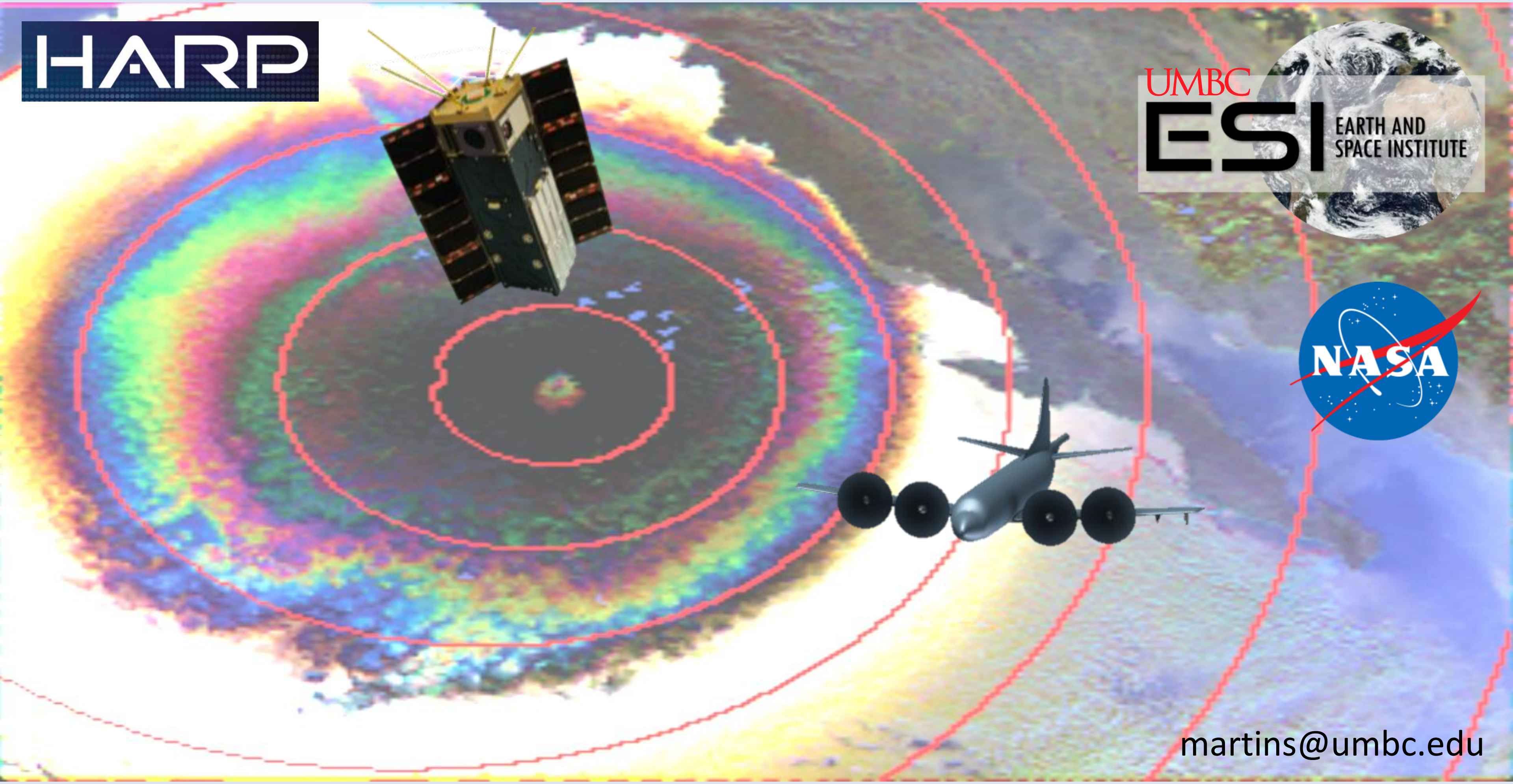
The Hyperangular Imaging Polarimeter (HARP) and the Use of Nanosatellites for Earth Science Remote Sensing



J. Vanderlei Martins

Department of Physics, UMBC - USA; JCET, UMBC and NASA Goddard- USA

Earth and Space Institute, UMBC – USA.

Use of Small Satellites for (Earth) Science Applications

- Nano-Satellites reached a level that they can be used as advanced platforms for Earth, Space and Planetary Sciences with impressive capabilities for pointing, stability, data storage and data downlink.
- Small payloads are also reaching high level of maturity for many important Earth Science measurements.
- The low cost of nano-satellites allow for unprecedent measurements and concepts that were not possible with large satellites.
- Nano-satellites are not only prototypes. They can also be used for the actual monitoring of our Planet.

Example: HARP CubeSat

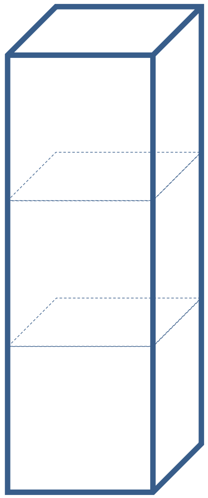
- HARP is a nanosatellite the size of a loaf of bread with big Earth Science ambitions.

CubeSats Small Satellites that are Scalable in size,

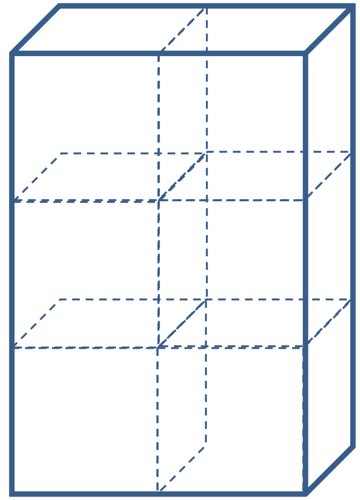
1U

4”

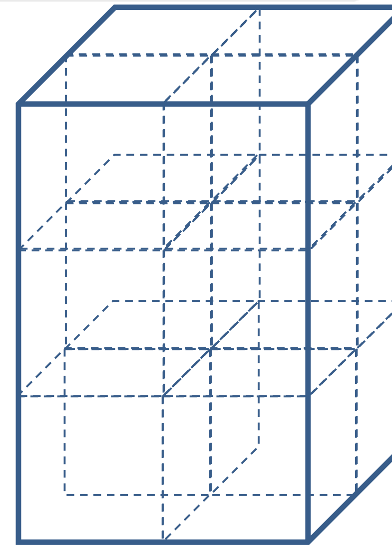
3U



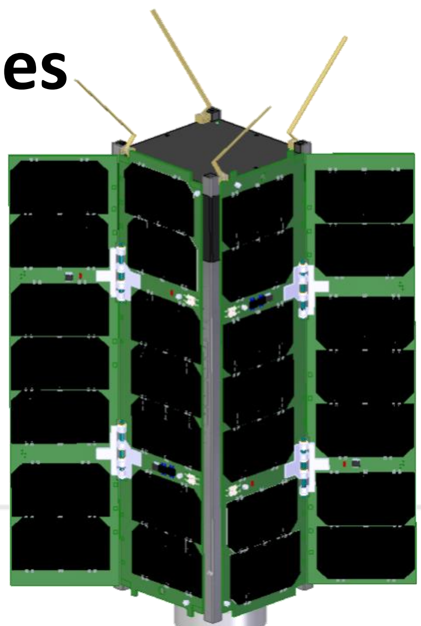
6U



12U

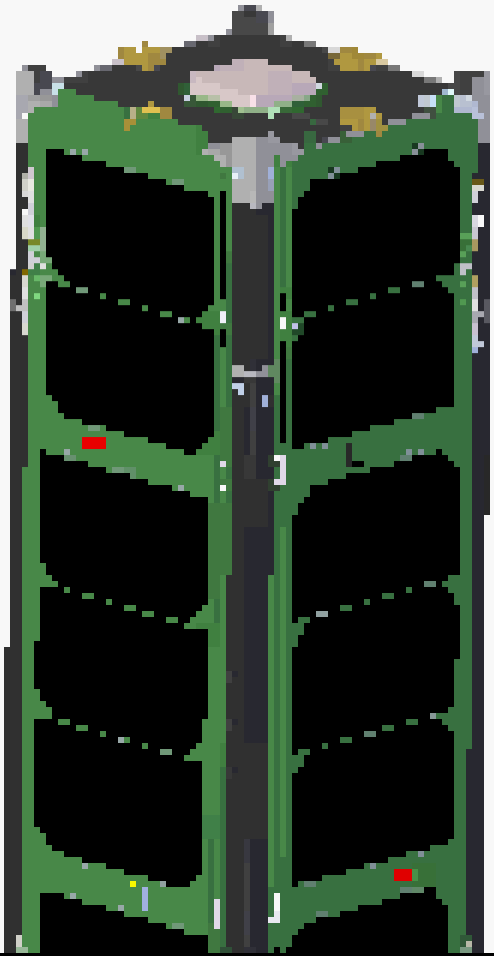


deployables, and capabilities



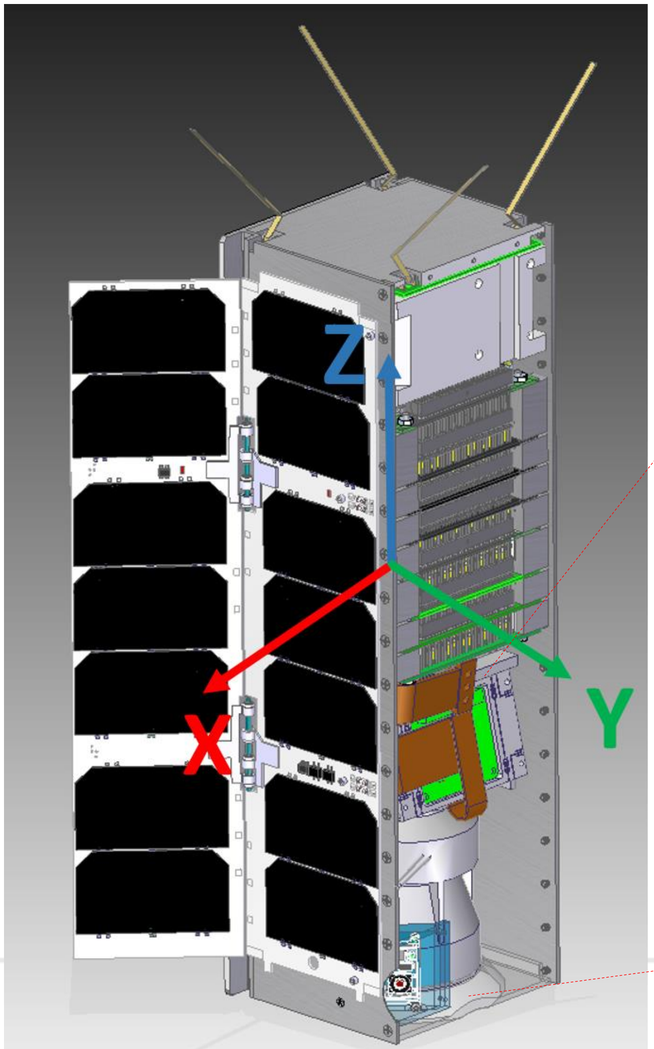
- Started as Engineering Education and training
- Were Developed as Proof of concepts, Demonstrations and testing
- Are Moving to Real Science and Operational Applications

HARP



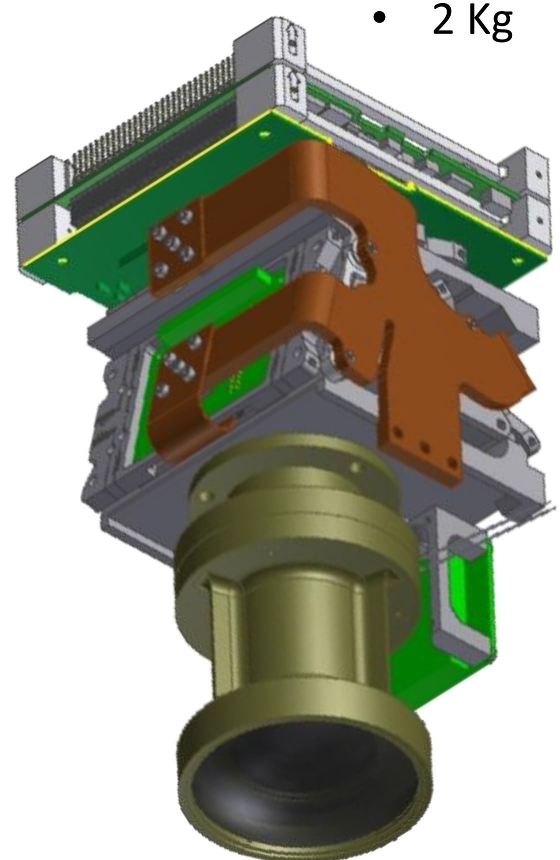
Example: HARP Instrument & Spacecraft – Funded by NASA ESTO InVest Program

HARP Spacecraft



HARP Imaging Polarimeter

- 6 inches long
- 2 Kg



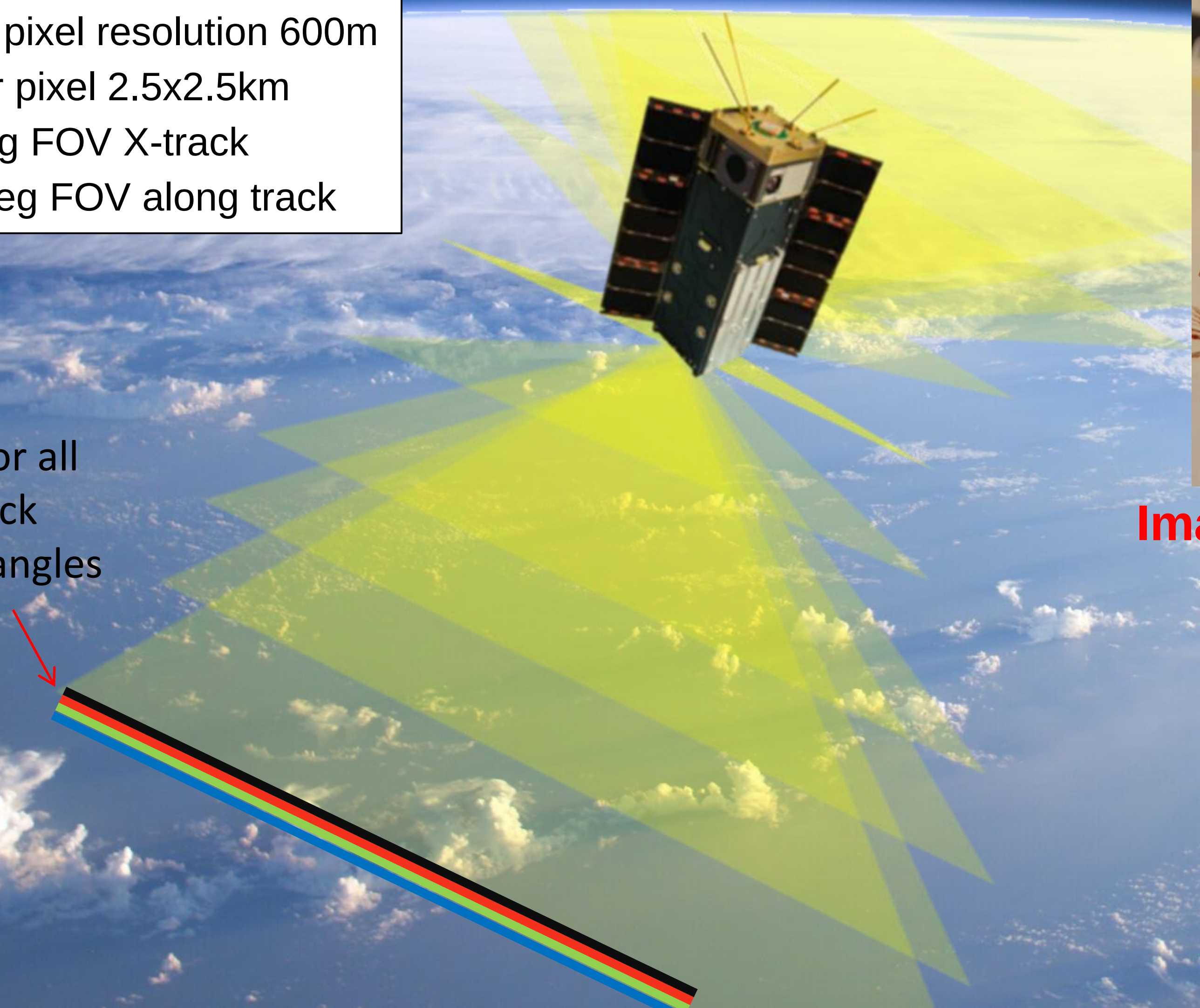
UMBC HARP

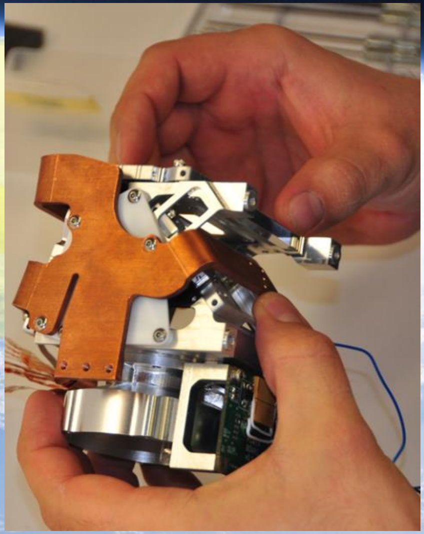
HARP CubeSat Satellite to launch in Dec. 2018

