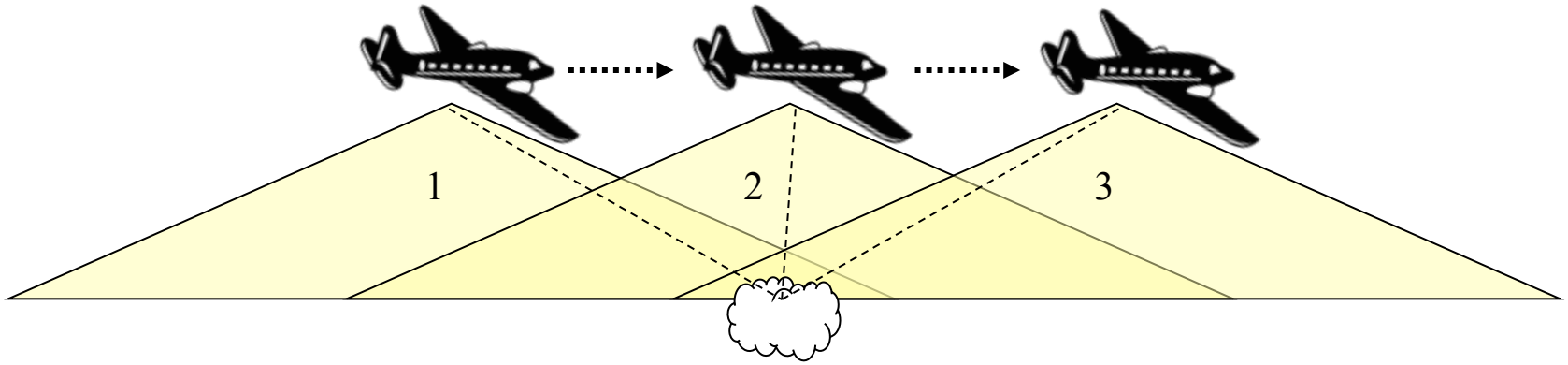
Zhibo Zhang, Chamara Rajapakshe
Department of Physics, University of Maryland, Baltimore County, USA

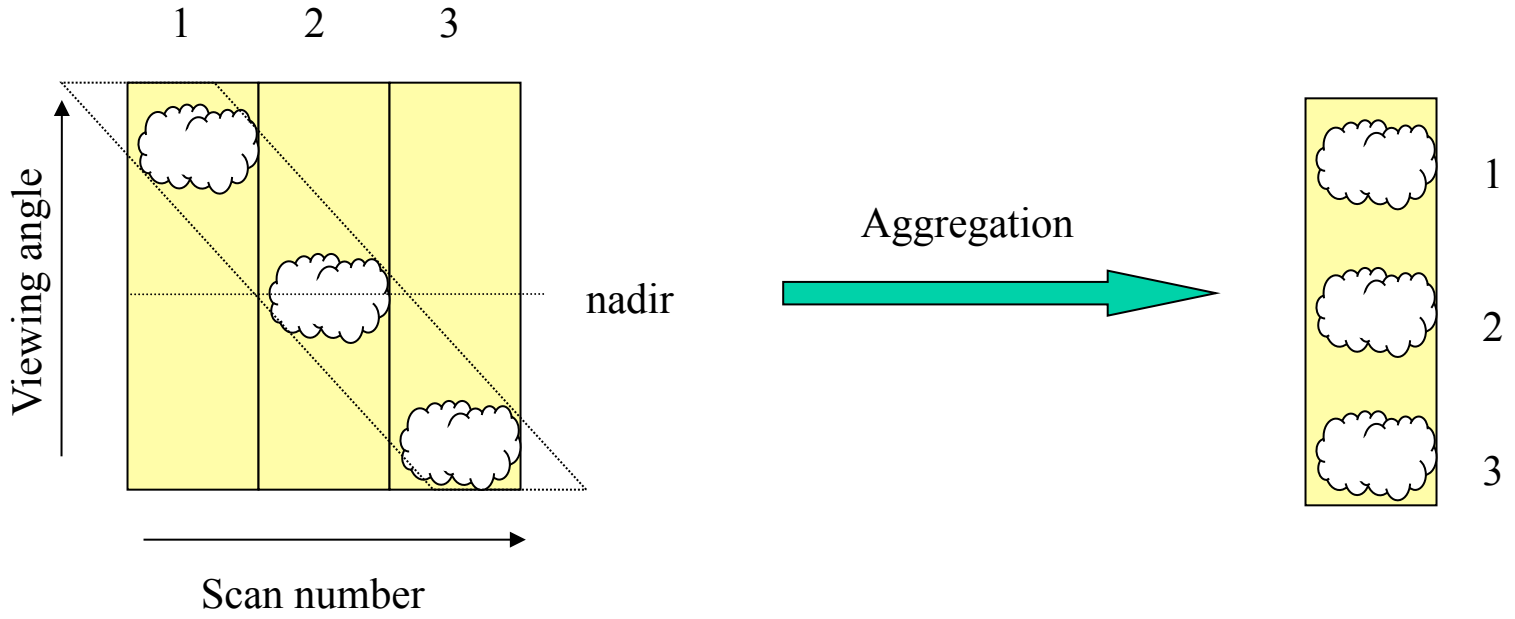
Research Scanning Polarimeter (RSP)

- High-resolution Along-track scanner
- Two versions built in 1999 and 2001
- Prototype for Aerosol Polarimetry Sensor on Glory mission (launch failed 2011)
- Simultaneous measurements of Stokes parameters *I* (intensity), *Q* and *U* (linear polarization)
- 0.2% uncertainty in degree of linear polarization
- 9 bands in visible and shortwave infrared: 410, 470, 555, 670, 864, 960, 1593, 1880, and 2263 nm
- Scanner: ±60° from nadir, 14 mrad FOV, 0.8° intervals, 150 views/scan

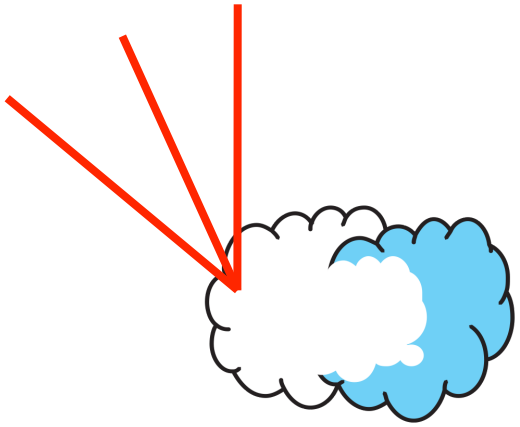
RSP's aerial platforms

Aggregation of RSP images





View-ray arrangements



Micro: Droplet size

Macro: Cloud shape

$$R_p(\theta) = -\frac{\pi Q(\theta)}{\mu_s I_0}$$

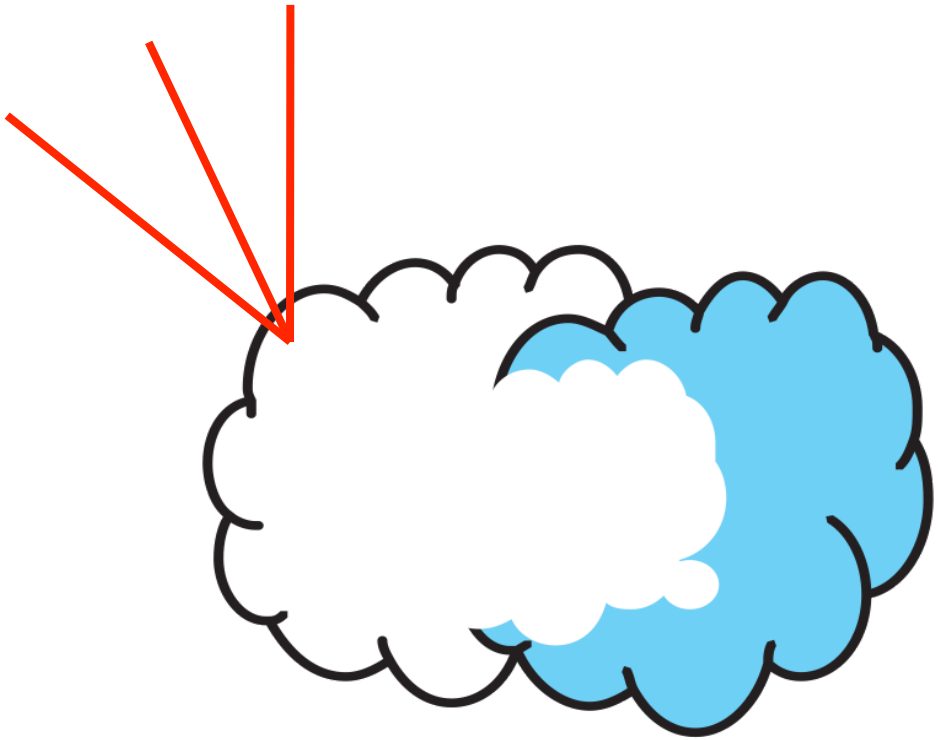
$$R(\theta) = \frac{\pi I(\theta)}{\mu_s I_0}$$

Polarized reflectance

Total reflectance

Macro + Micro: Droplet size **profiles**

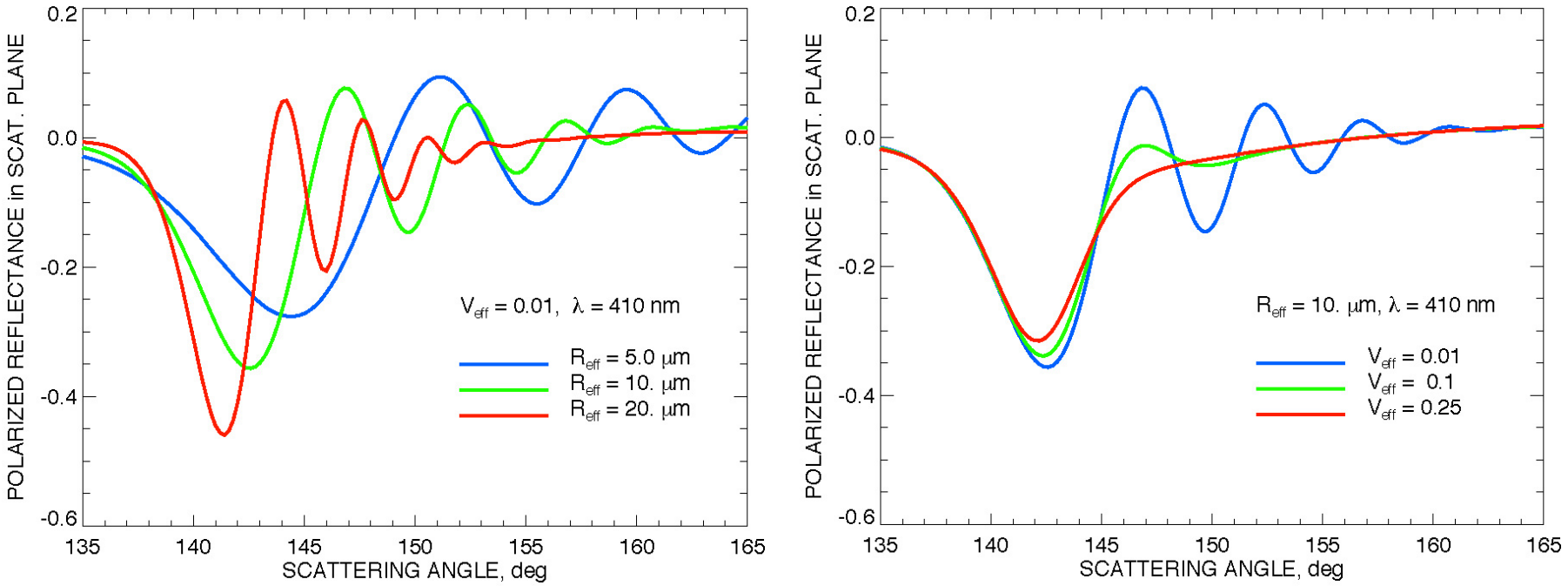
Micro: Droplet size



Polarized reflectance

Cloud droplet size retrievals from polarized reflectance in rainbow region

- Stokes parameter *Q* in the plane of scattering is dominated by the Mie phase matrix element P_{12} (single scattering).
- This makes the retrievals insensitive to cloud heterogeneity and 3D effects.
- No restrictions on cloud optical thickness.