HARP Polarimeter Specs

- ISS orbit
- 60 angles for cloudbows
- 20 angles for aerosols
- 440, 550, 670, 870nm
- Nadir pixel resolution 600m
- Super pixel 2.5x2.5km
- 94 deg FOV X-track
- 117 deg FOV along track

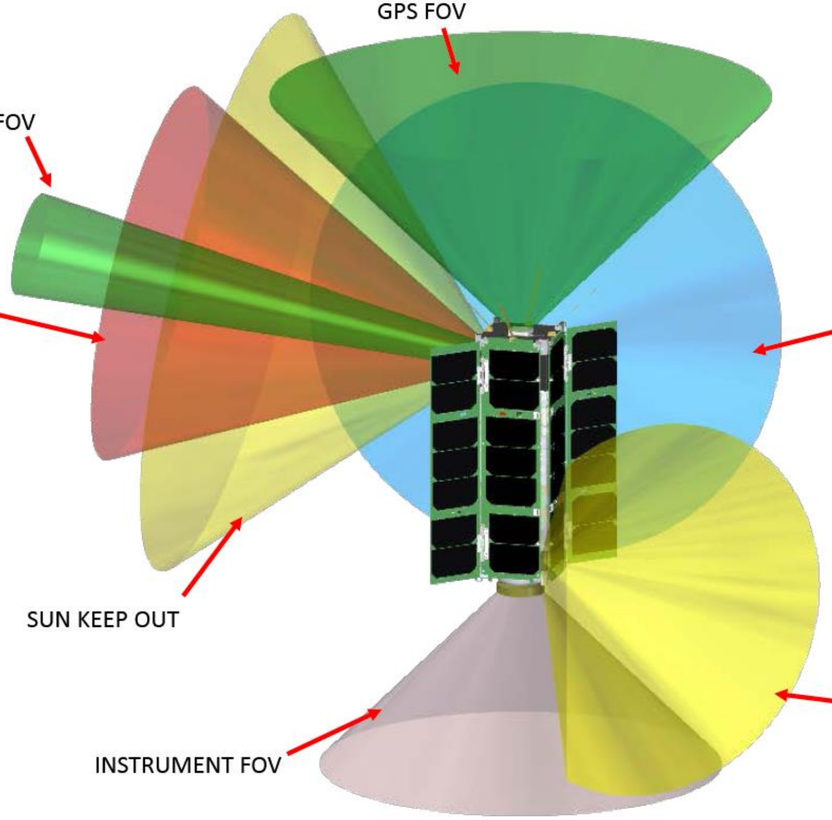
Repeat for all along track viewing angles





Imaging polarimeter

HARP – Full Feature Earth Sciences Satellite



- Accurate ACDS
- Sun Sensor + Star tracker
- < 0.66km pointing knowledge/geolocation
- UHF radio up to 3Mbits/s

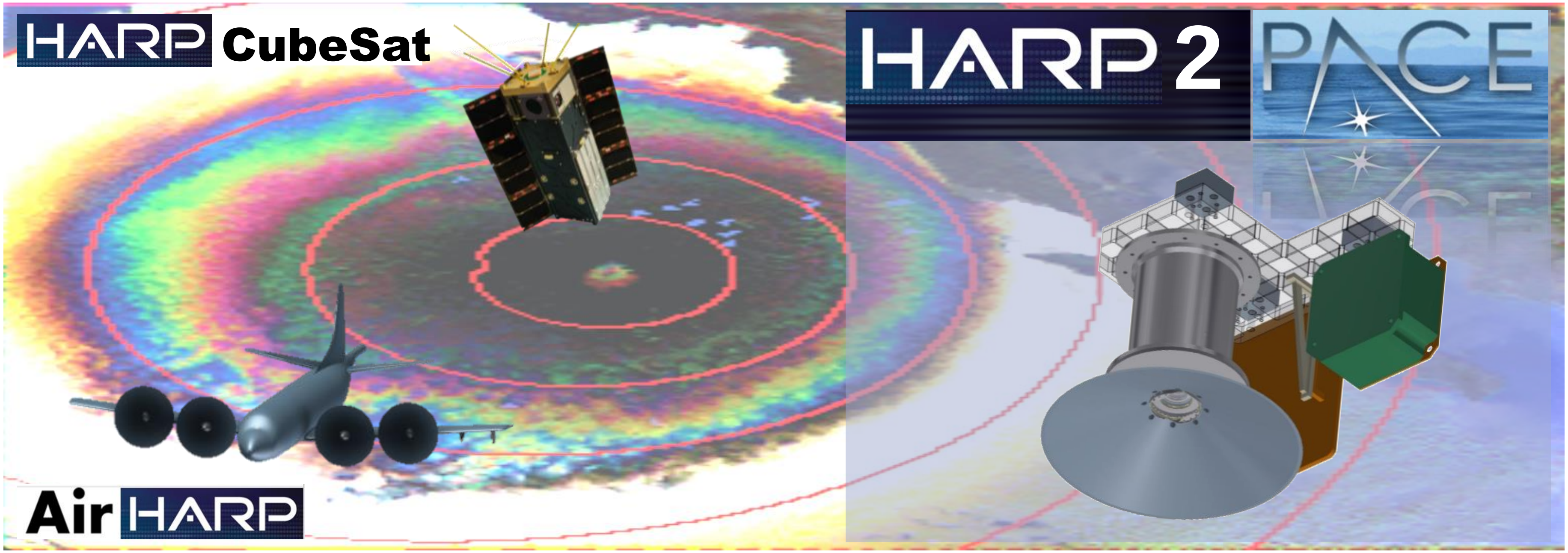
ISS orbit crosses within minutes of other satellites several times a day (example: 13 Apr 2016):

- Terra < 1 min
- NPP < 1min
- Aqua < 5 min
- Aqua < 5 min
- NPP < 5 min

UMBC Space Dynamics LABORATORY Utah State University Research Foundation

Hyper-Angular Rainbow Polarimeter Versions

Small sensor for a Large Satellite



And In situ airborne Measurements

HARP Objectives

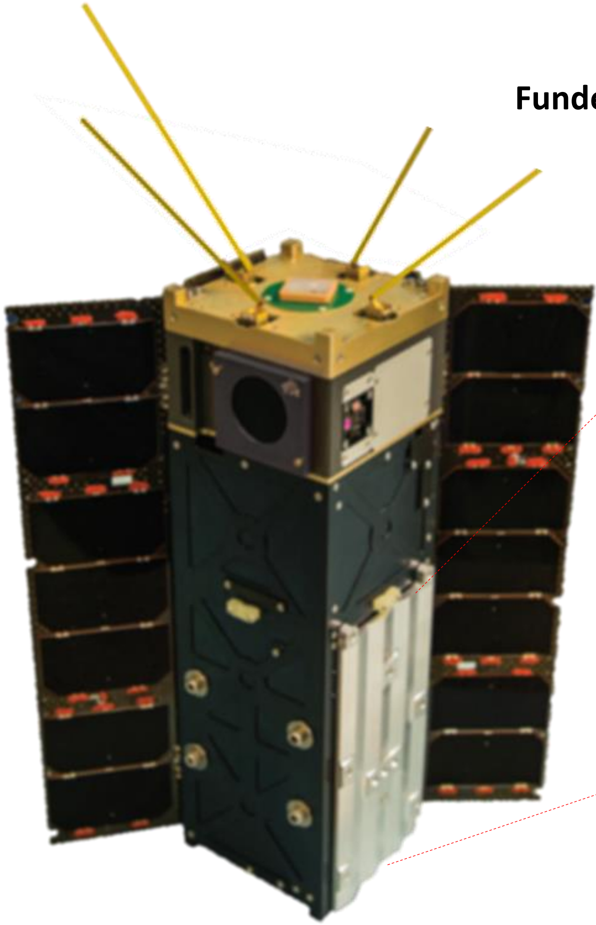
- Validate the in-flight capabilities of a highly accurate and precise wide field of view hyperangular polarimeter for characterizing aerosol and cloud properties.
- Prove that CubeSat technology can provide science-quality multi angle imaging data paving the way for lower cost aerosol-cloud instrument developments.
- Provide opportunities for student research and engineering training in implementing a space mission.

HARP Science Goal

- Demonstrate the ability to characterize the micro physical properties of aerosols and clouds at the scale of individual moderate-sized clouds for the ultimate purpose of narrowing uncertainties in climate change.

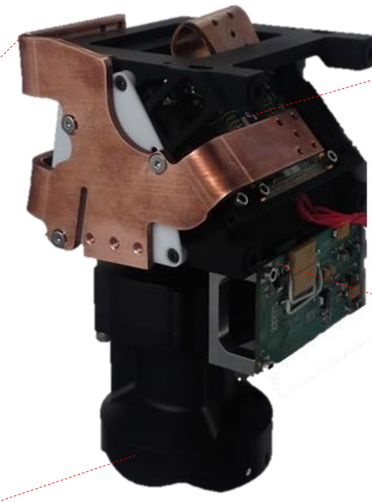
HARP Payload and Spacecraft

Funded by NASA-ESTO InVEST Program - Expected Launch May/2018

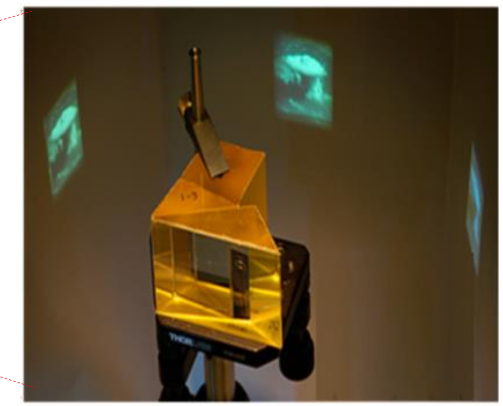


SDL Spacecraft

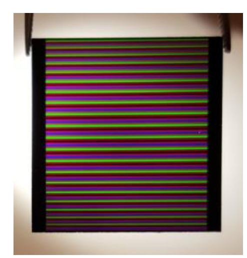
UMBC Sensor



HARP Prism



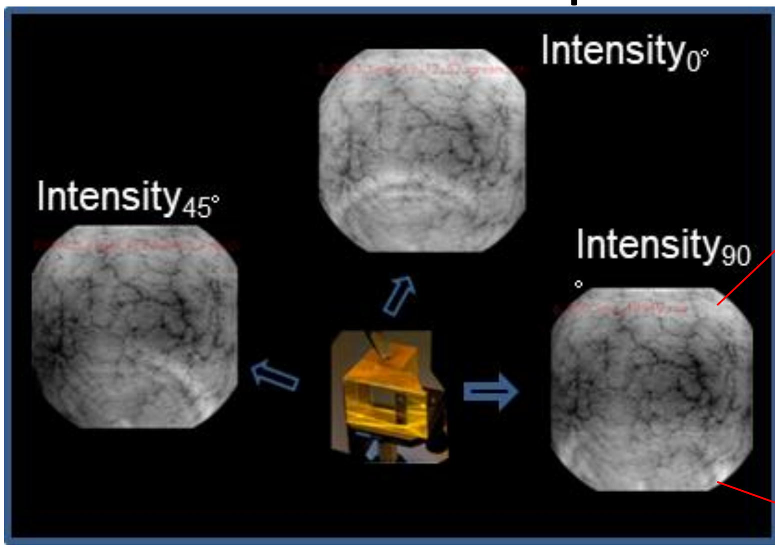
HARP Stripe Filter



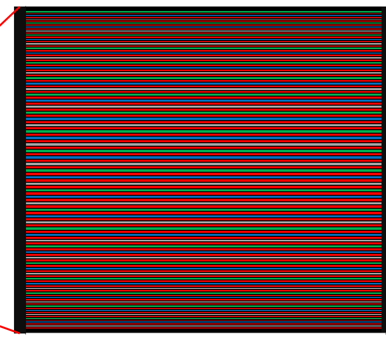
HARP
- Up to 60 viewing angles
- 440, 550, 670, 870nm
- 4 km binned resolution
- 94 deg FOV X-track
- 113 deg FOV along track

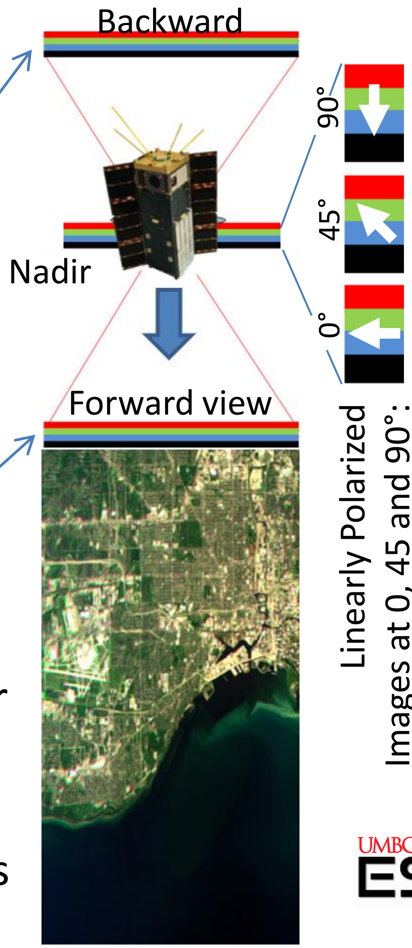
HARP Hyper-Angular Multi-Wavelength Polarization Images

HARP Prism Polarization Separation

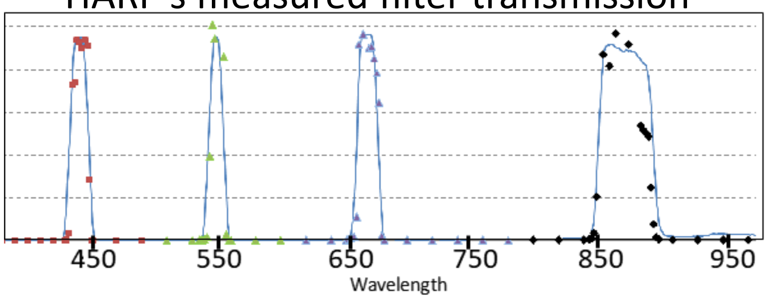


Stripe Filters: Angular and Wavelength Separation



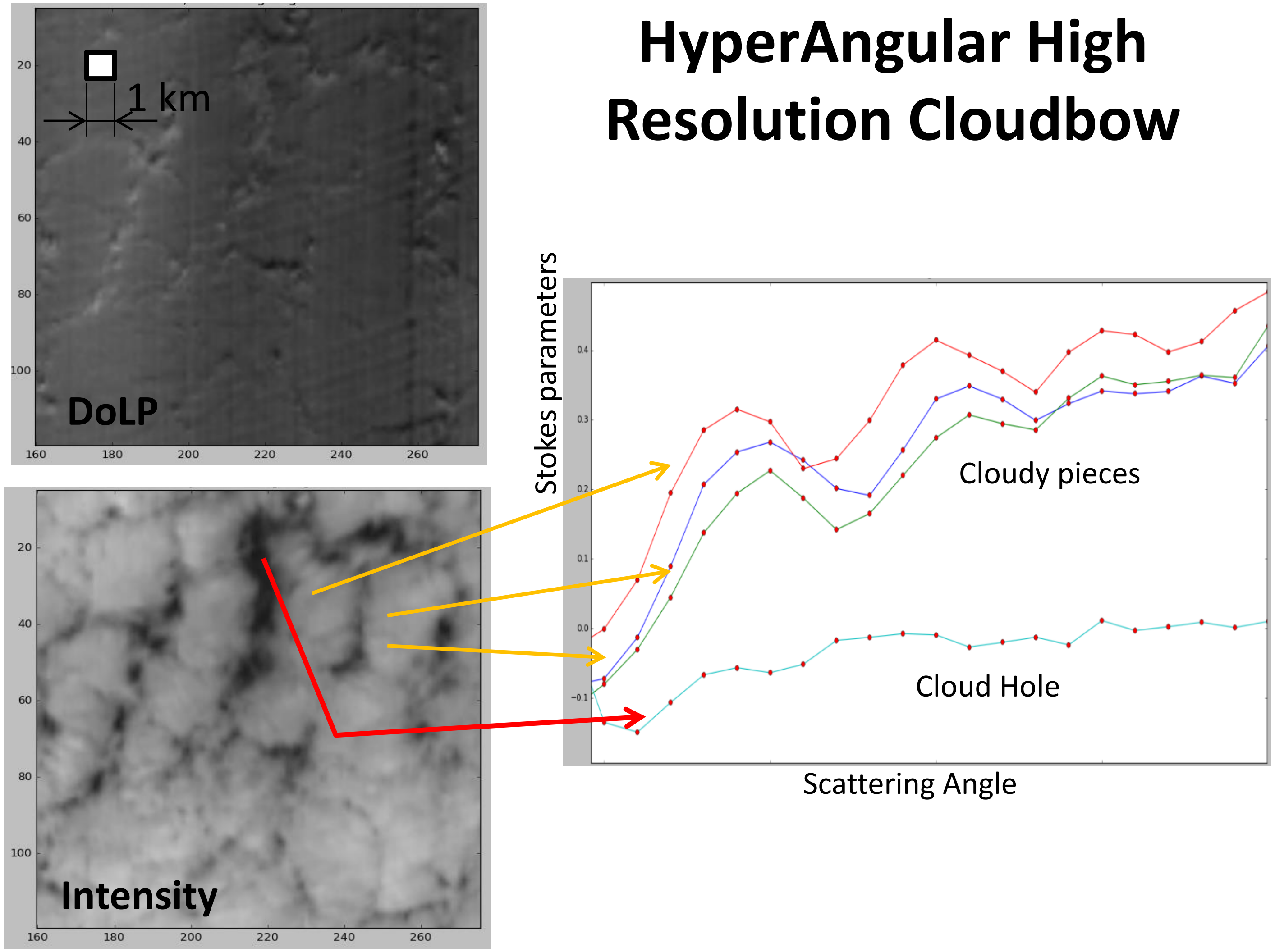


HARP's measured filter transmission



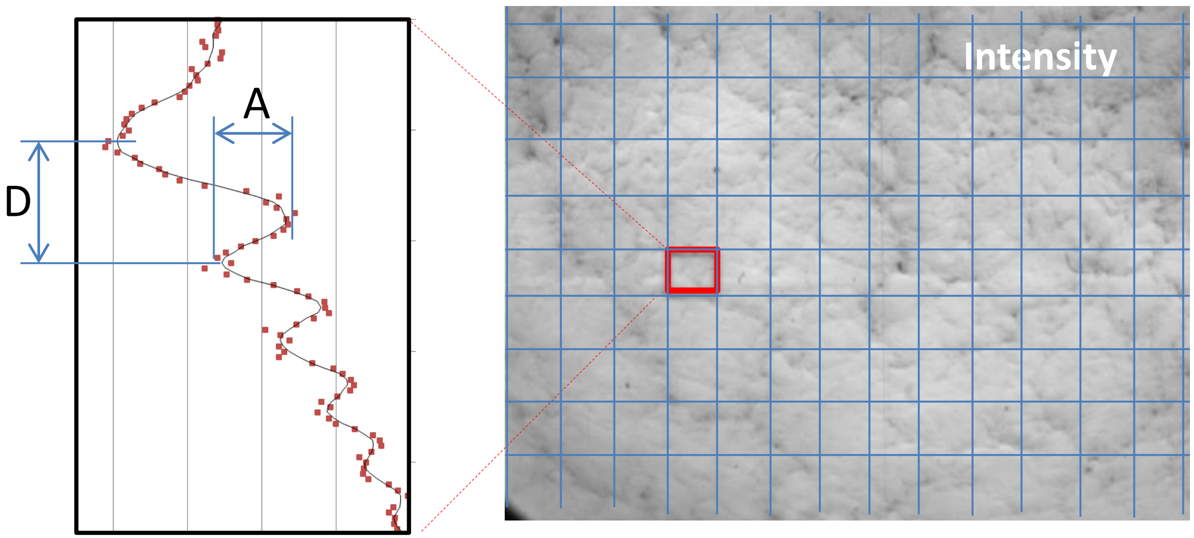
Multi/Hyper Angle with multiple pushbrooms

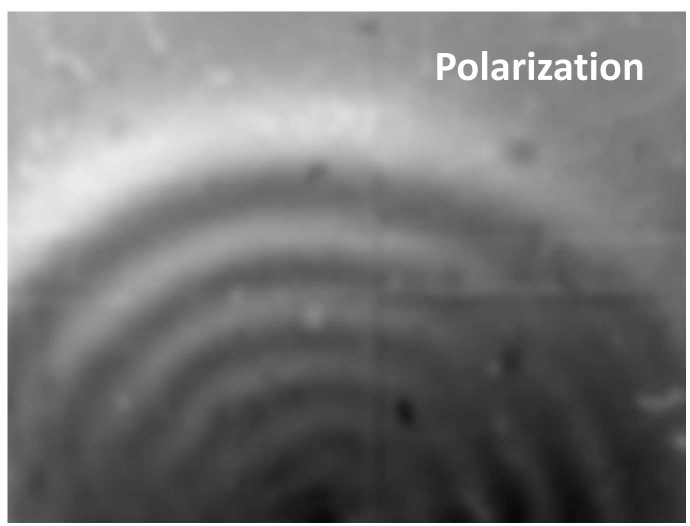
HyperAngular High Resolution Cloudbow



HARP CubeSat Polarimeter

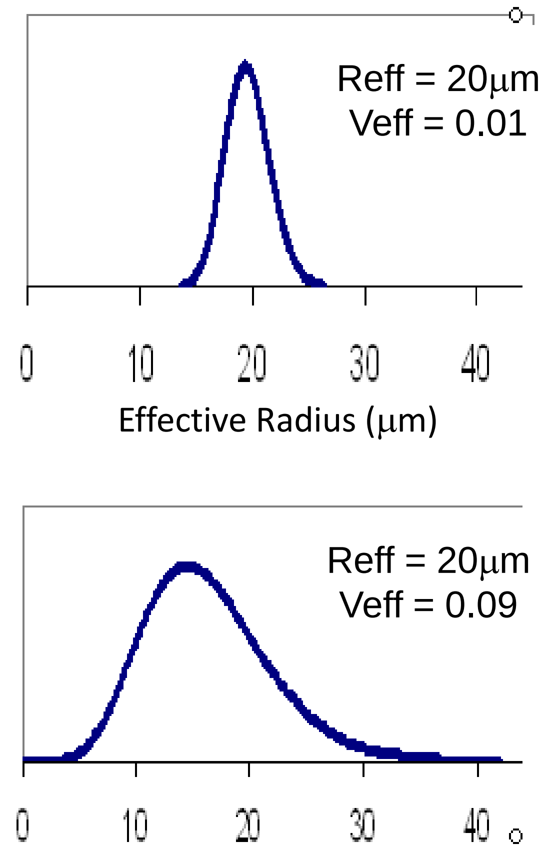
HARP Pioneering Hyper-Angular Capability will Provide Full Cloudbow Retrievals from Small Area (< 4x4km from space)





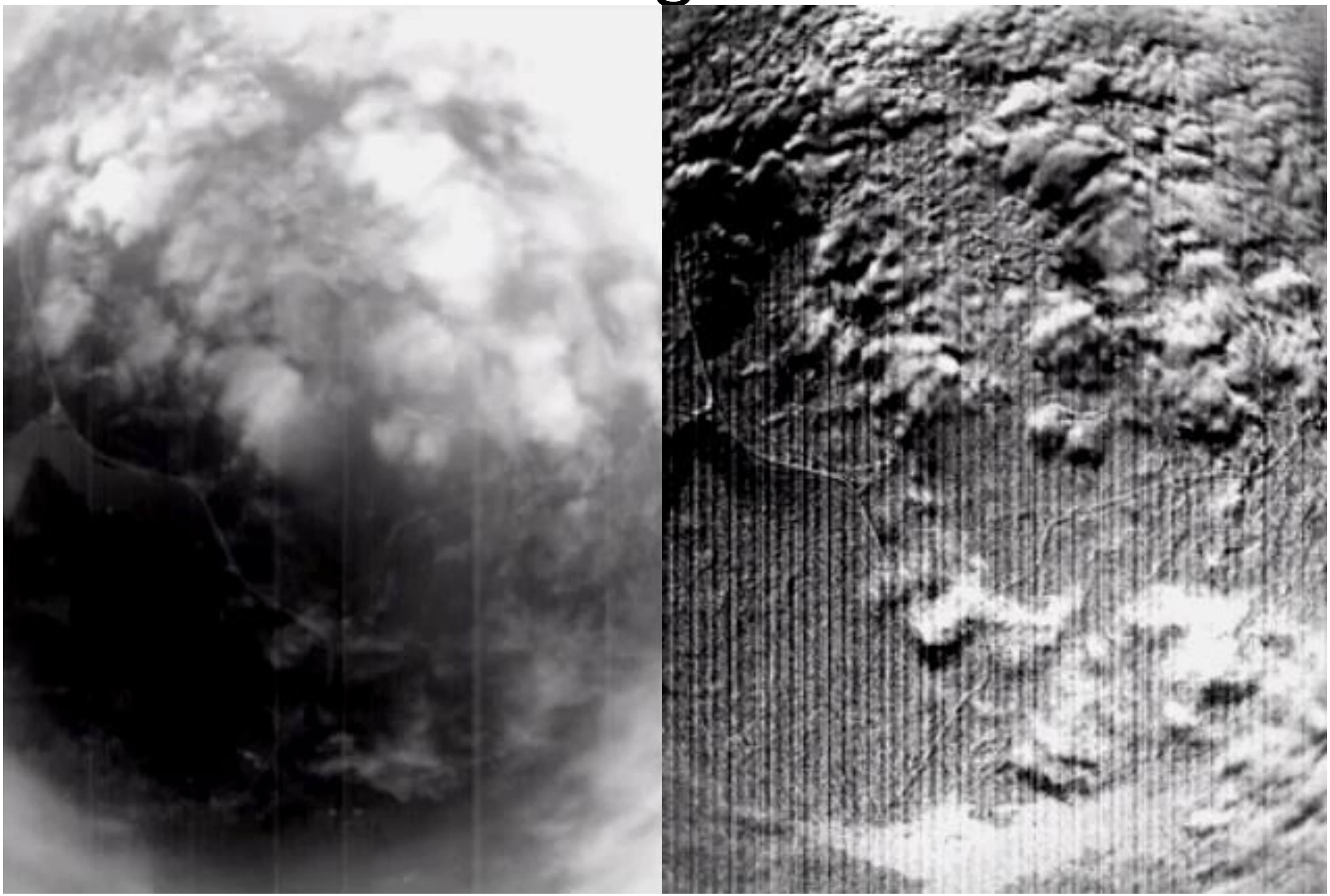
Same retrieval capability for all individual pixels with < 4x4km resolution

Water Droplet Distribution

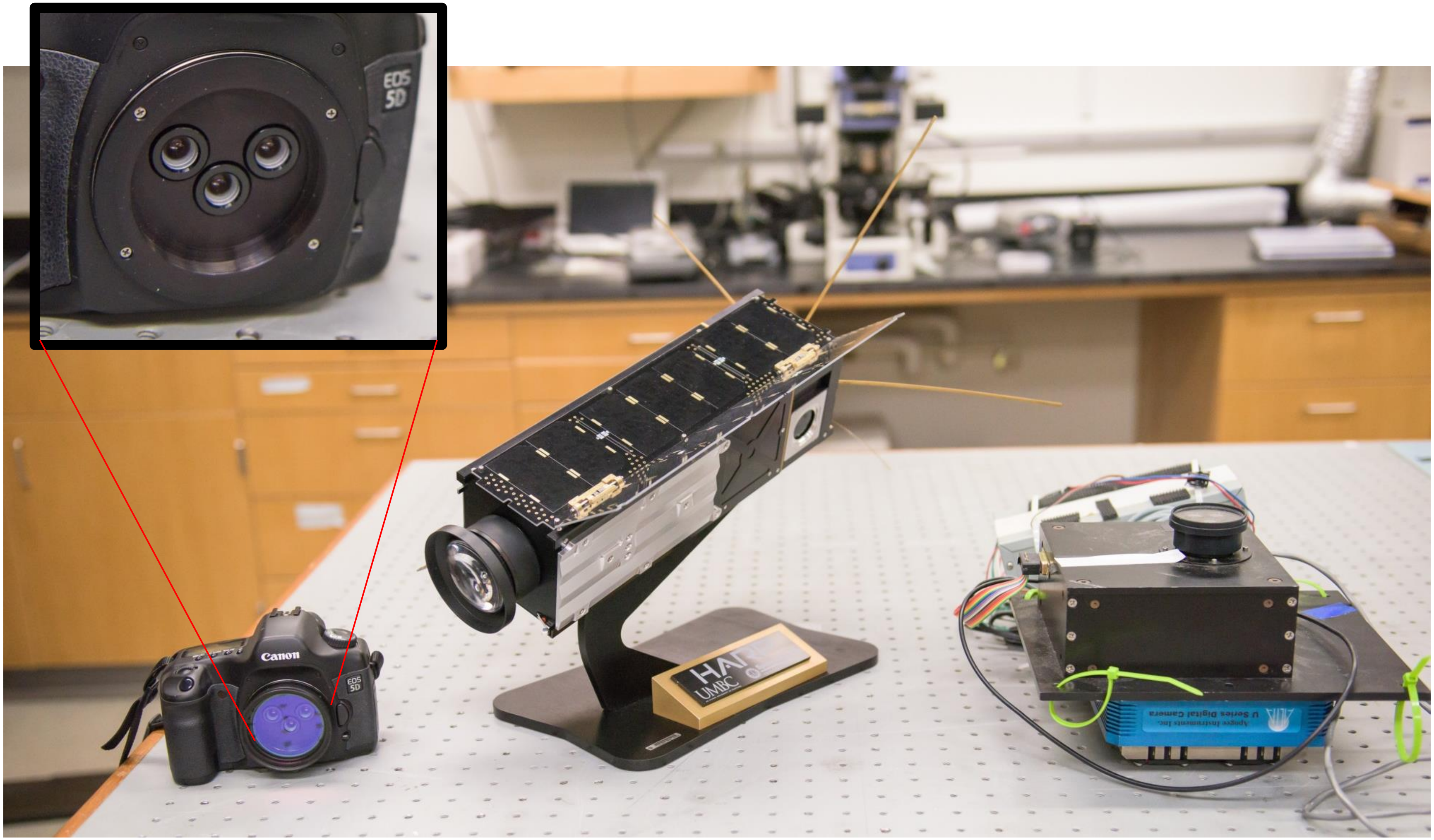


These two cases are undistinguishable from Intensity measurements only (MODIS/VIIRS)