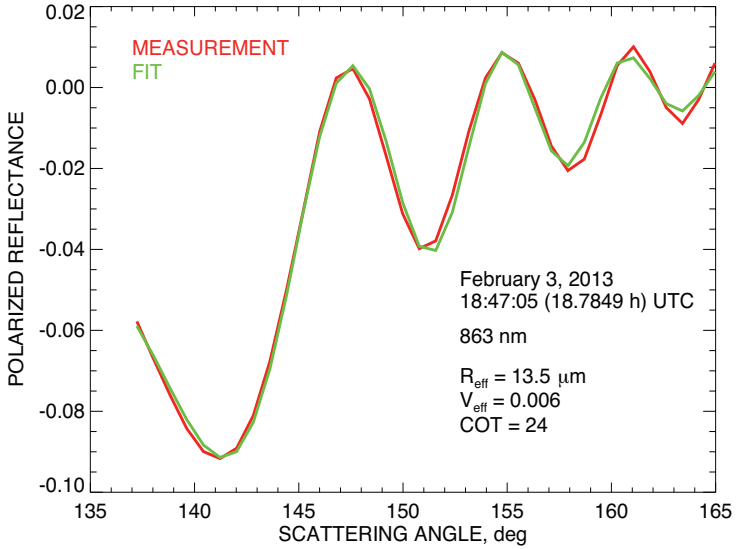


Sensitivity of polarized reflectance to effective radius (left) and variance (right) of cloud droplet size distribution. "Frequency" of the rainbow depends on the droplet size.

Cloud droplet size retrieval methods

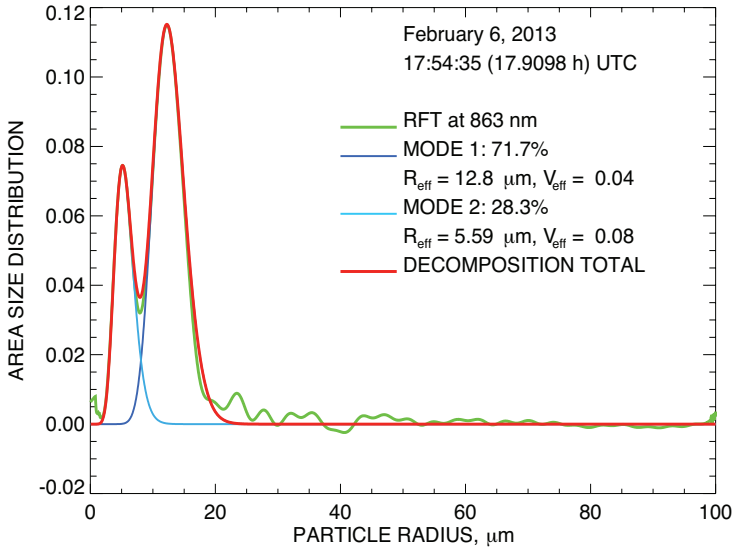
Parametric fitting using assumed size distribution family (single-mode gamma distribution). Retrieves effective radius and variance of the distribution.

Alexandrov, M. D., B. Cairns, C. Emde, A. S. Ackerman, & B. van Diedenhoven (2012a). Accuracy assessments of cloud droplet size retrievals from polarized reflectance measurements by the Research Scanning Polarimeter. *Remote Sensing of Environment*, **125**, 92–111.



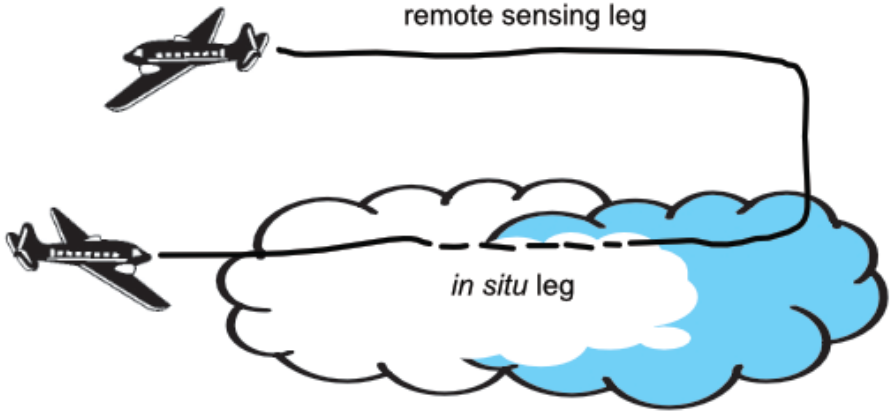
Non-parametric, Rainbow Fourier Transform (RFT) allows for multi-modal droplet size distributions and retrieves full distribution shape.

Alexandrov, M. D., B. Cairns, & M. I. Mishchenko (2012). Rainbow Fourier transform. *J. Quant. Spectrosc. Radiat. Transfer*, **113**, 2521–2535.



Validation with *in situ* measurements

North Atlantic Aerosols and Marine Ecosystems Study (May 2016)



NAAMES
North Atlantic Aerosols and Marine Ecosystems Study

Remote Sensing of Environment 210 (2018) 76–95

Contents lists available at ScienceDirect

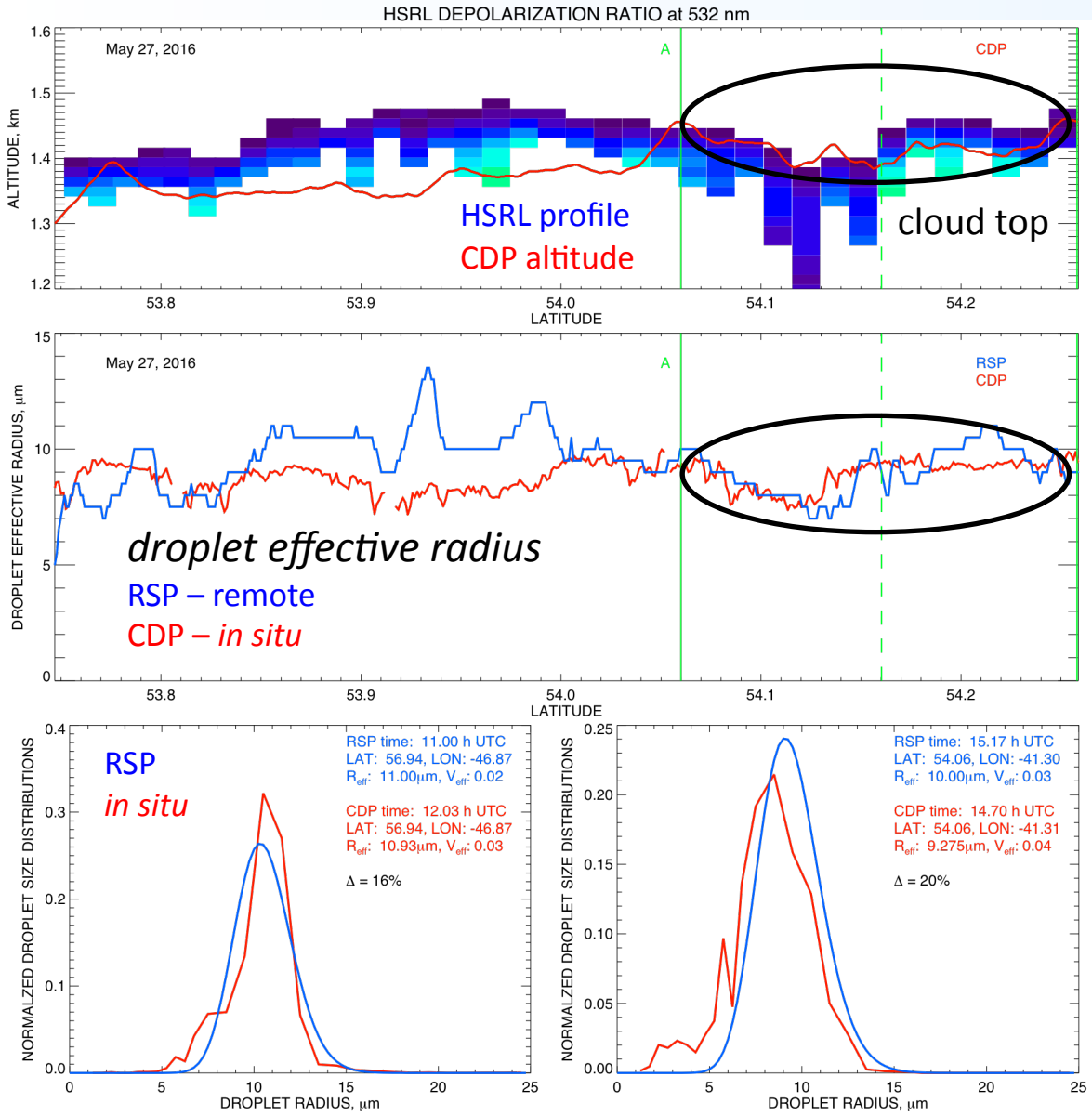
Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Retrievals of cloud droplet size from the research scanning polarimeter data: Validation using in situ measurements

Mikhail D. Alexandrov[a,b,*], Brian Cairns[b], Kenneth Sinclair[c,b], Andrzej P. Wasilewski[d,b], Luke Ziemba[e], Ewan Crosbie[f,e], Richard Moore[e], John Hair[e], Amy Jo Scarino[f,e], Yongxiang Hu[e], Snorre Stamnes[e], Michael A. Shook[e], Gao Chen[e]