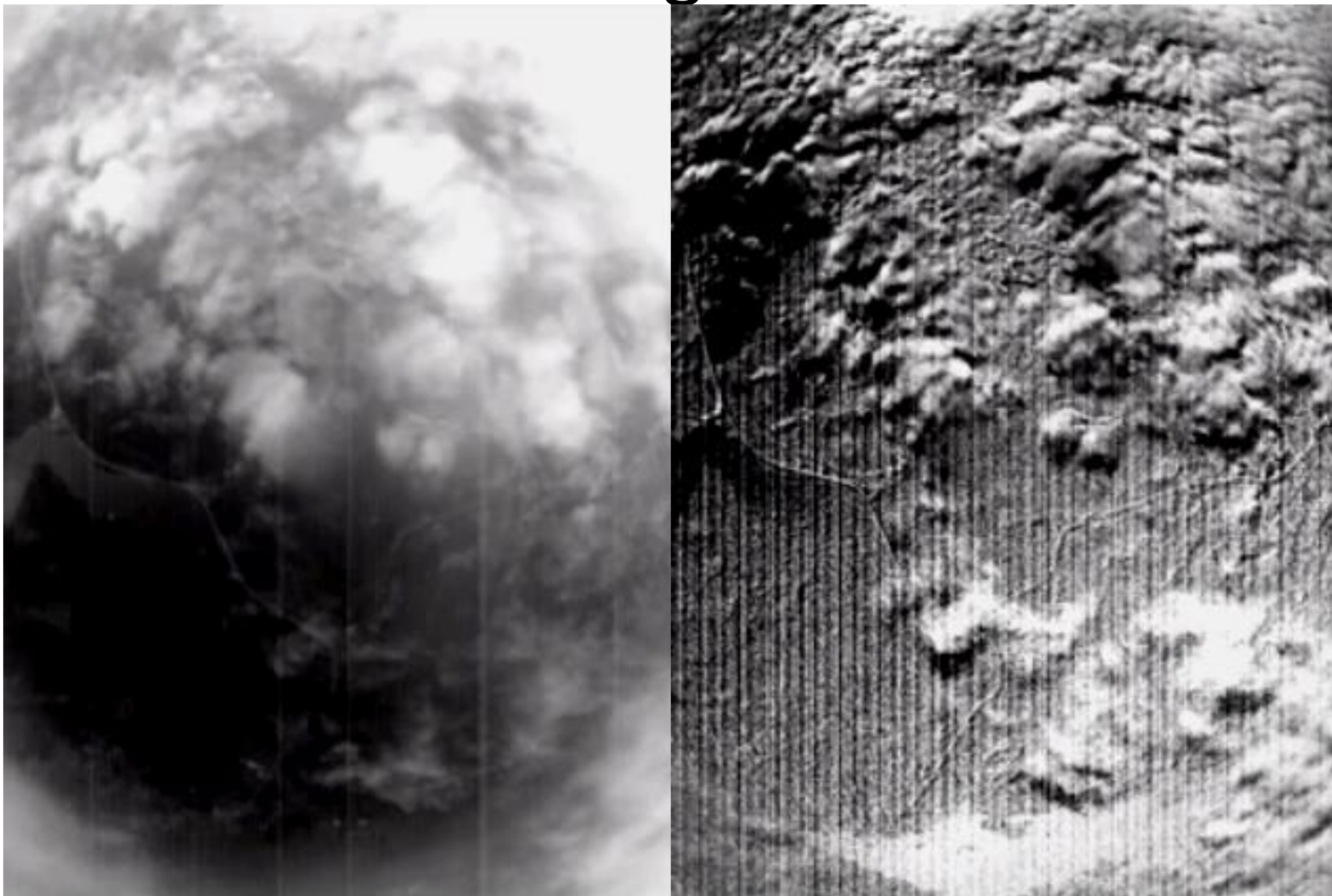
RPI Early Polarimeter Prototype
23 Aug 2013



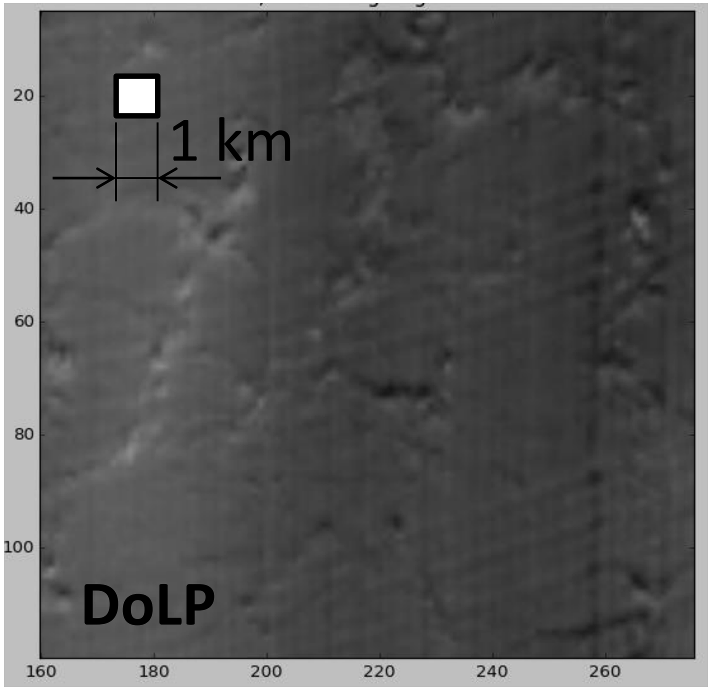
HARP and its first precursors:

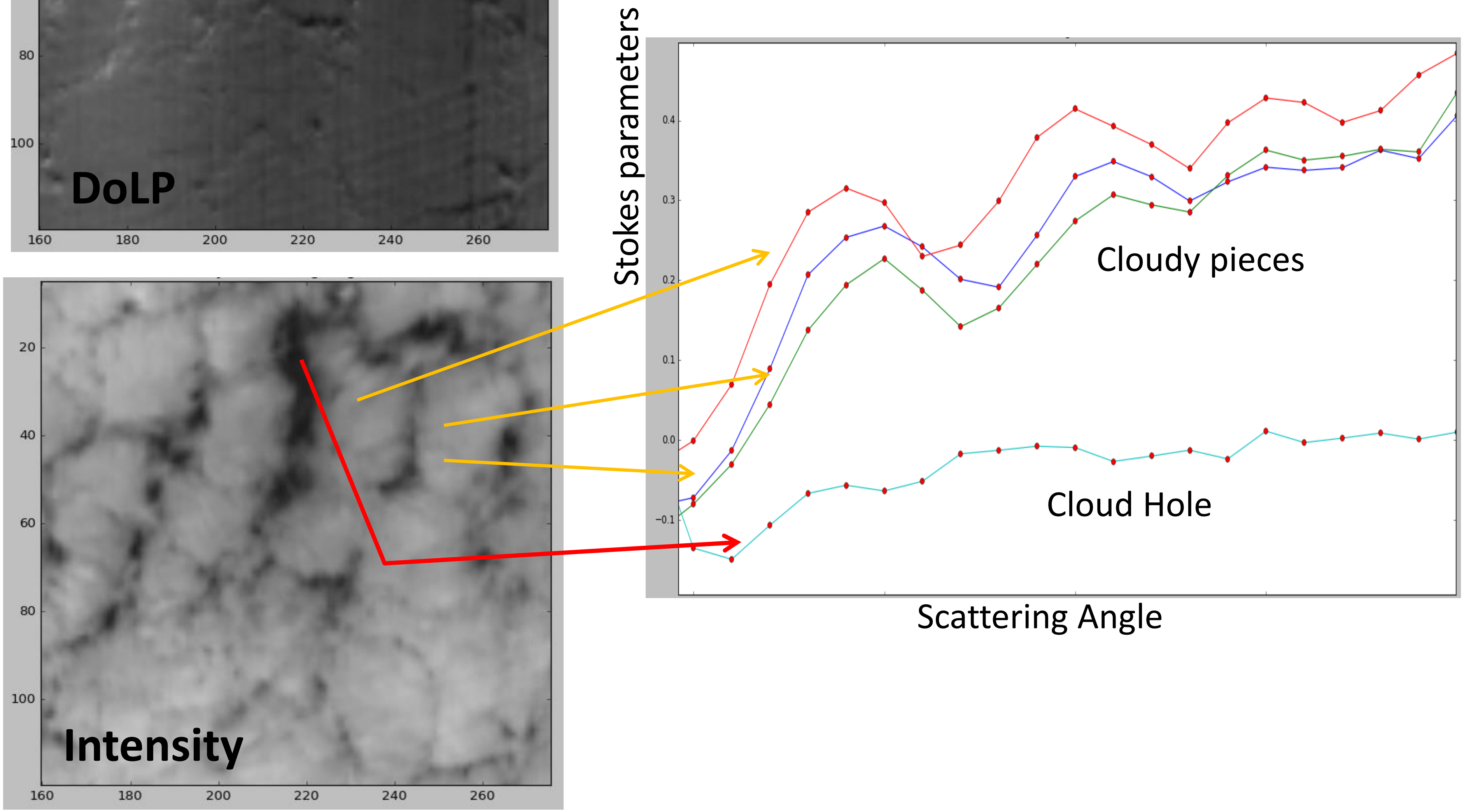


RPI Early Polarimeter Prototype
23 Aug 2013



HyperAngular High Resolution Cloudbow



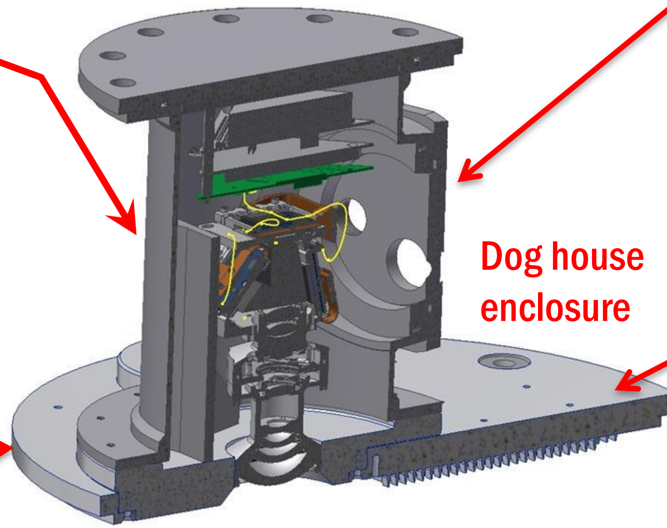


NASA ER2 - Oct 2017

UMBC

AirHARP

NASA Langley UC12 June 2017

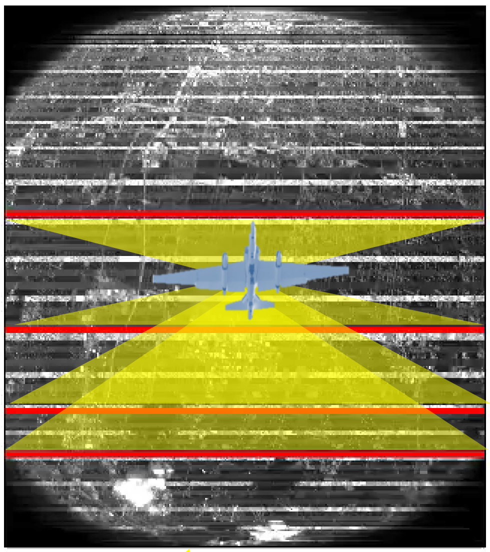


Dog house enclosure

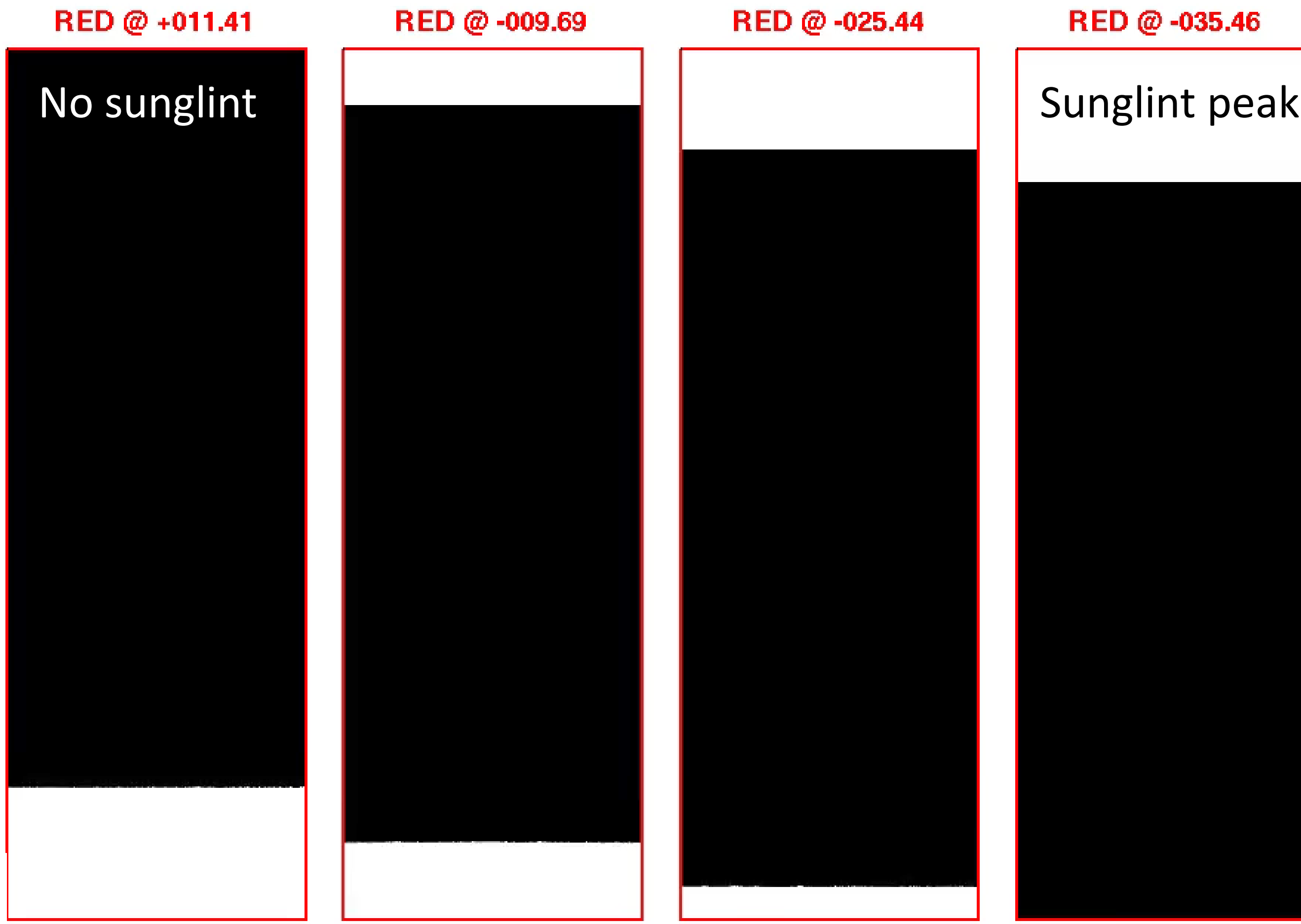
AirHARP front lens underneath aircraft

AIRHARP

Multi-Angle Observation



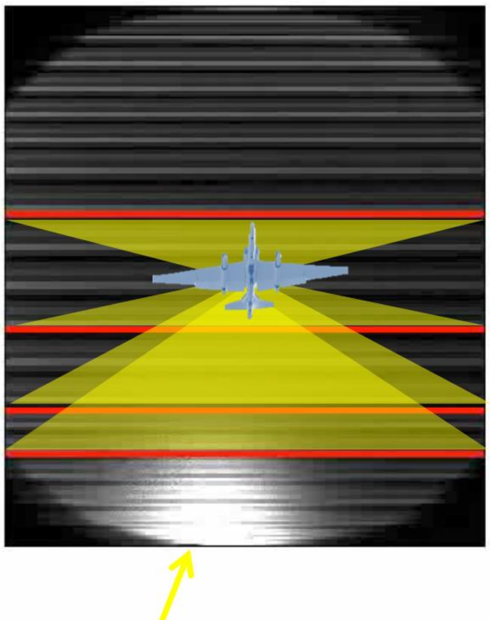
Notice that sunglint
Is not visible in all angles



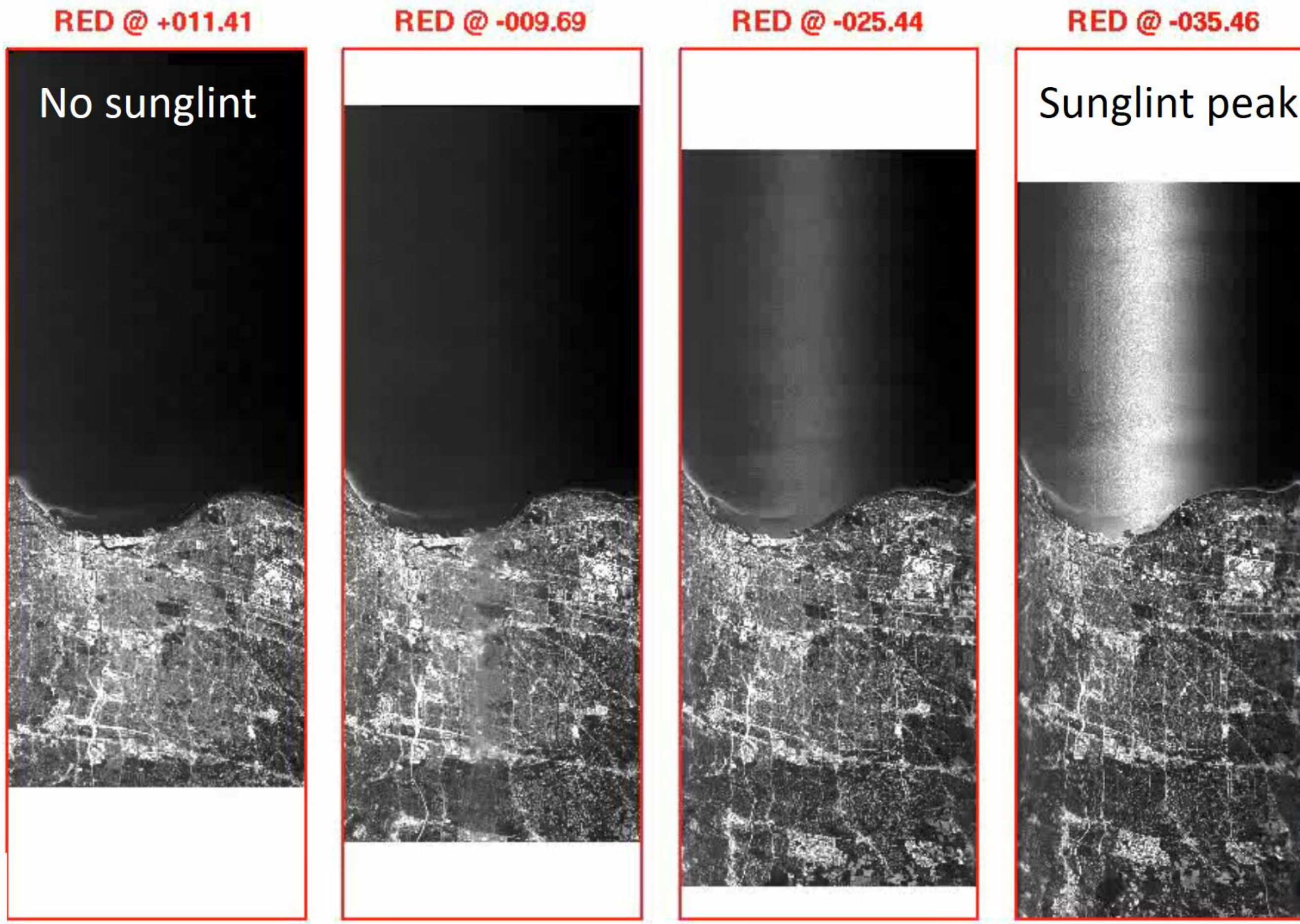
Multiple Angles

AIRHARP

Multi-Angle Observation

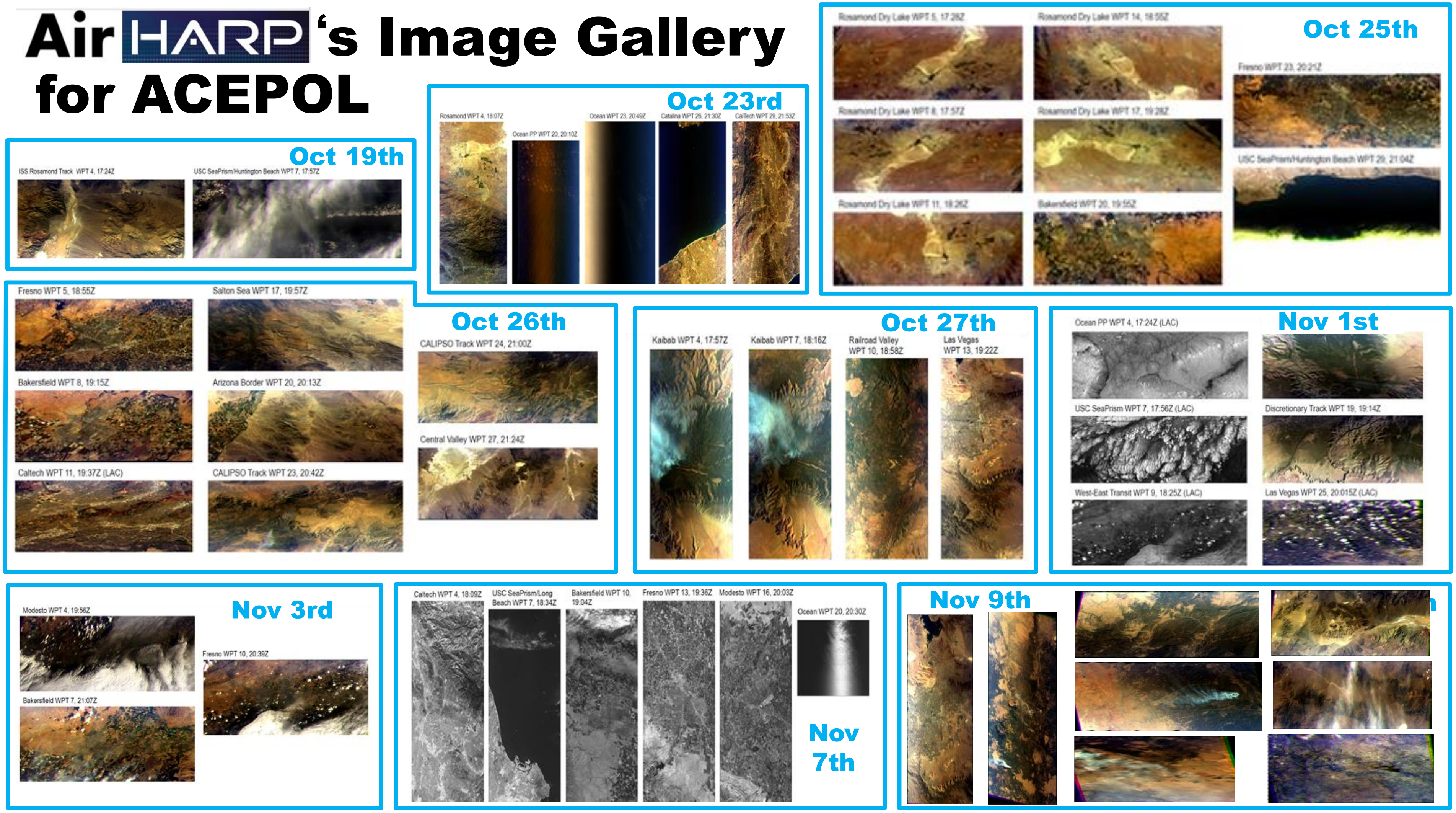


Notice that sunglint
Is not visible in all angles

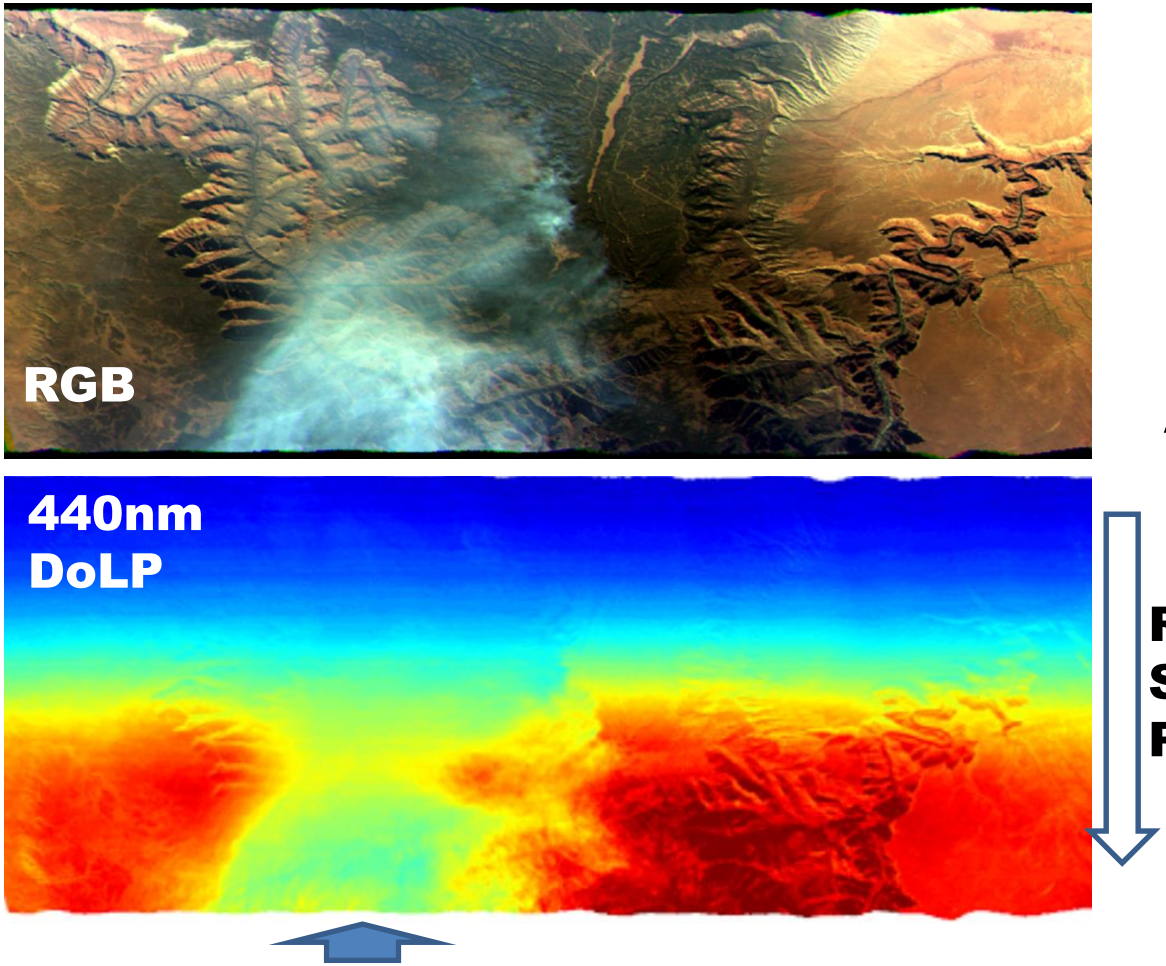


Multiple Angles

AirHARP's Image Gallery for ACEPOL



Arizona Fires During ACEPOL



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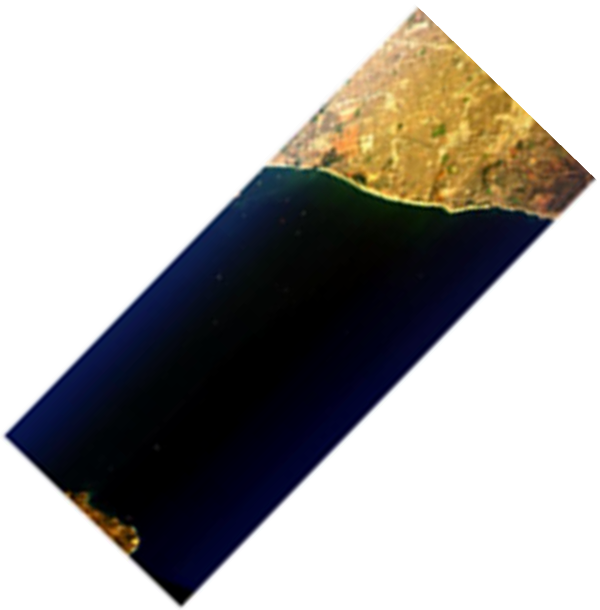
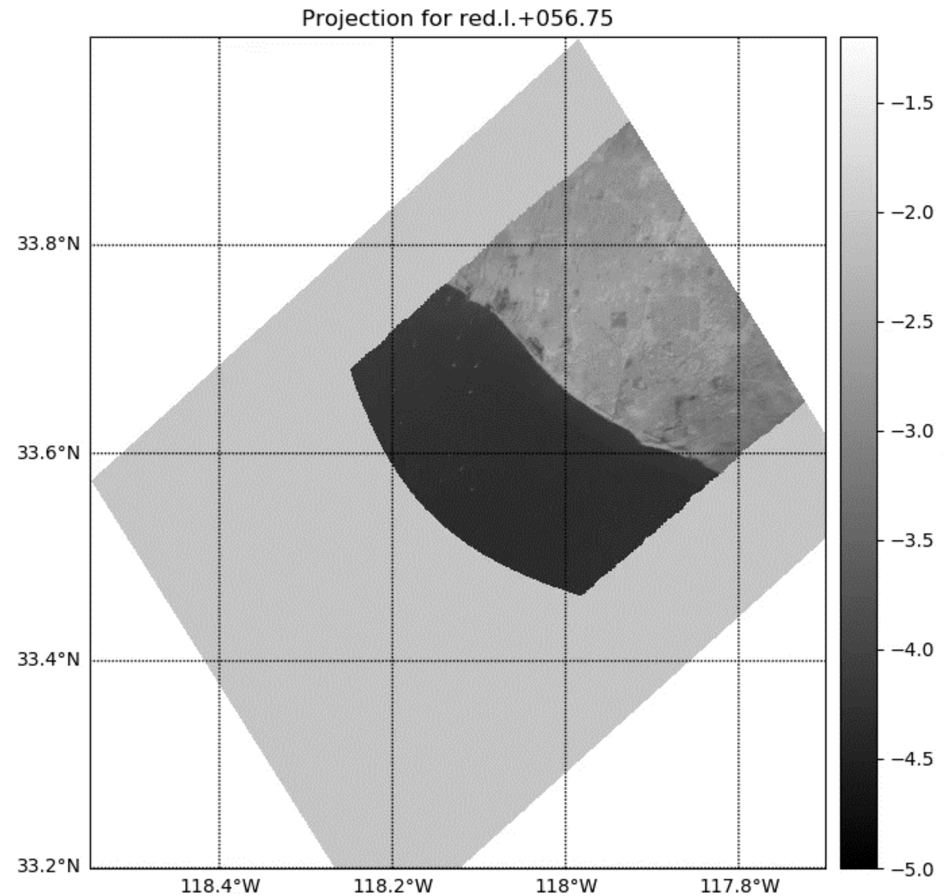
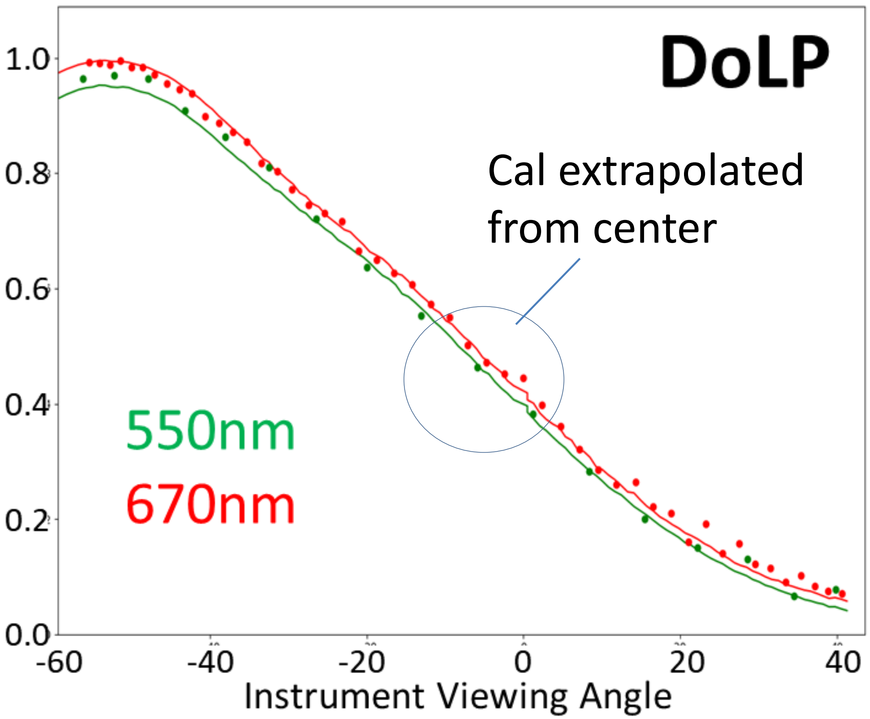
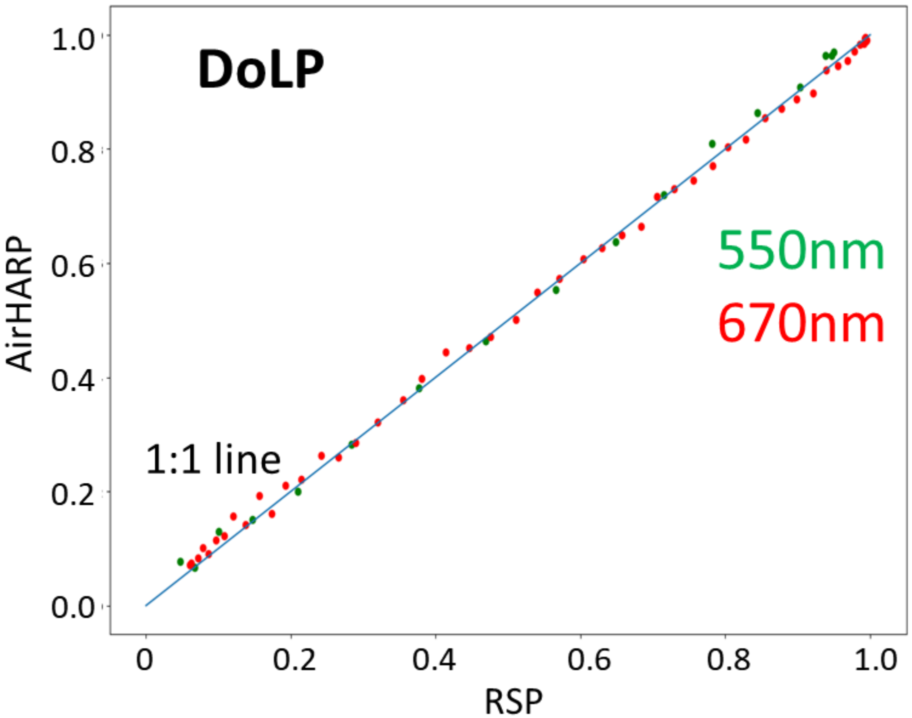
Ocean measurements during ACEPOL