Validation with *in situ* measurements



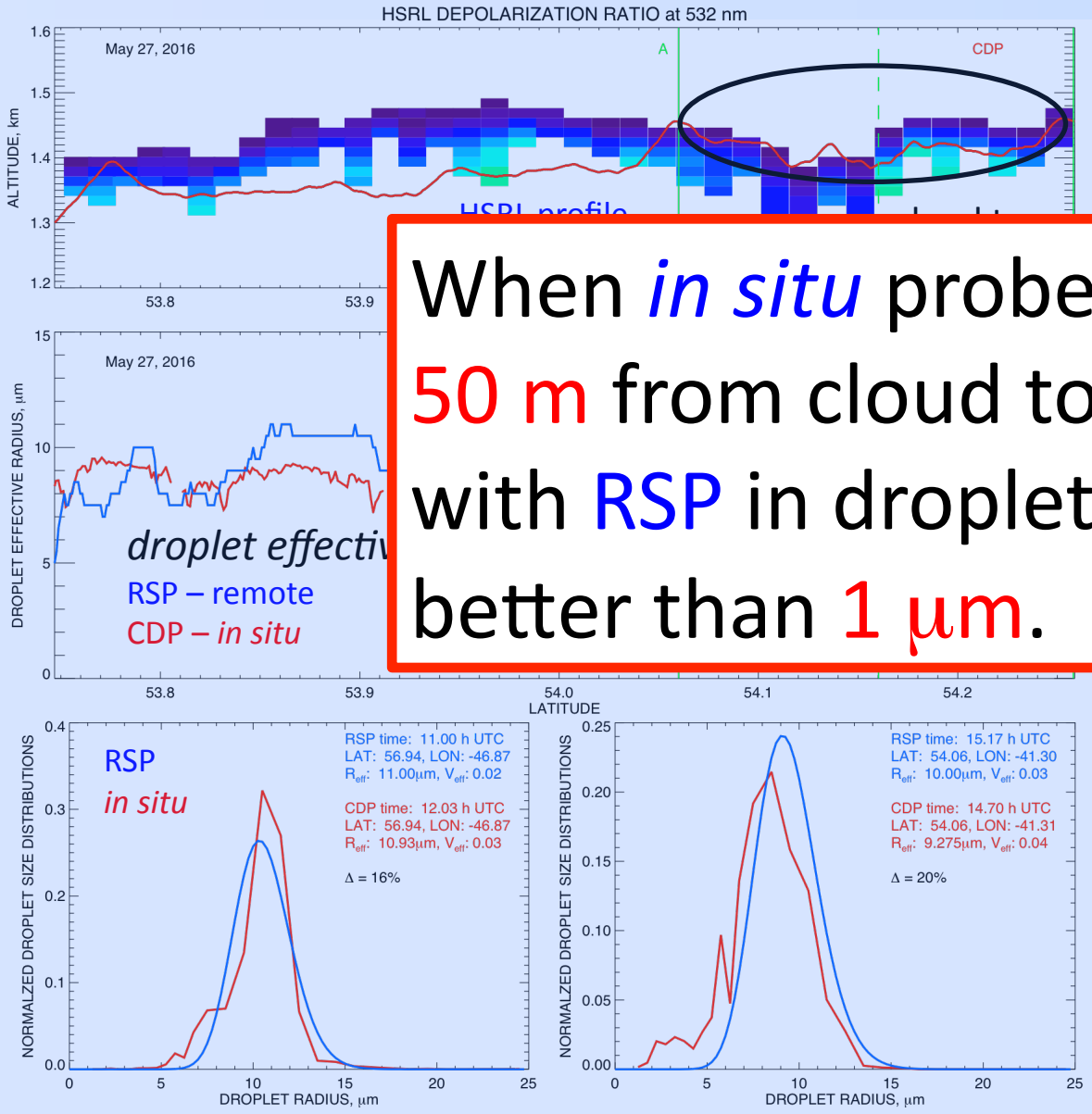
RSP retrievals were validated against *in situ* measurements by the Cloud Droplet Probe (CDP) in May 2016.

The cloud bow, dominated by single scattering, is characteristic of droplet sizes within ~ 50 m from cloud top.

Comparisons show good agreement: better than 1 µm for effective radius and in most cases better than 0.02 for effective variance.

Deviations are explainable by aircraft position within cloud and/or presence of additional cloud layers not sampled *in situ*.

Validation with *in situ* measurements



When *in situ* probe is within 50 m from cloud top it agrees with RSP in droplet size by better than 1 µm.

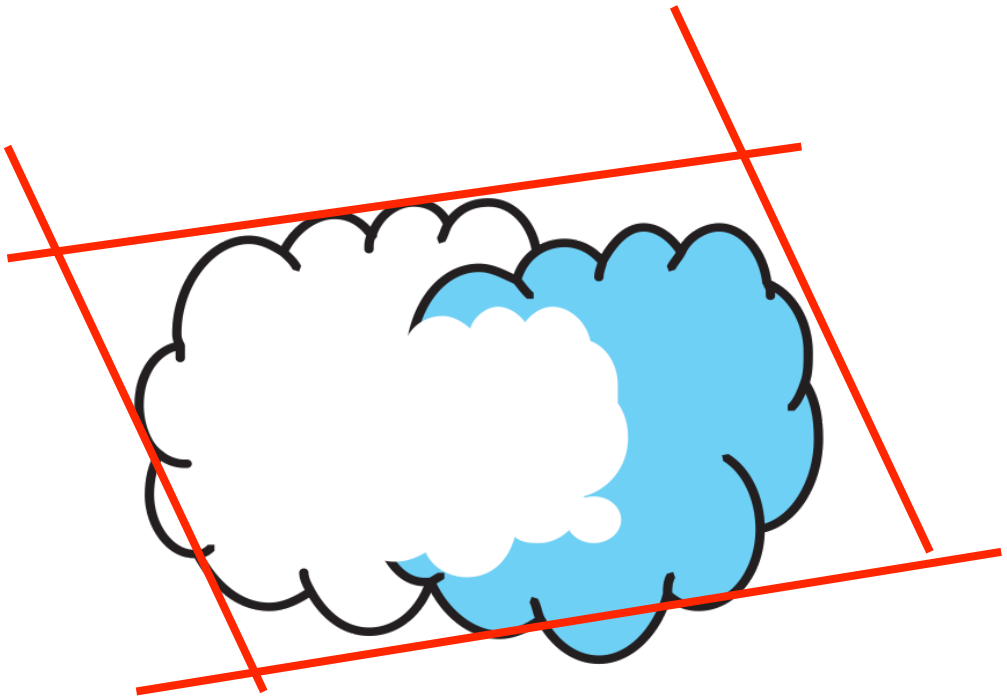
RSP retrievals were validated against *in situ* measurements by the Cloud Droplet Probe (CDP) in

ated by single acteristic of ~ 50 m from

ow good an 1 µm for effective radius and in most cases better than 0.02 for effective variance.

Deviations are explainable by aircraft position within cloud and/or presence of additional cloud layers not sampled *in situ*.

Macro: Cloud geometric shape



Total reflectance

Cloud dimensions and shape

Remote Sensing of Environment 177 (2016) 144–152

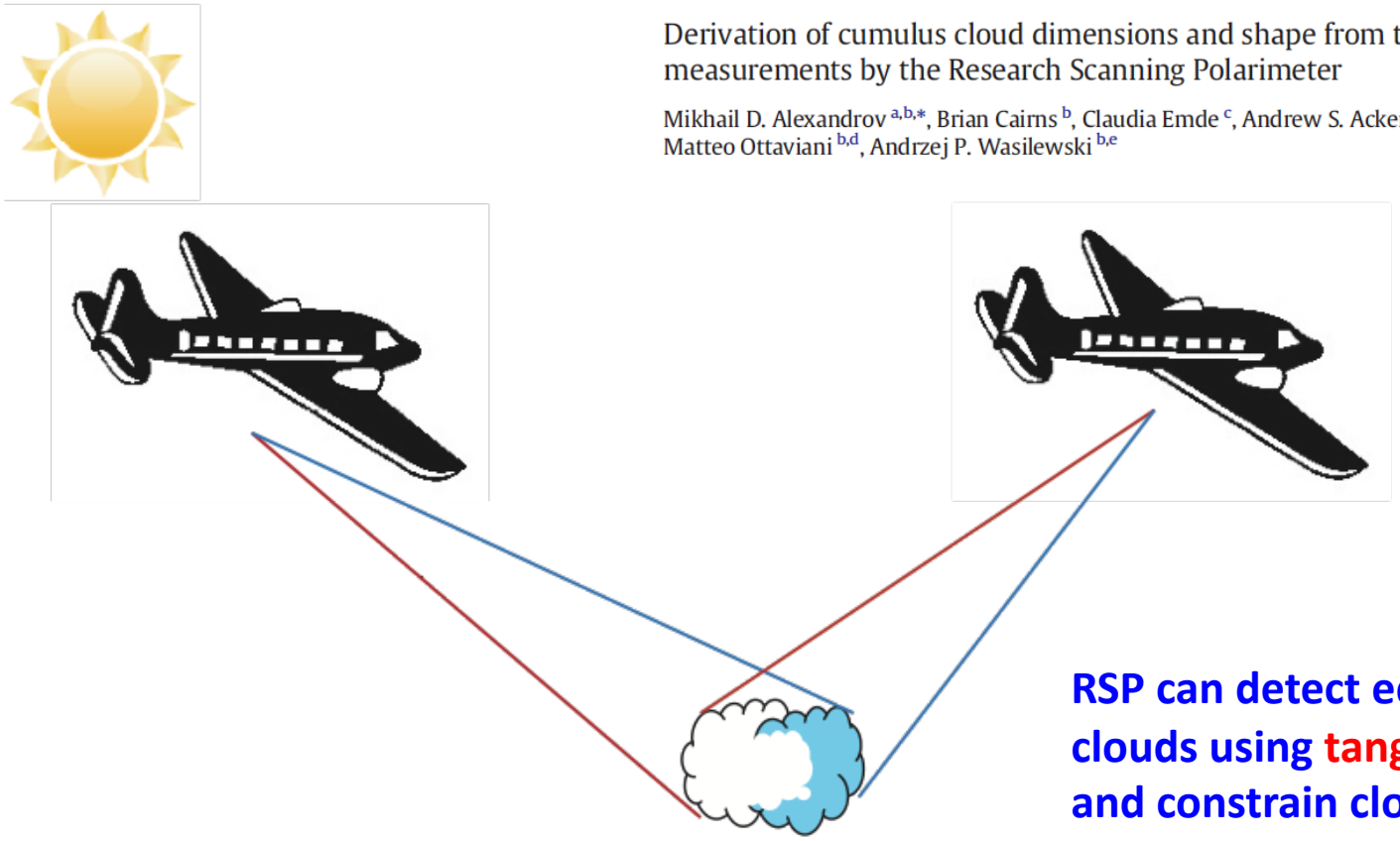
Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