Preliminary Intercomparison with RSP Red and Green





- AirHARP data based on pre-campaign calibration (still missing post-calibration)
- AirHARP calibration at the center FOV and extended to all other angles
- Results for single gridded pixel – HARP2-PACE averages many tens of pixels for better SNR

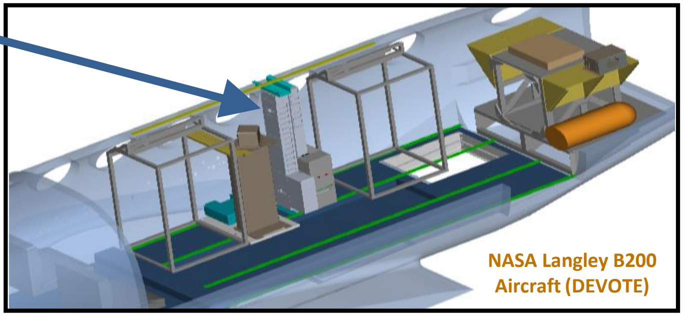
In Situ Measurements in Conjunction with HARP:

Polarized **I**maging Polar **Neph**elometer **(PI-Neph)**

PI-Neph 1 Experiments: DEVOTE, **DC3**, DISCOVER-AQ CA, STEAR, DISCOVER-AQ CO
PI-Neph 2 Experiments: STEAR, **SEAC4RS**, DISCOVER-AQ CO, **UMBC Humidification Measurements**

PI-Neph 1 (2011)

- PI-Neph is mounted in cabin of aircraft
- Sample brought inside chamber through inlet
- Developed here in LACO lab at UMBC



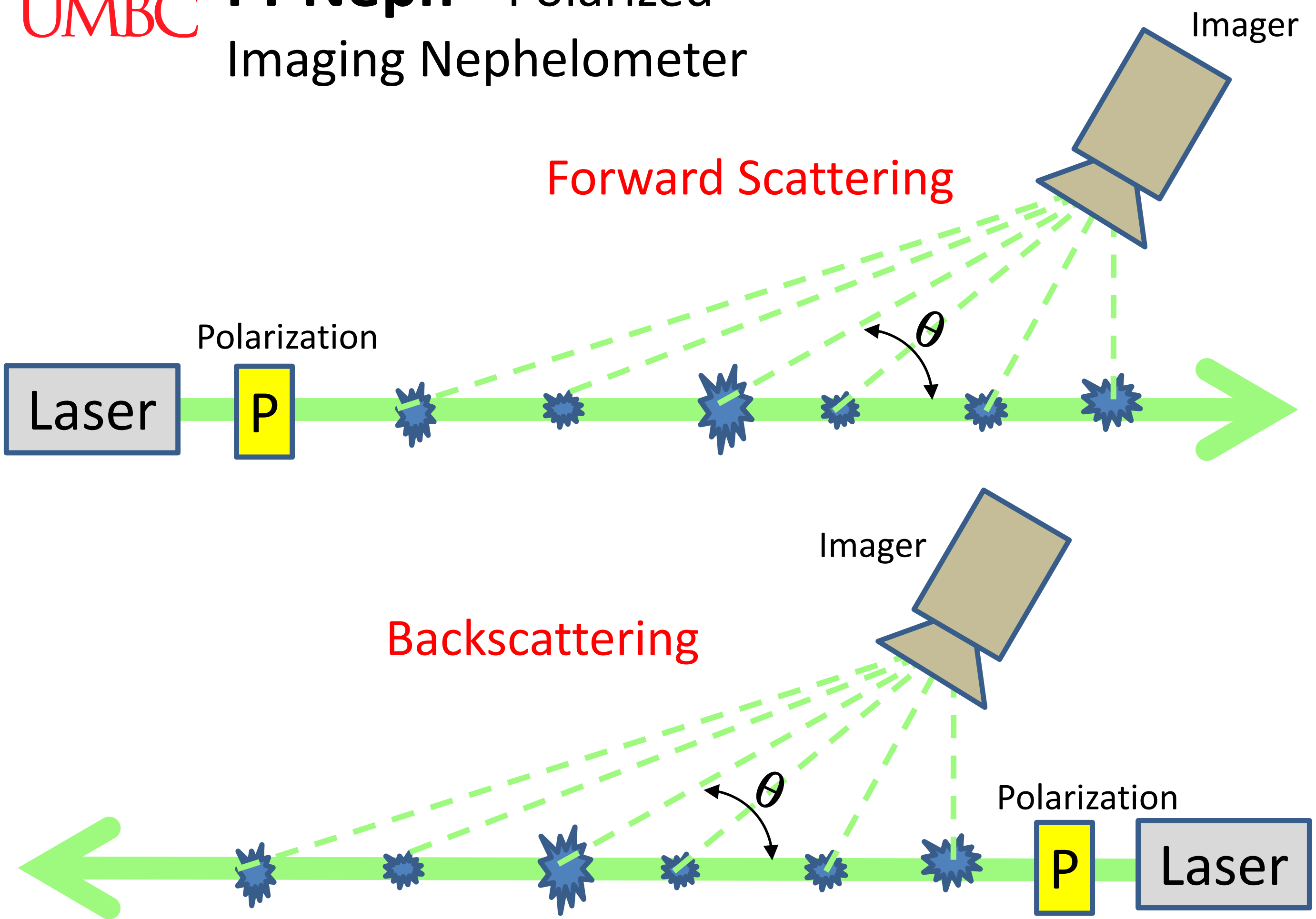
1000+ hours of airborne data

PI-Neph 2 (2013)

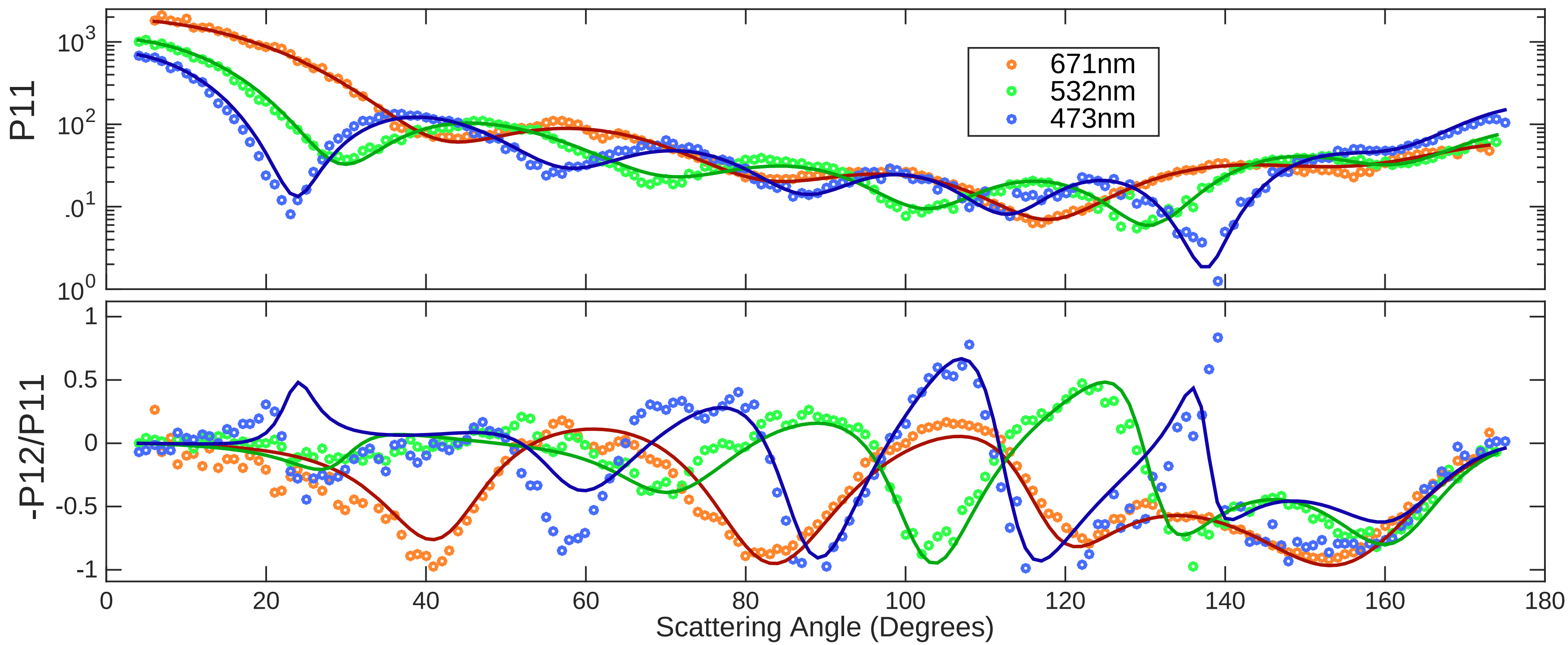
Direct In situ measurements of the Optical Properties of Aerosols