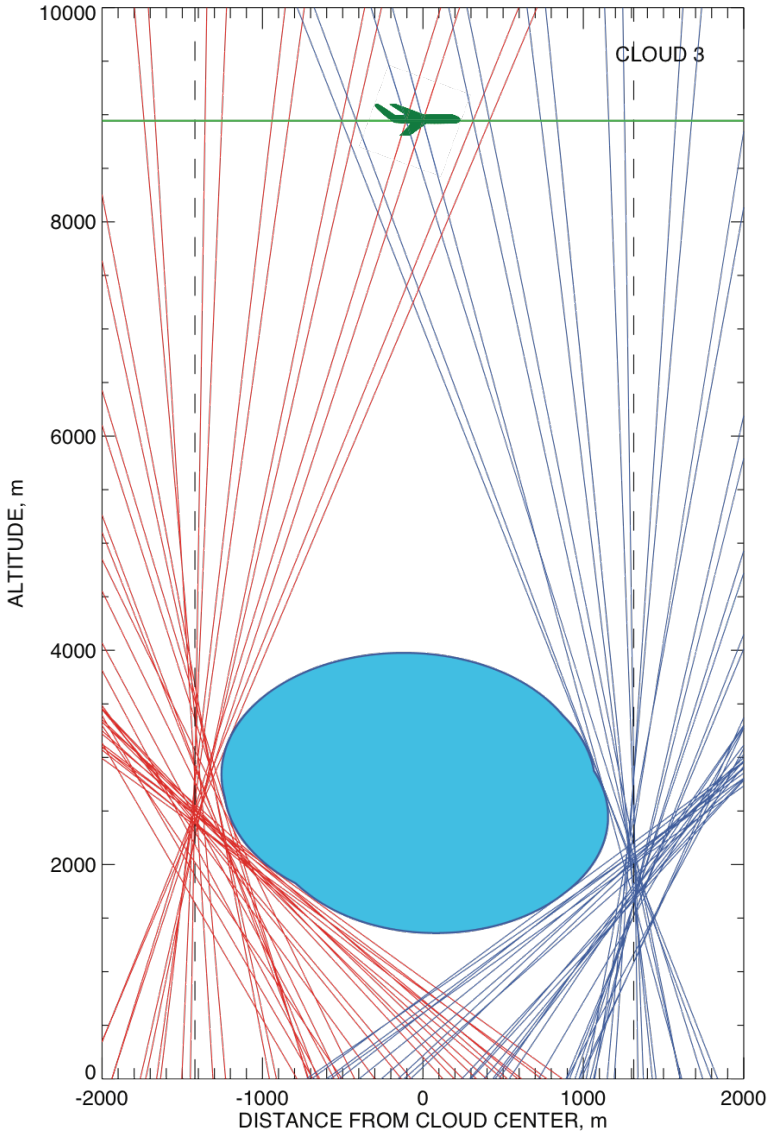
Derivation of cumulus cloud dimensions and shape from the airborne measurements by the Research Scanning Polarimeter

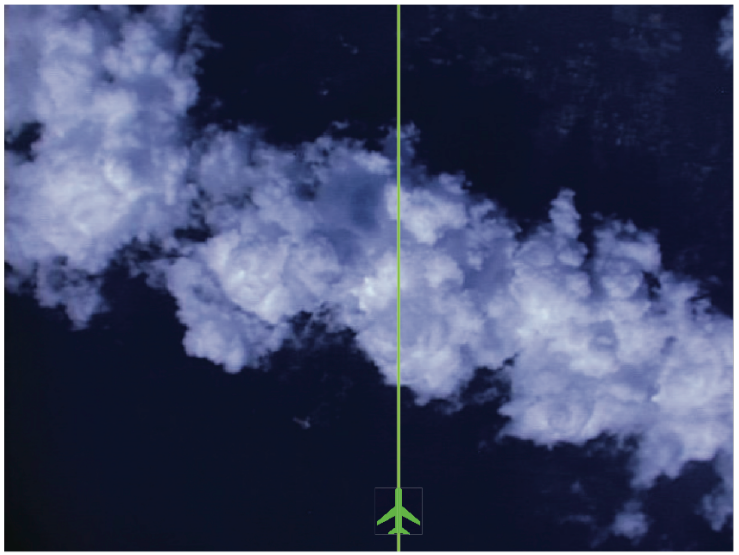
Mikhail D. Alexandrov [a,b,*], Brian Cairns [b], Claudia Emde [c], Andrew S. Ackerman [b], Matteo Ottaviani [b,d], Andrzej P. Wasilewski [b,e]

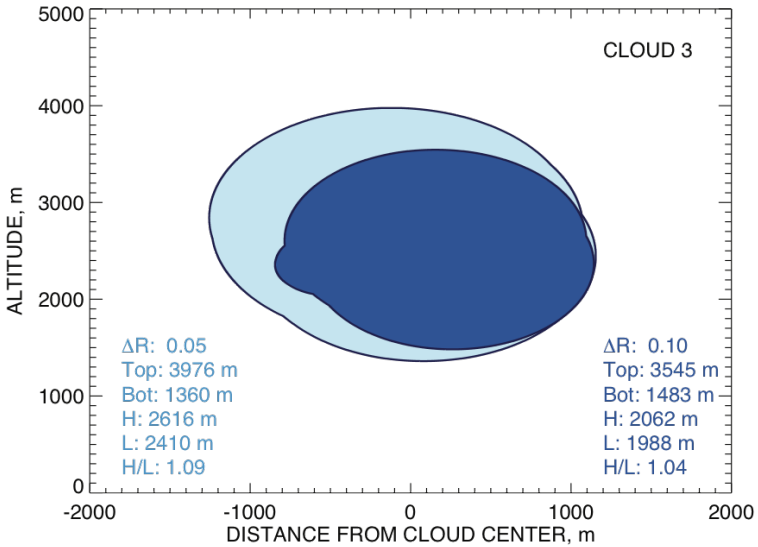


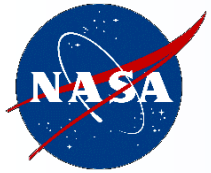
RSP can detect edges of Cu clouds using tangent view-rays and constrain cloud shape.

Example from DEVOTE campaign





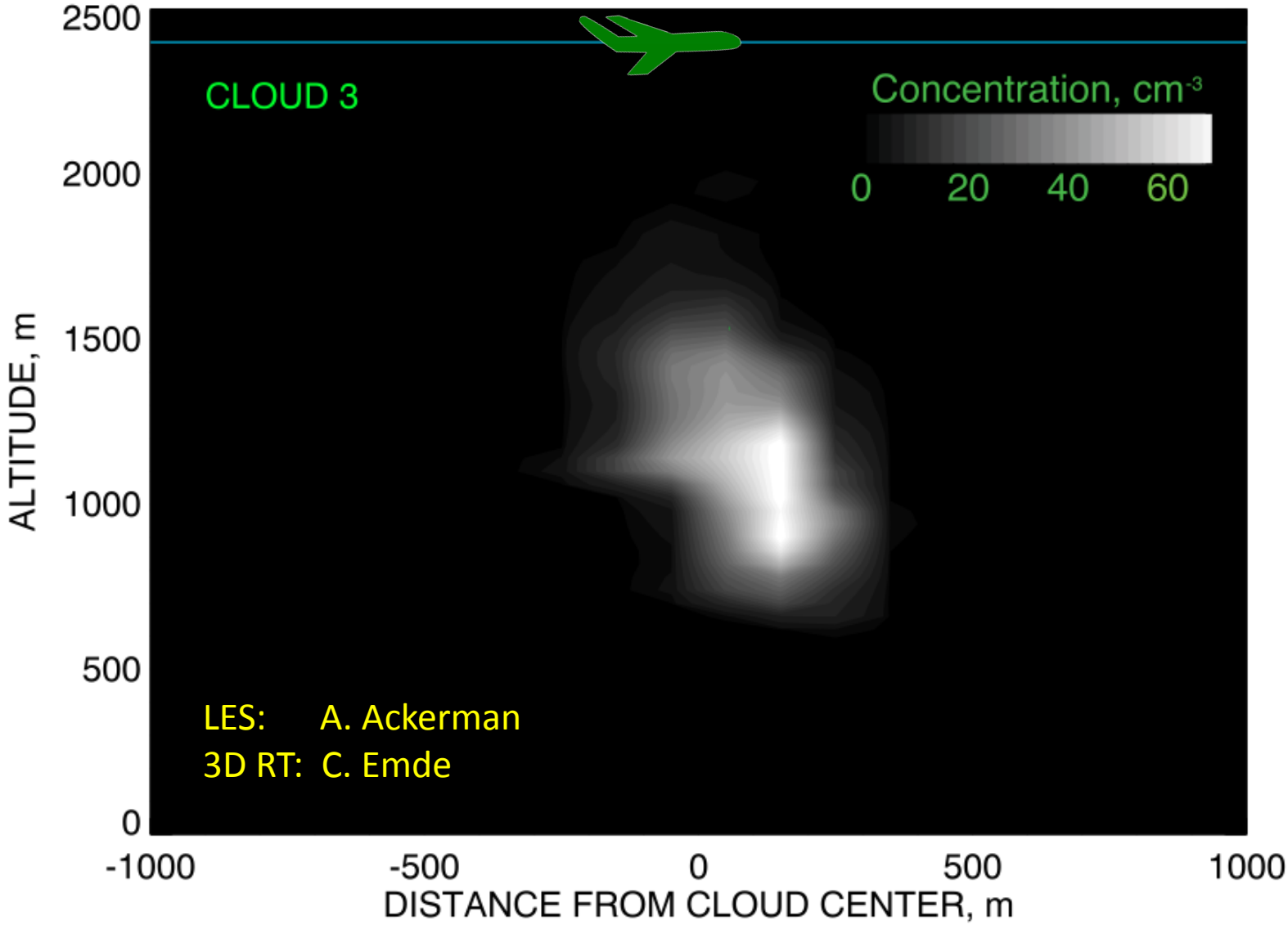




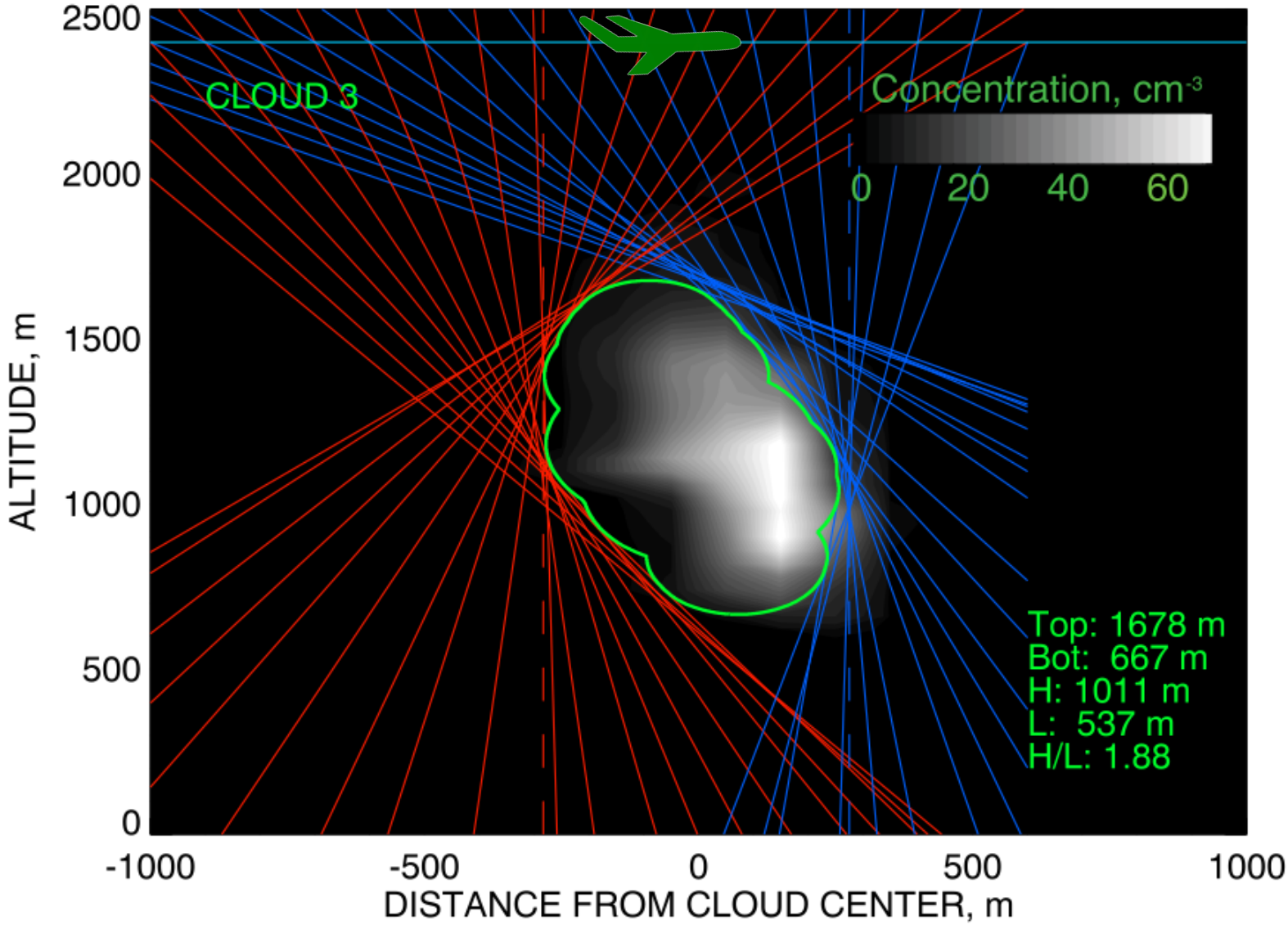
Macro + Micro = Profile

in LES + 3D RT simulations

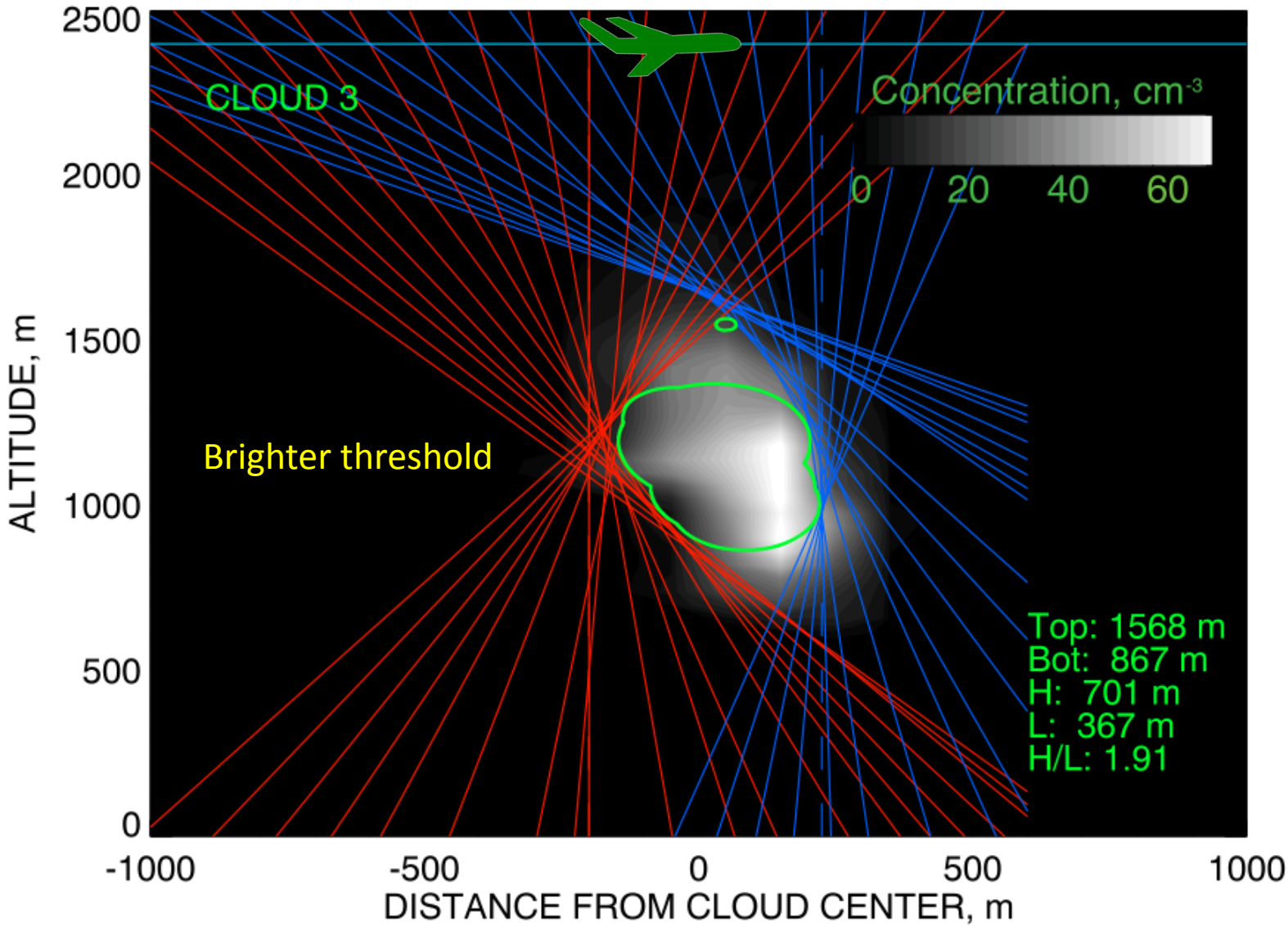
Cloud shape: LES + 3D RT simulations



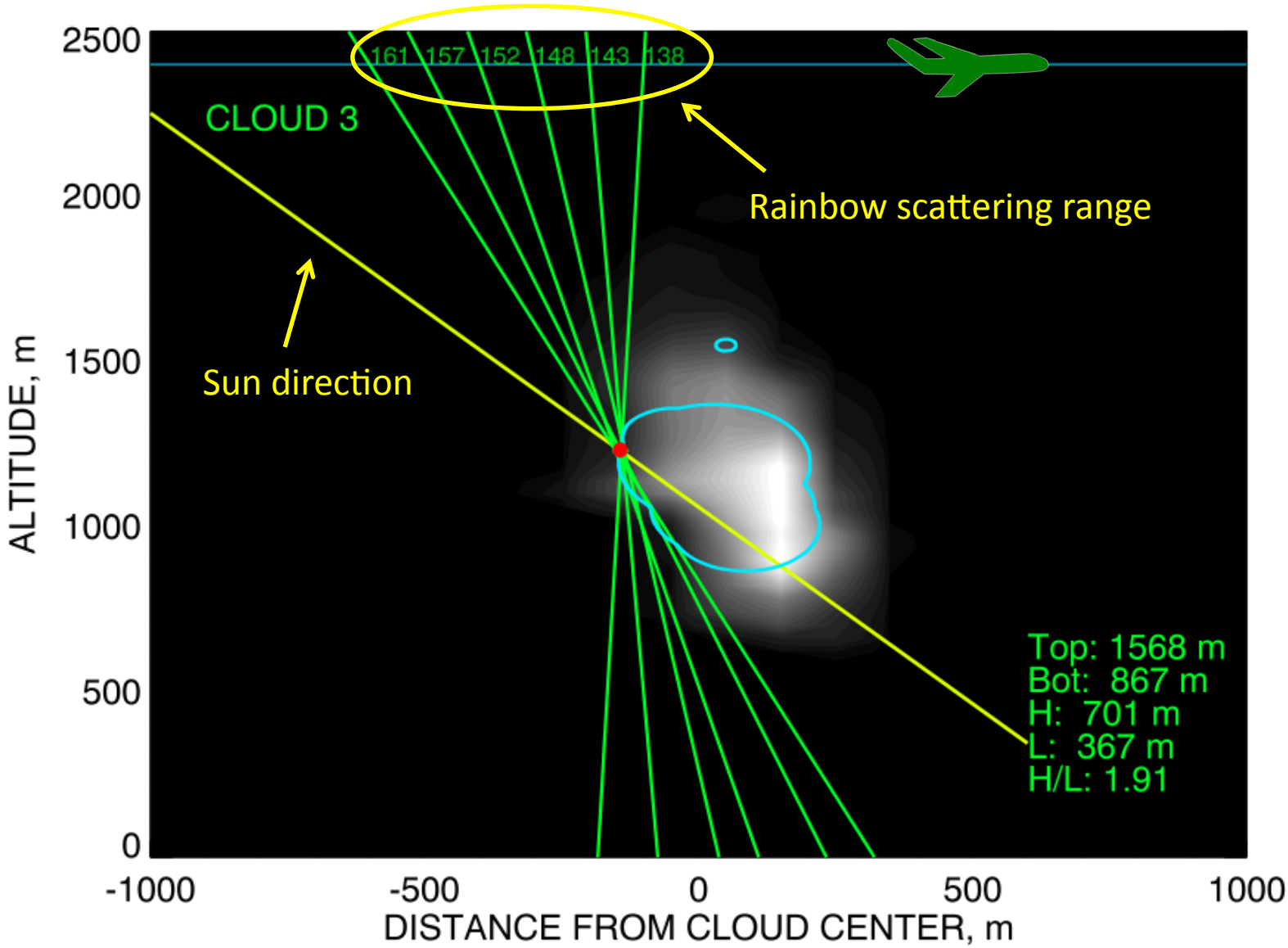
Cloud shape: LES + 3D RT simulations