UMBC

PI-Neph - Polarized Imaging Nephelometer



903nm Monodisperse Polystyrene Latex (PSL) Spheres: Measurements and Fit



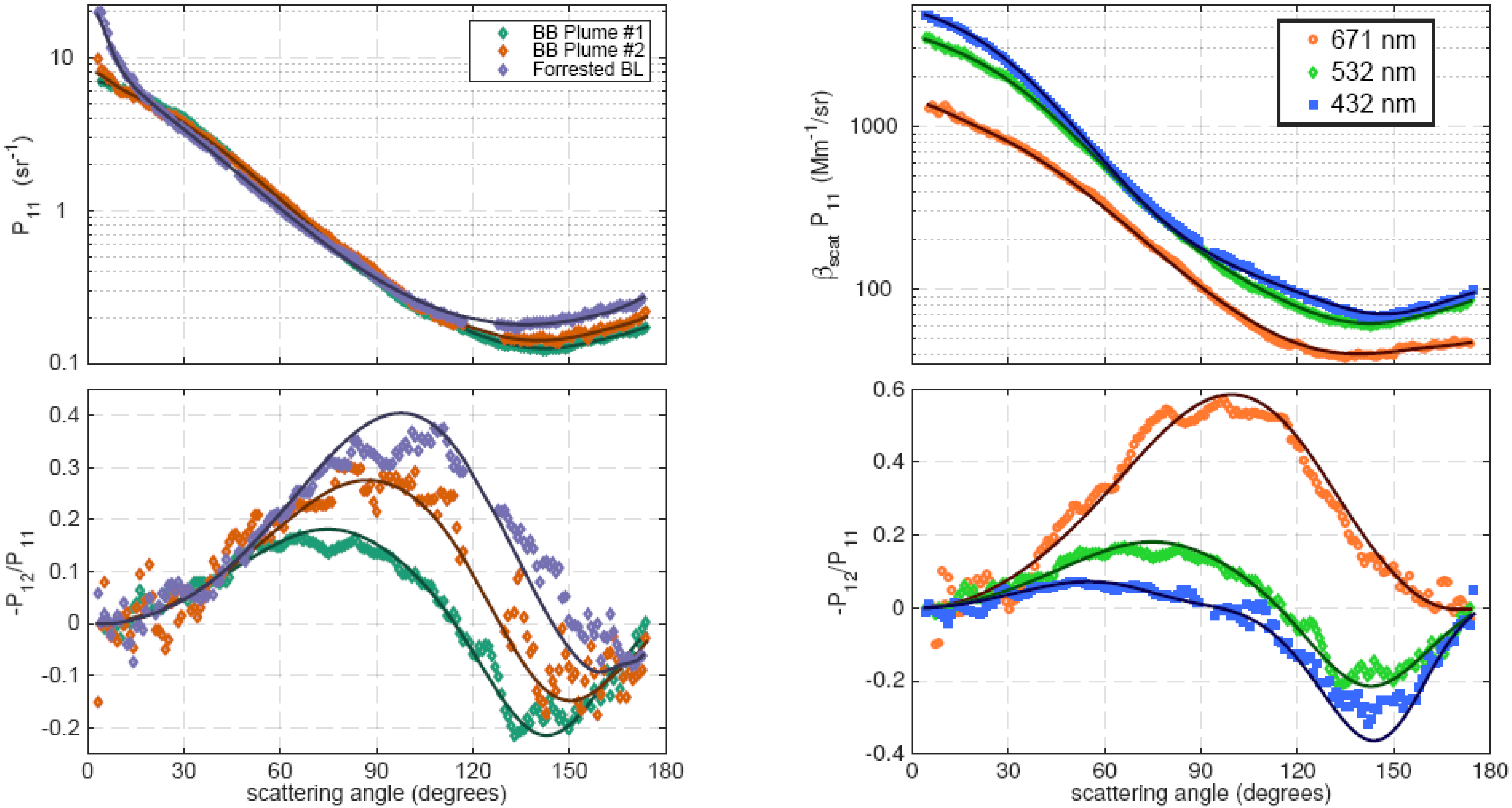
Espinosa et al. AMT, 10, 811–824, 2017

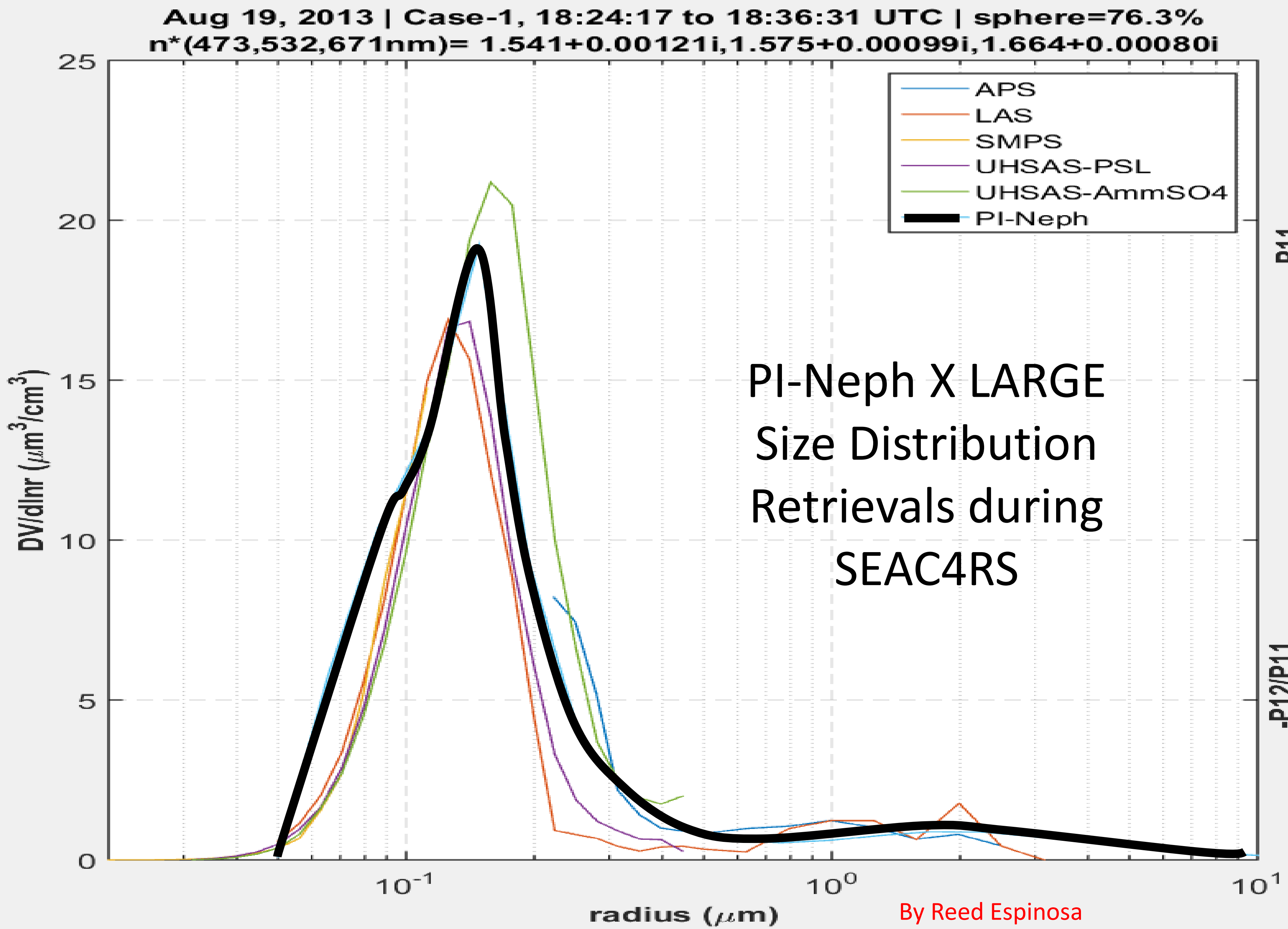
Retrievals of Aerosol Optical and Microphysical Properties from Imaging Polar Nephelometer Scattering Measurements

Espinosa et al., 2017 - *AMT*

W. Reed Espinosa[1,2,*], Lorraine Remer[1,2], Oleg Dubovik[3], Luke Ziemba[4], Andreas Beyersdorf[4,5], F. Daniel Orozco[1,2], Gregory Schuster[4], Tatyana Lapyonok[3], David Fuertes[6], and J. Vanderlei Martins[1,2]

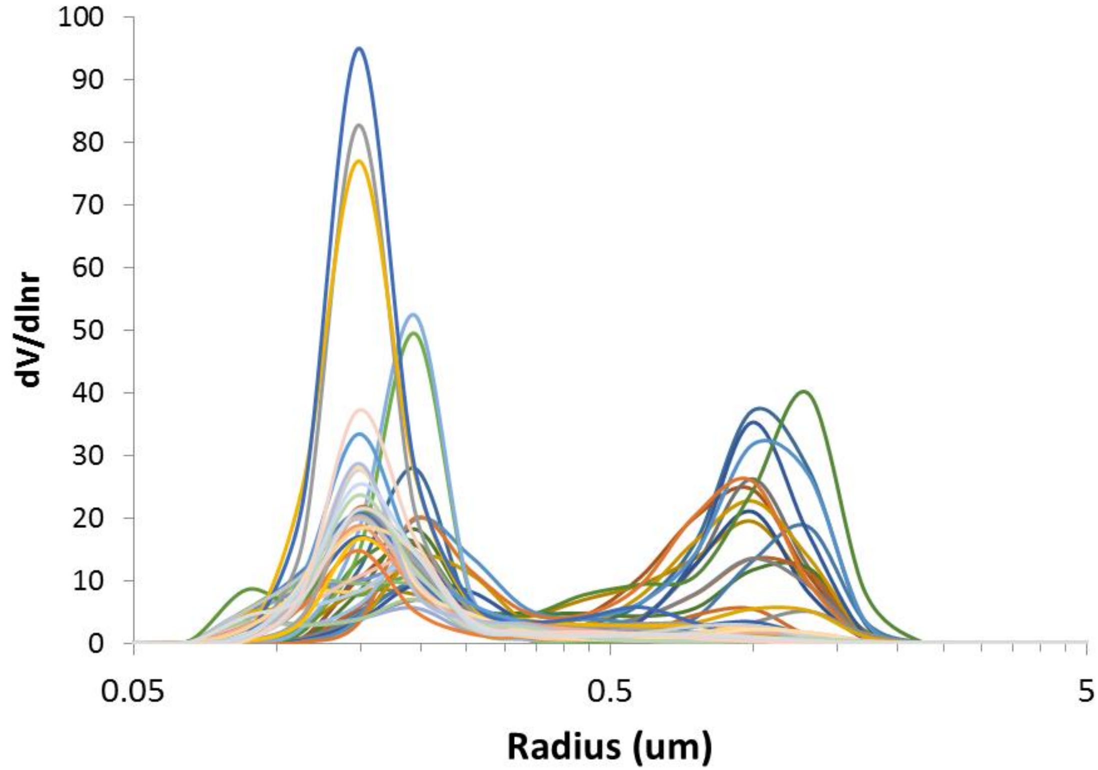
Airborne Measurements from SEAC4RS Experiment