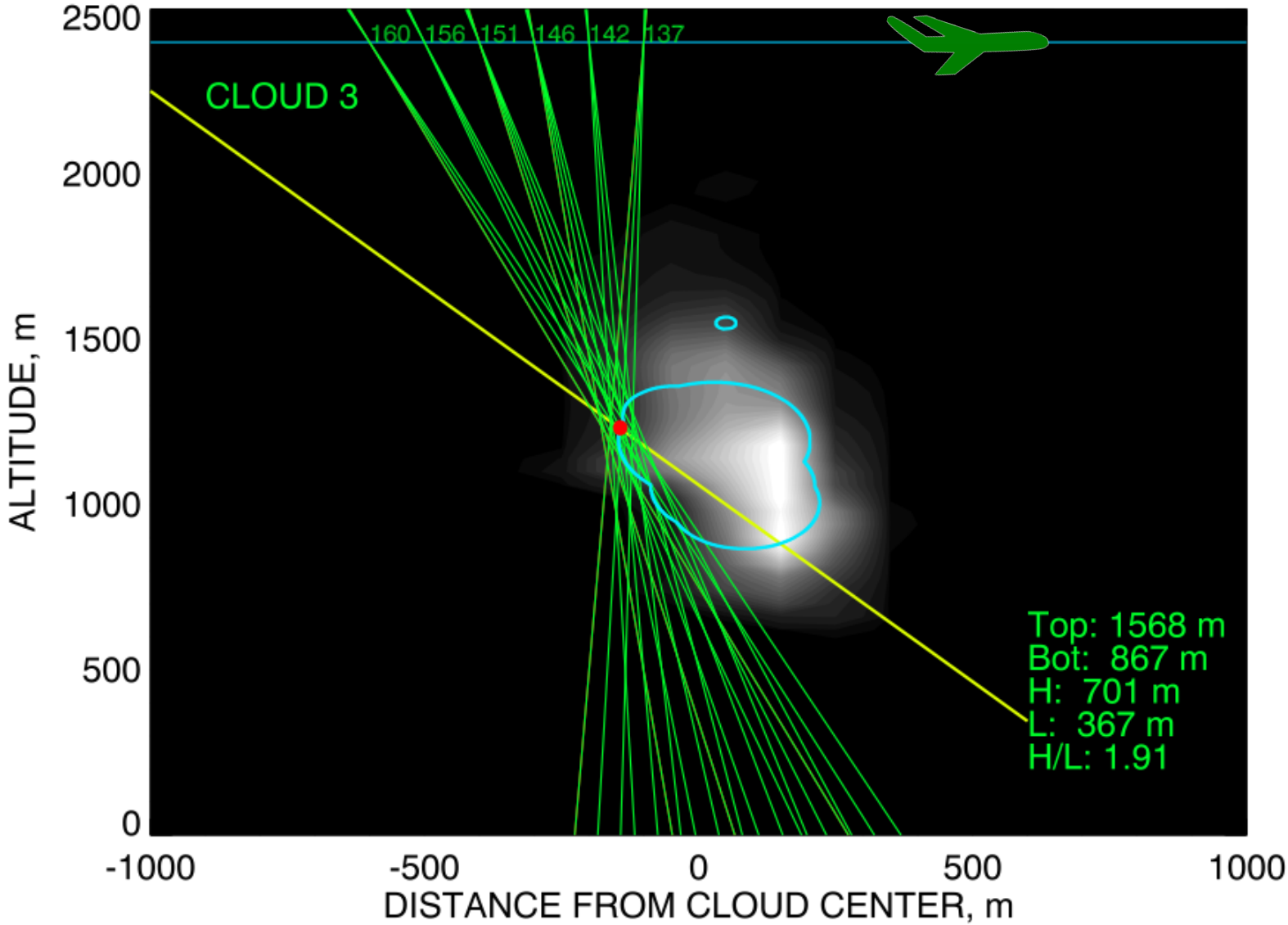
Cloud shape: LES + 3D RT simulations



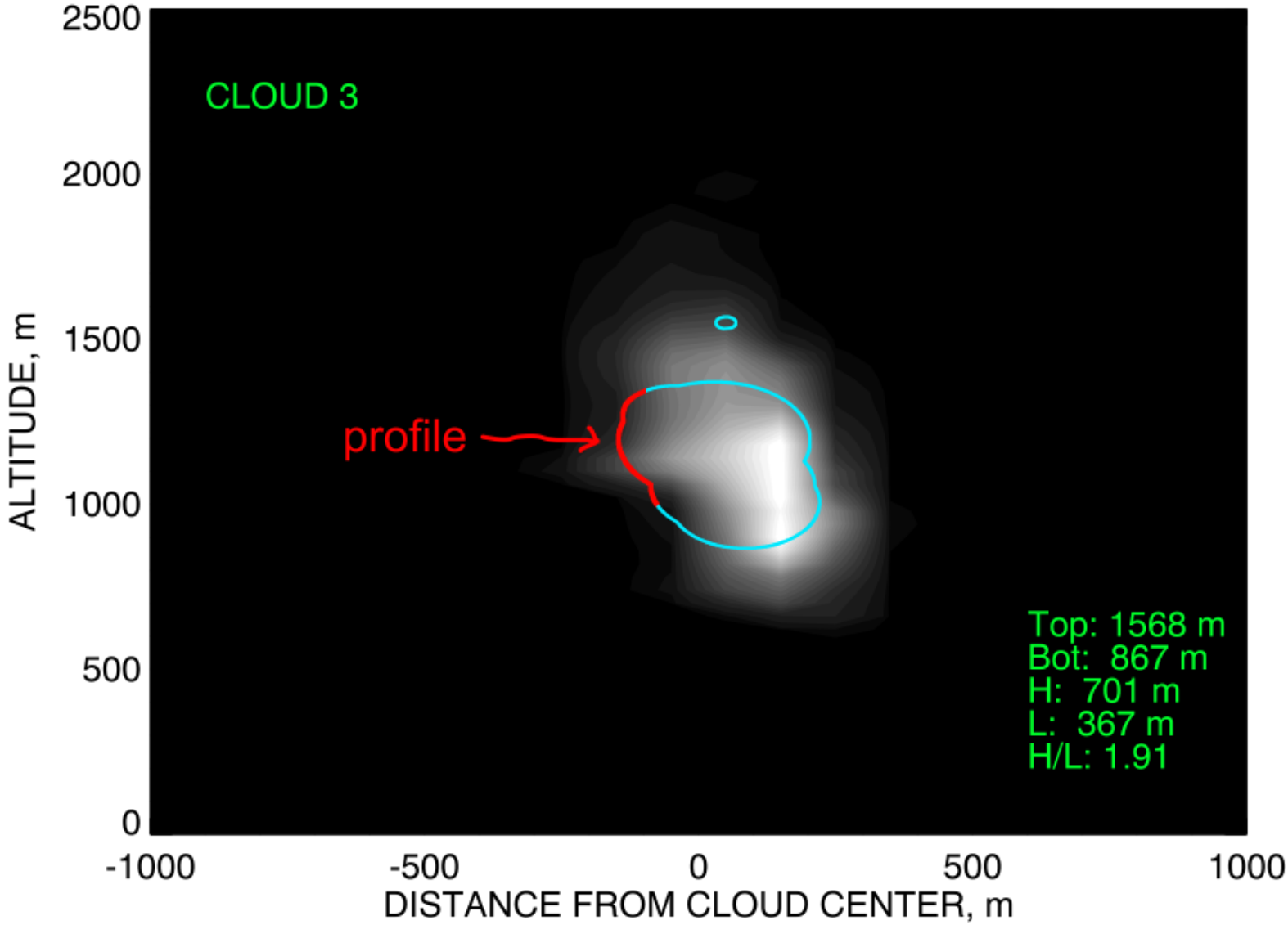
Cloud profile: LES + 3D RT



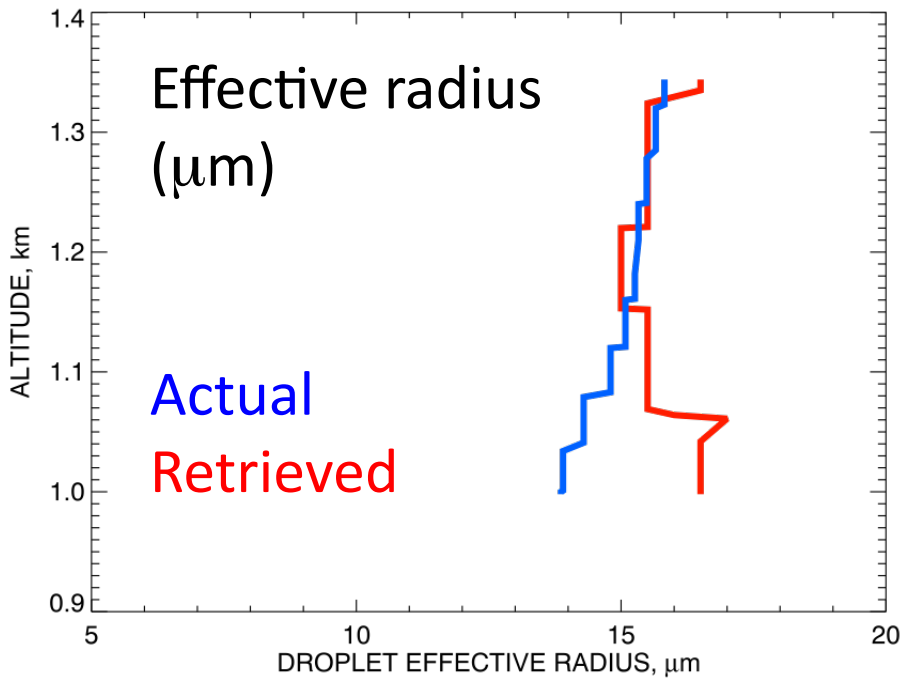
Cloud profile: LES + 3D RT

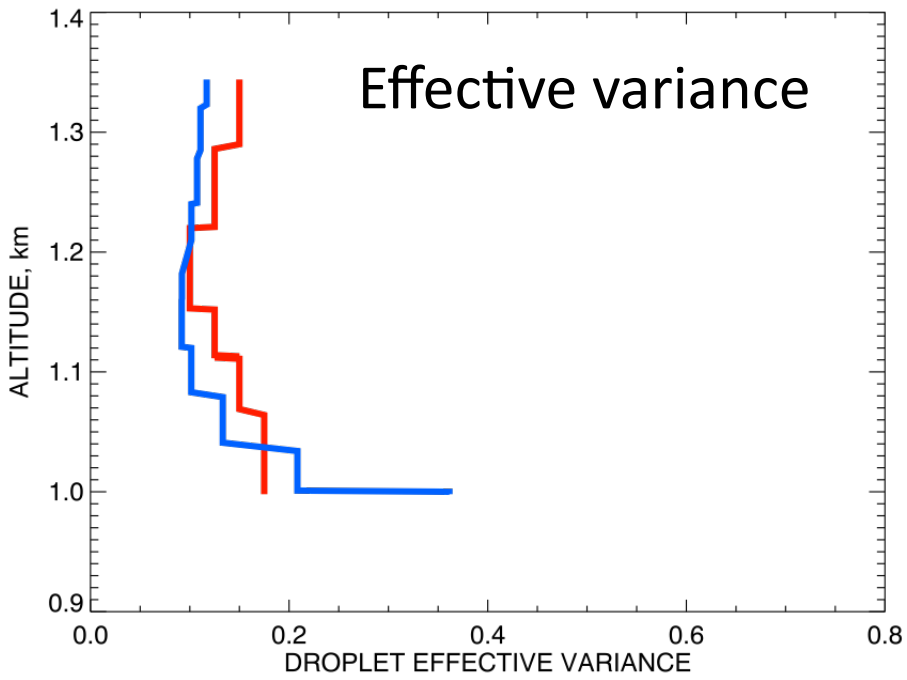


Cloud profile: LES + 3D RT



Cloud profile: LES + 3D RT





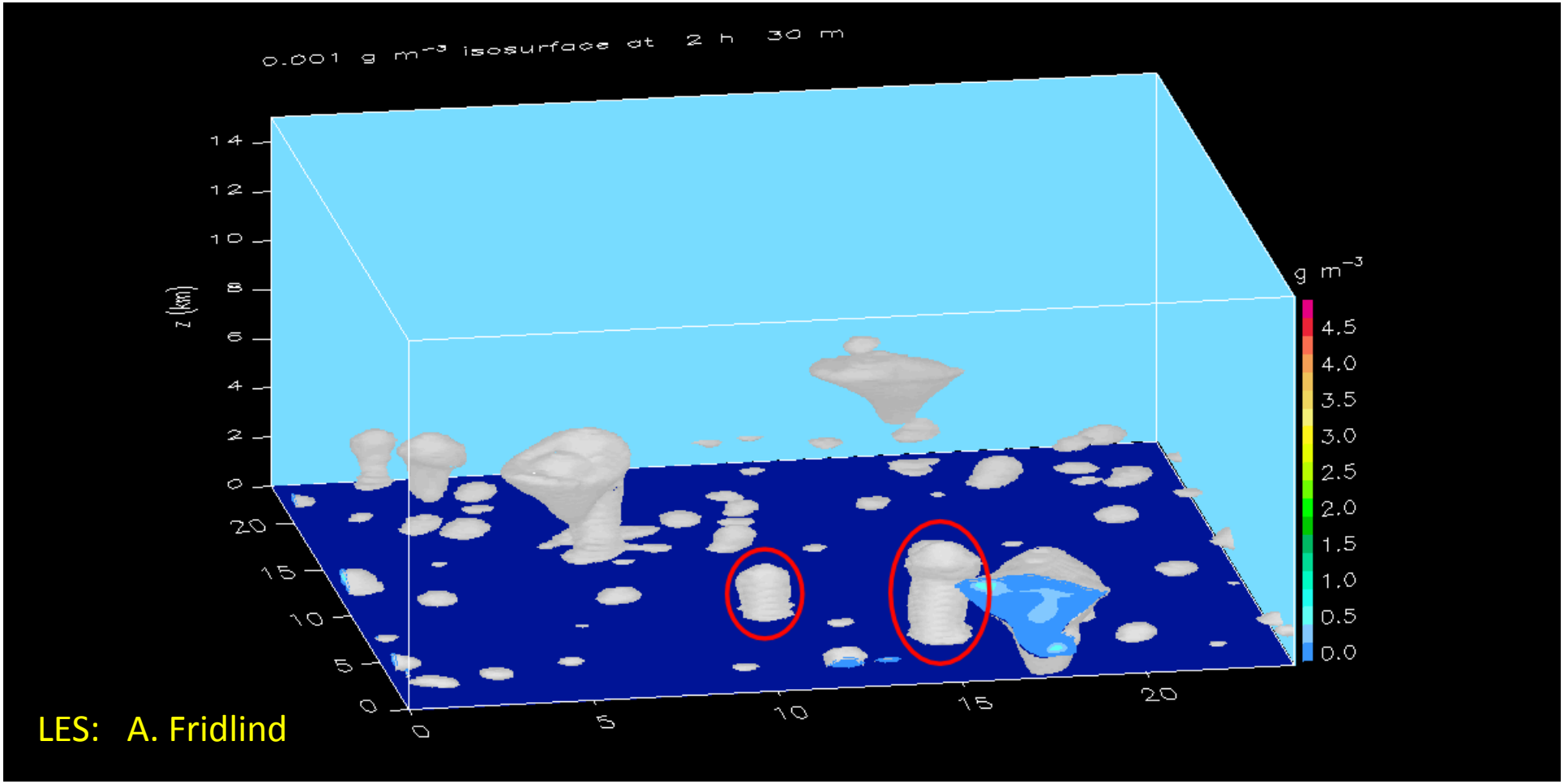
Agreement: in R_{eff} within 1 μm
in V_{eff} within 0.05

CAMP²EX

The Cloud, Aerosol and Monsoon Processes Philippines Experiment (CAMP²Ex)
Subic Bay (Philippines), mid July-August 2019.

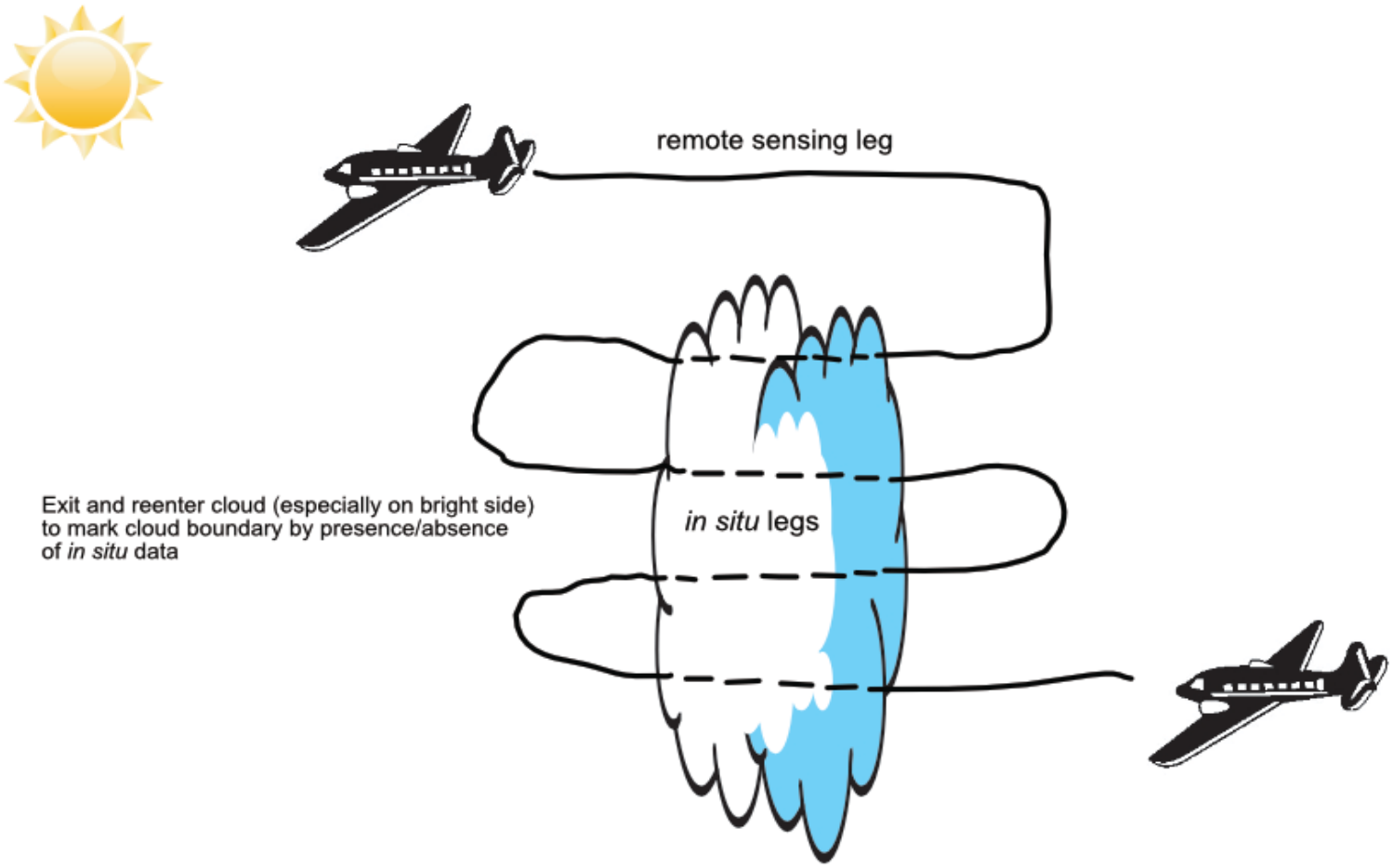
Grant: NNH16ZDA001N-CAMP2EX

Baby (no anvil) Cu congestus (Tcu)

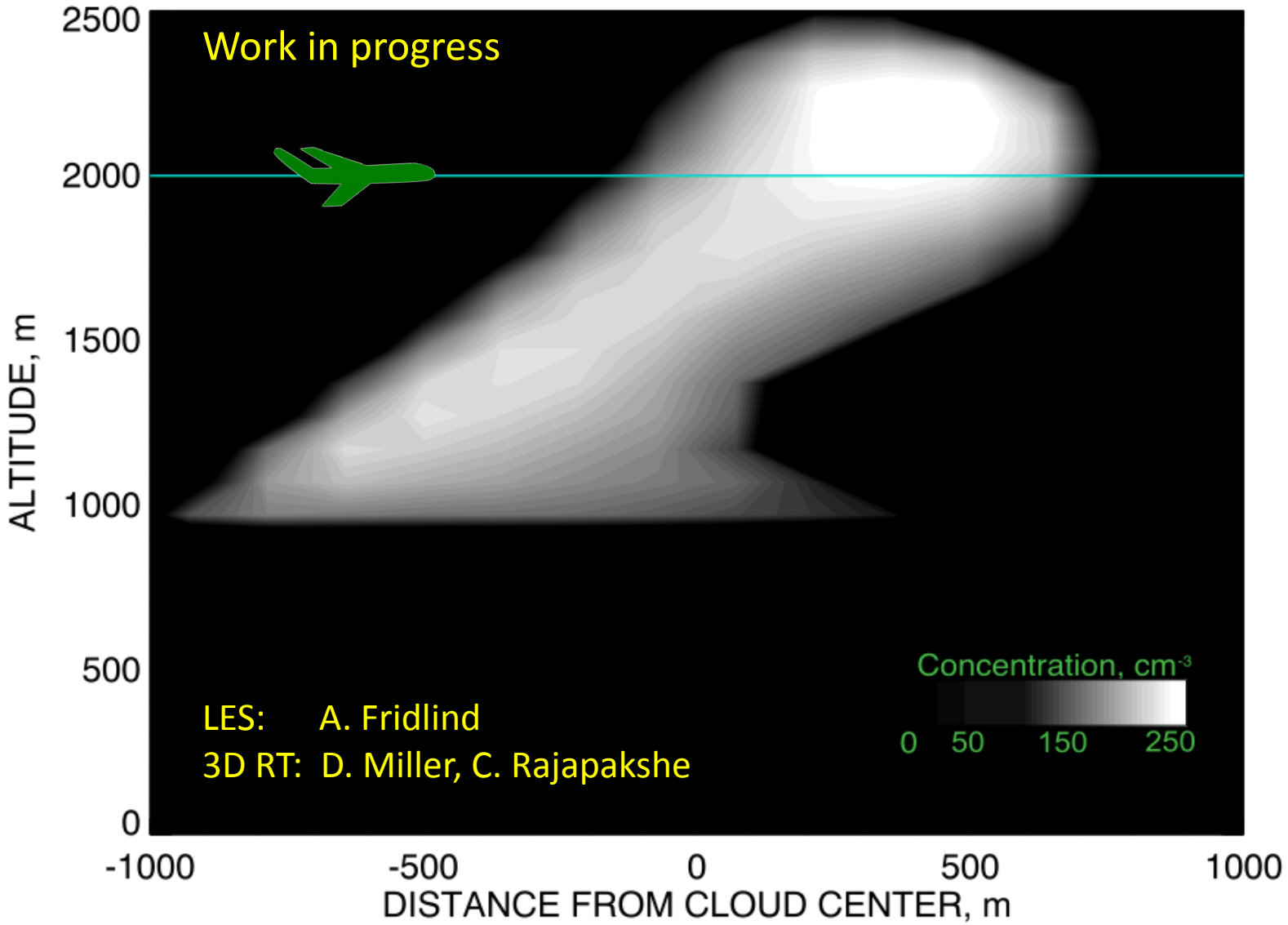


LES: A. Fridlind

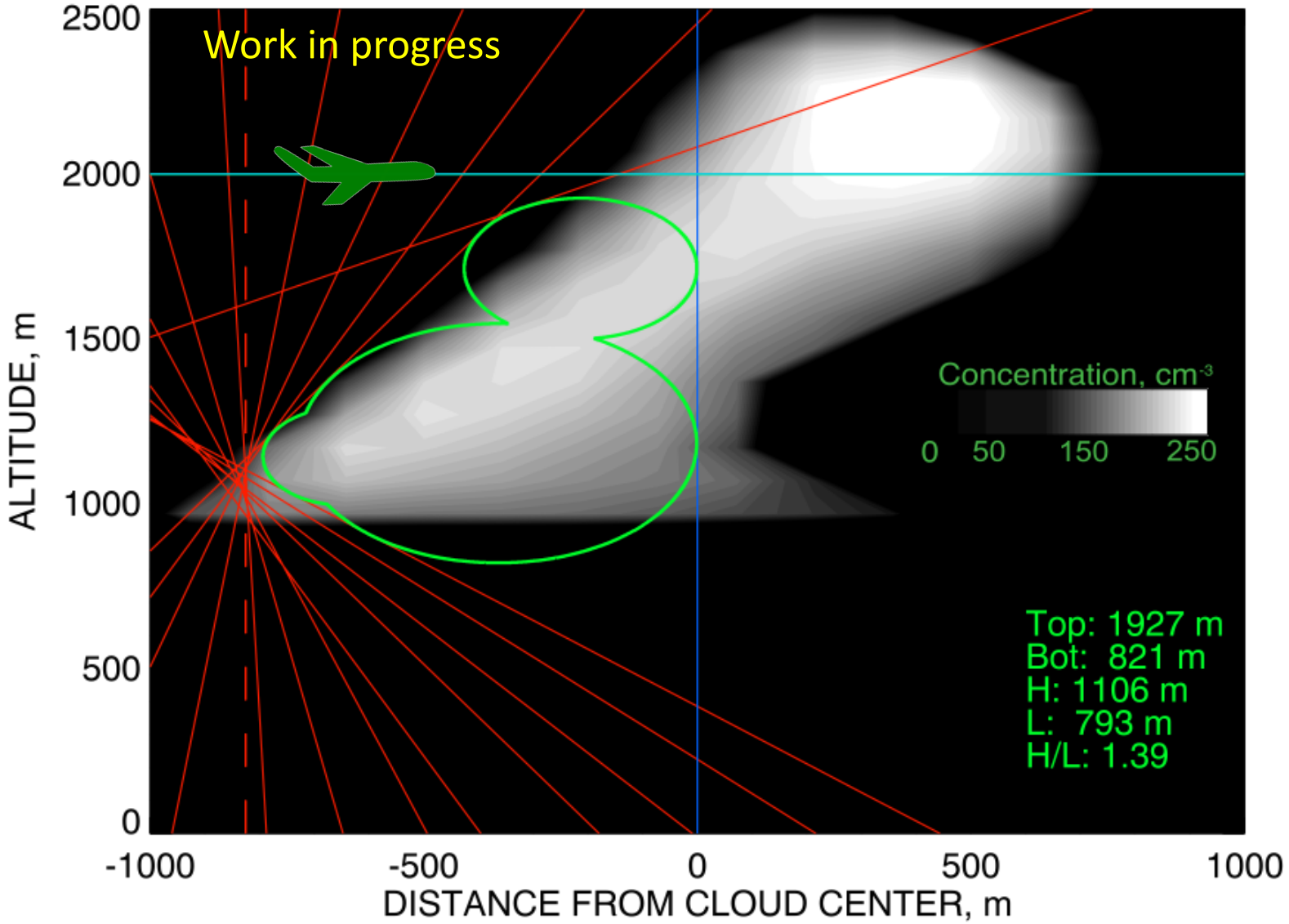
In situ validation flight pattern



Towering Cu: LES + 3D RT simulations



Towering Cu: LES + 3D RT simulations



Summary

- The Research Scanning Polarimeter (RSP) facilitates retrievals of both microphysical (droplet size) and macrophysical (geometrical shape) cloud parameters.

- Polarimetric droplet size estimates were successfully validated against correlative in situ measurements (NAAMES, May 2016).

- Cloud shape retrieval techniques were tested on realistic simulations (LES + 3D RT) and applied to real data (DEVOTE, October 2011).

- Combination of micro- and microphysical retrieval allows to use RSP data to derive droplet size profiles along cloud side.

- This has been demonstrated on simulated data. We expect to apply this technique to RSP observations of Cumulus congestus (towering cumulus, Tcu) clouds during the upcoming CAMP^{2}Ex field campaign (July-August 2019).

Additional slides

Total and Polarized reflectances

Current methods for remote sensing of cloud droplet size in the solar spectral domain use:

- **Total Reflectance** $$R(\theta) = \frac{\pi I(\theta)}{\mu_s I_0}$$

in an absorbing and non-absorbing band (e.g. Nakajima and King, Platnick et al. using MODIS)

- **Polarized Reflectance** $$R_p(\theta) = -\frac{\pi Q(\theta)}{\mu_s I_0}$$

(e.g., Bréon et al. using POLDER)

I_0 - TOA irradiance, μ_s - cosine of SZA, θ - scattering angle.

RSP allows both methods to be used simultaneously.

Cloud droplet size retrievals from polarized reflectance in rainbow region

The measured polarized reflectance R_p :

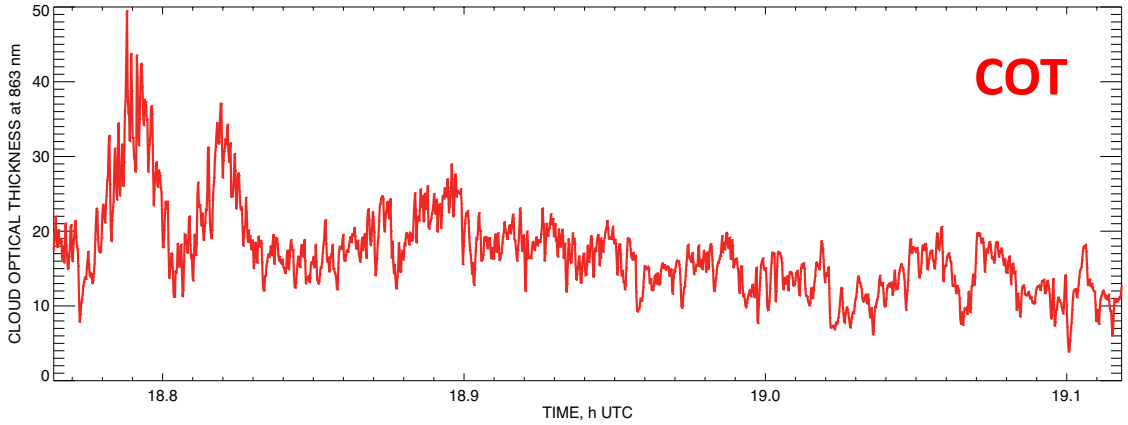
$$R_p(\theta) = aP_{12}[\theta, n(r)] + b\cos^2\theta + c$$

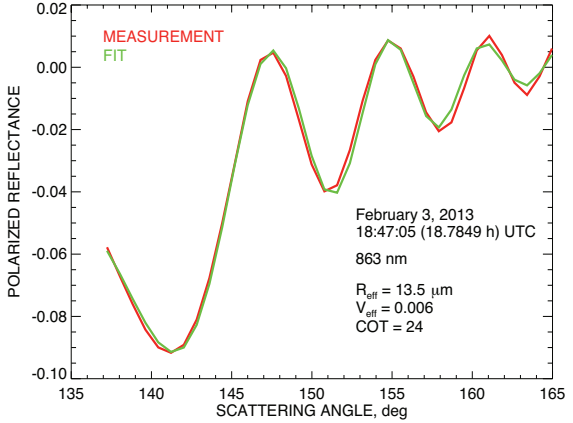
P_{12} represents contribution of single scattering by cloud drops

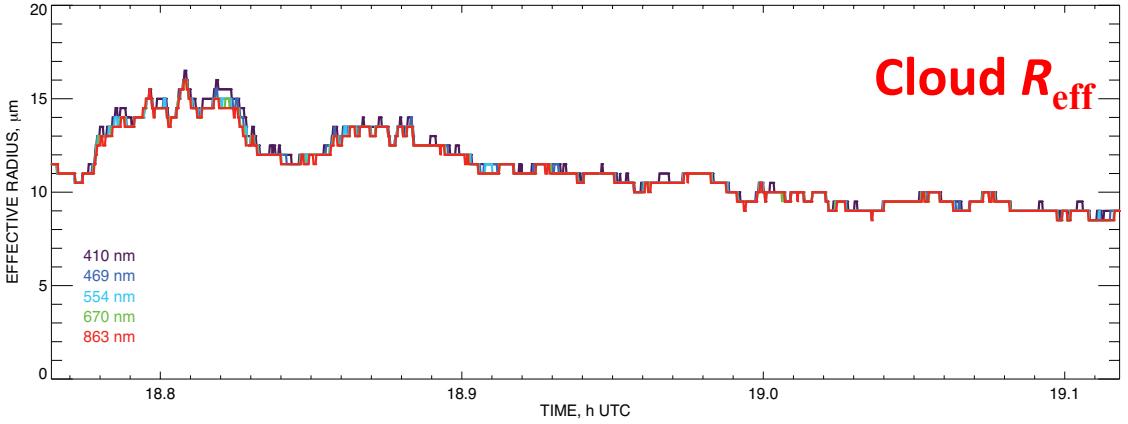
a, ***b***, and ***c*** account for the effects of multiple scattering, Rayleigh, aerosols, etc.

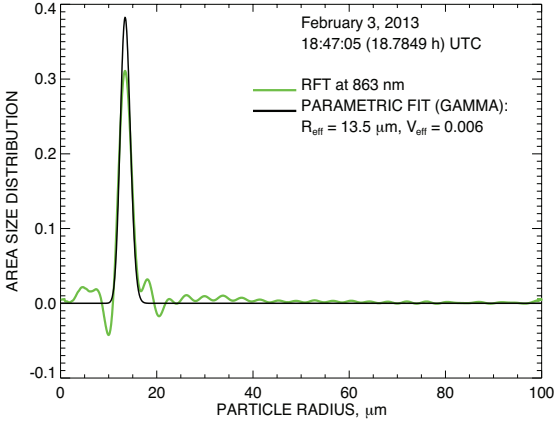
Marine stratocumulus

- Variation of droplet size in marine Sc cloud deck off California coast.
- Very low effective variance of 0.01 is also typically observed *in situ* for marine stratocumulus clouds (*Pawlowska et al.*, 2006).









Cloud shape: LES + 3D RT simulations