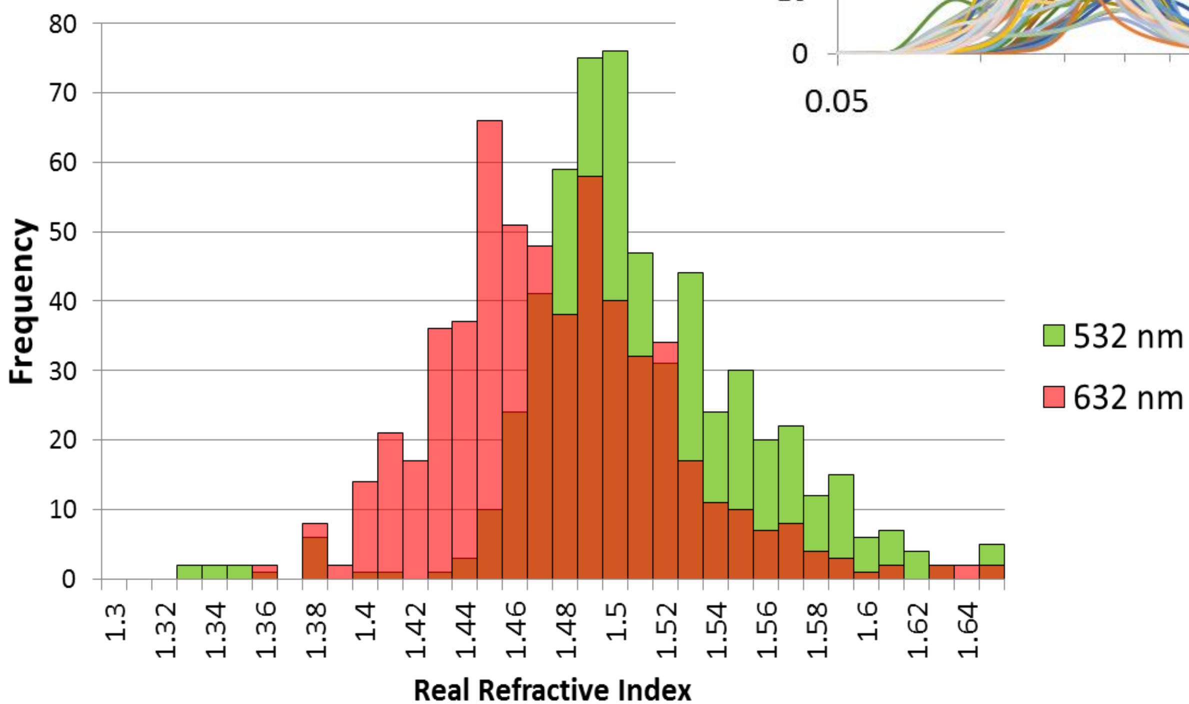




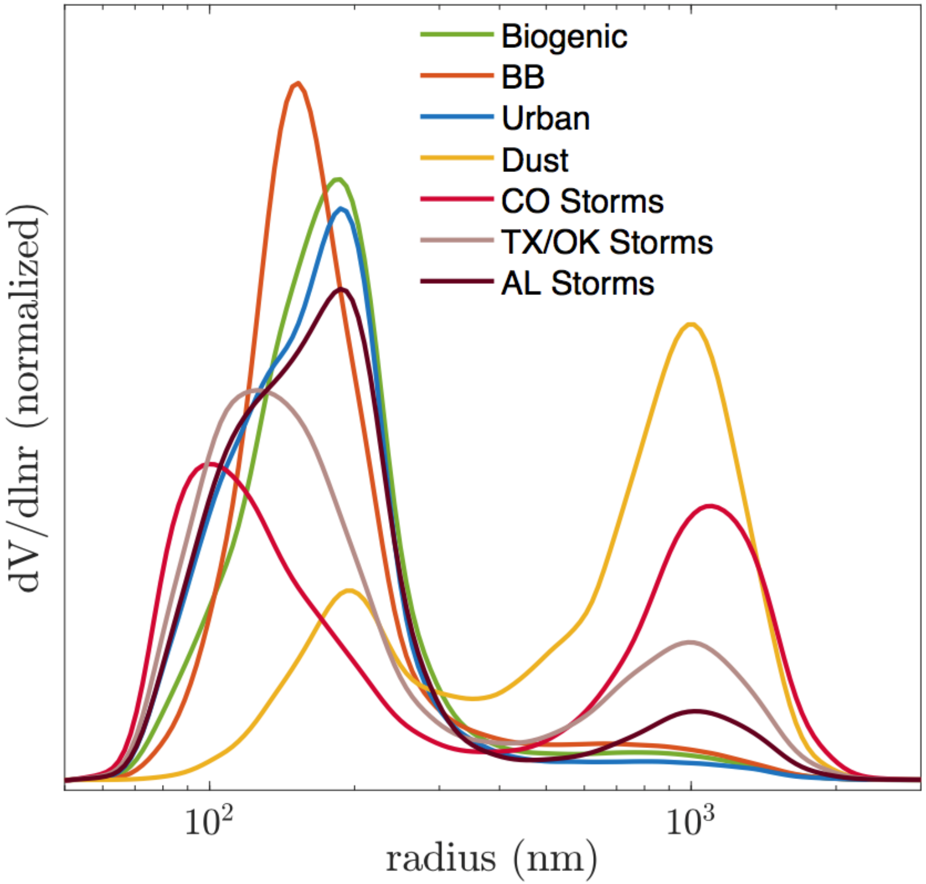
By Reed Espinosa

Results from SEAC4R Experiment

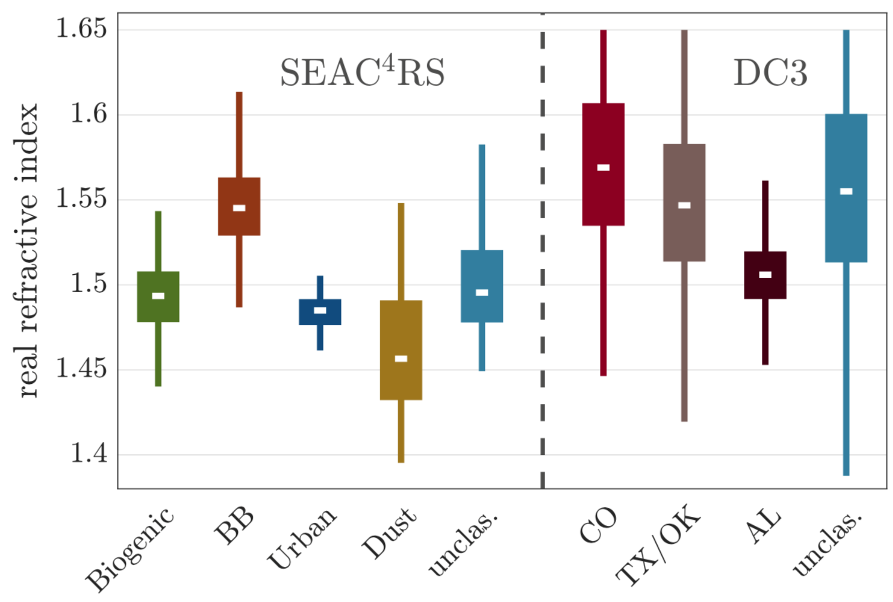




GRASP Retrievals Averaged by Type



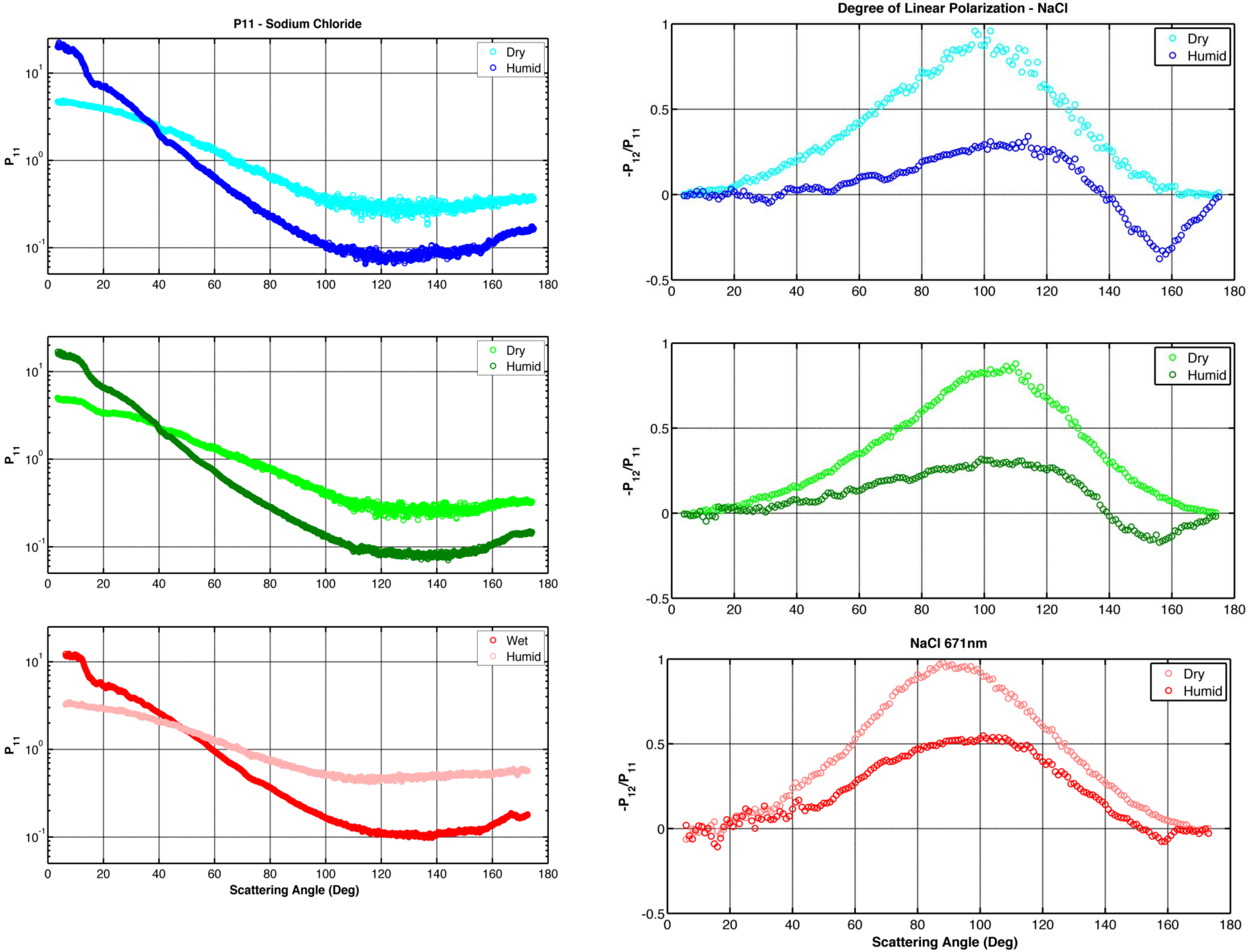
- Real Refractive Indices from PI-Neph + GRASP



Espinosa et al. GRL, In Prep., 2017

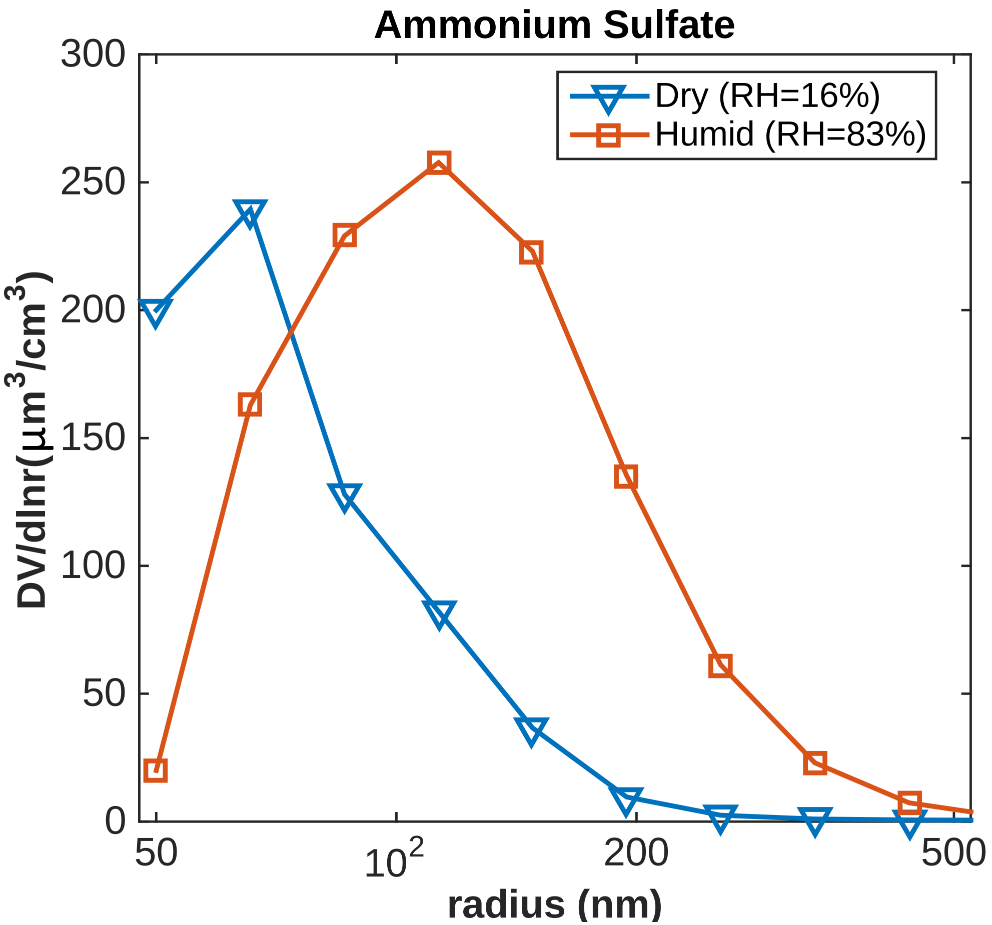
How the particle properties depend on Ambient conditions?

In Particular RH…



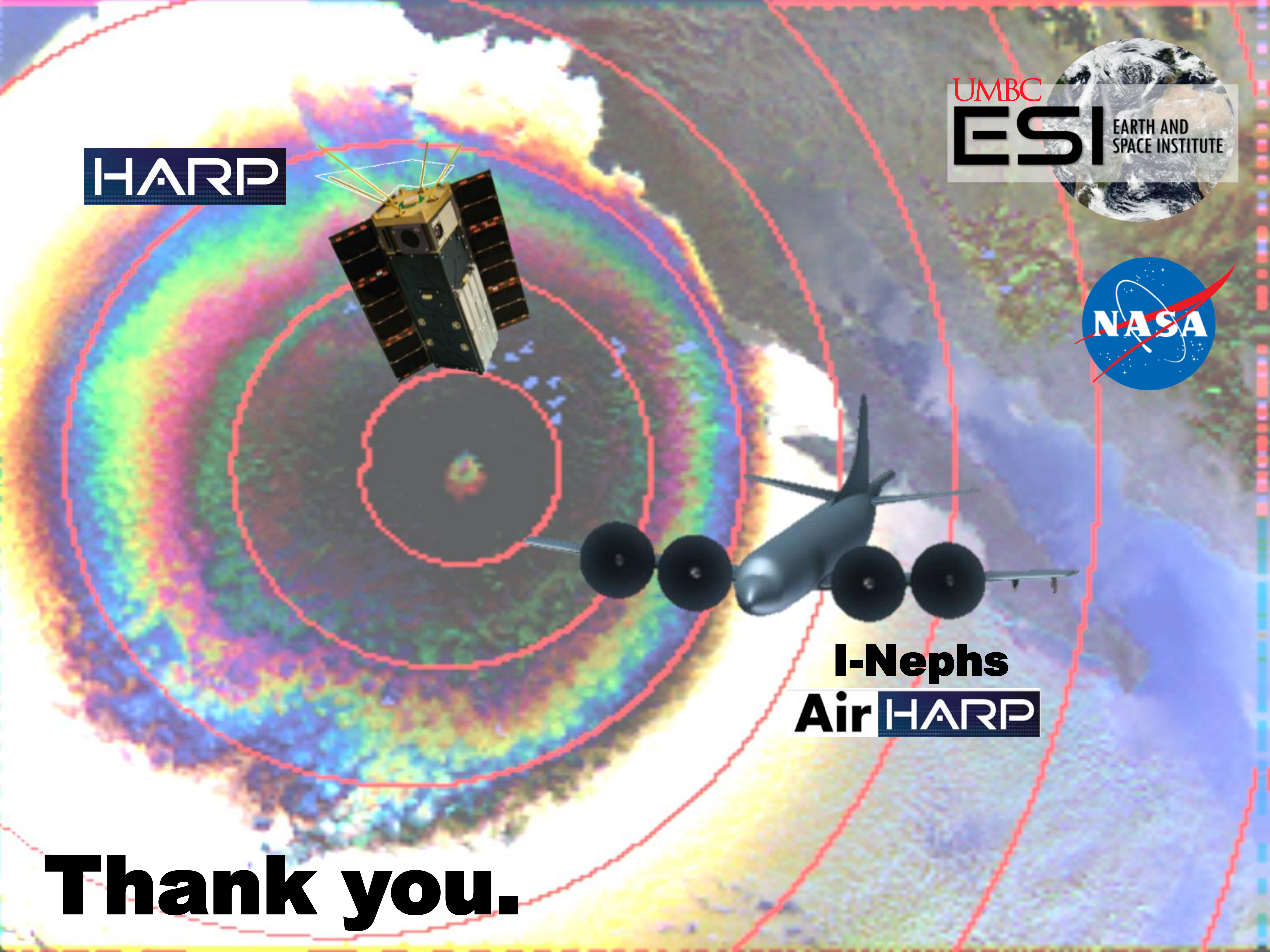
P11 - Sodium Chloride
Degree of Linear Polarization - NaCl
NaCl 671nm
Dry
Humid
Wet
P11
-P12/P11
Scattering Angle (Deg)

Humidified and Dried Aerosol Measurements with PI-Neph



Humidified Salts (RH > 80 %)

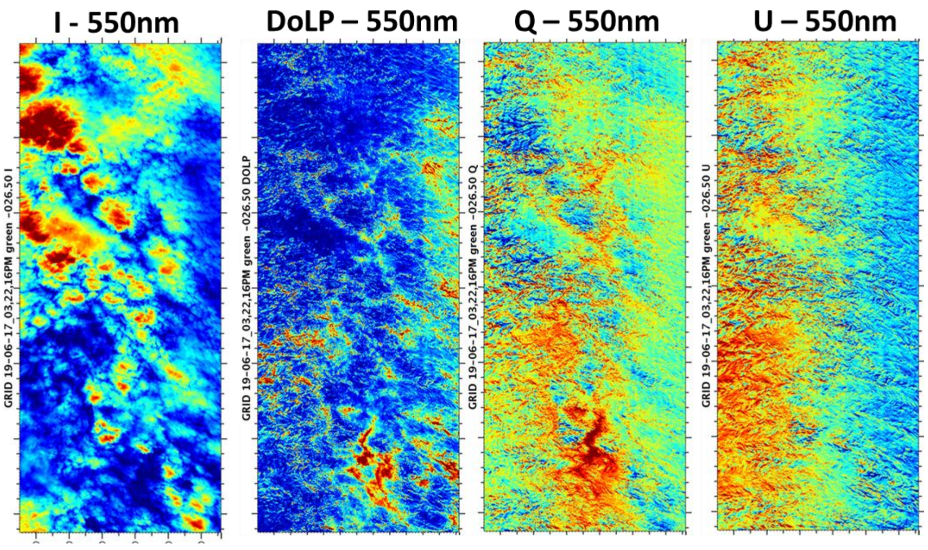
Compound	$Sphere(\%)$	n_{GRASP}	$n_{\kappa K\ddot{o}hler}$
$NaCl$	100	1.395	1.353-1.372
$(NH_4)_2SO_4$	100	1.383	1.370-1.414
NH_4NO_3	54	1.392	1.371-1.393


HARP
UMBC
ESI
EARTH AND SPACE INSTITUTE
NASA
I-Nephs
AirHARP
Thank you.

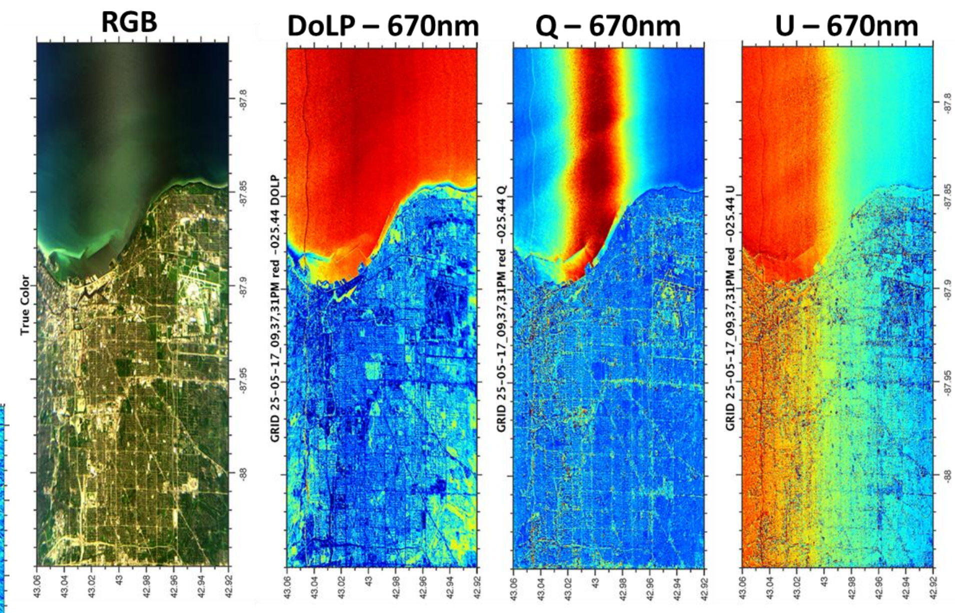
Additional Slides

Preliminary AirHARP Data
LMOS Campaign June 2017

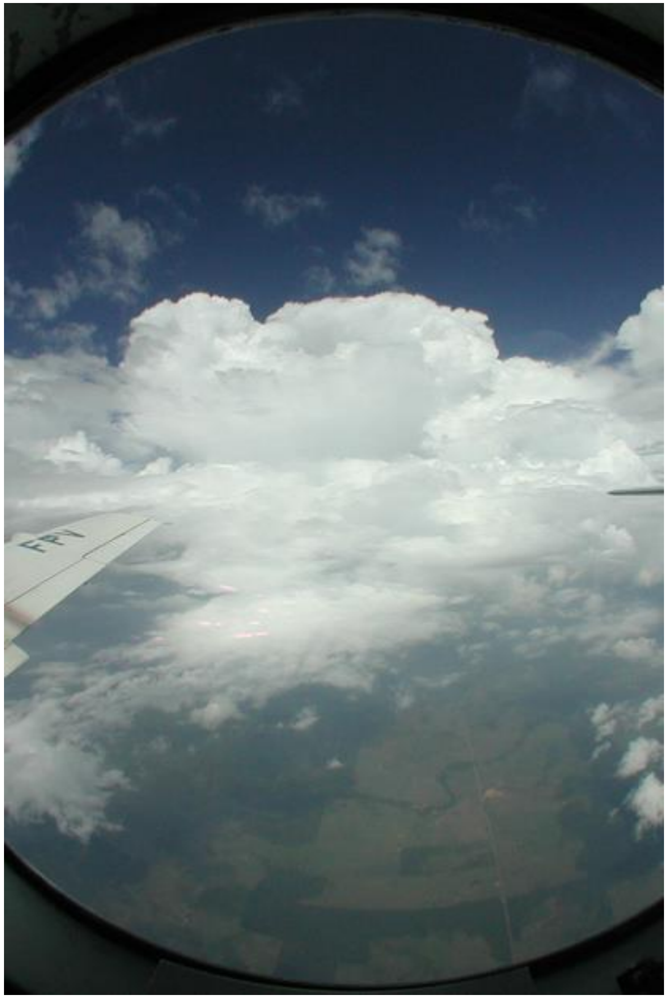
Low Clouds

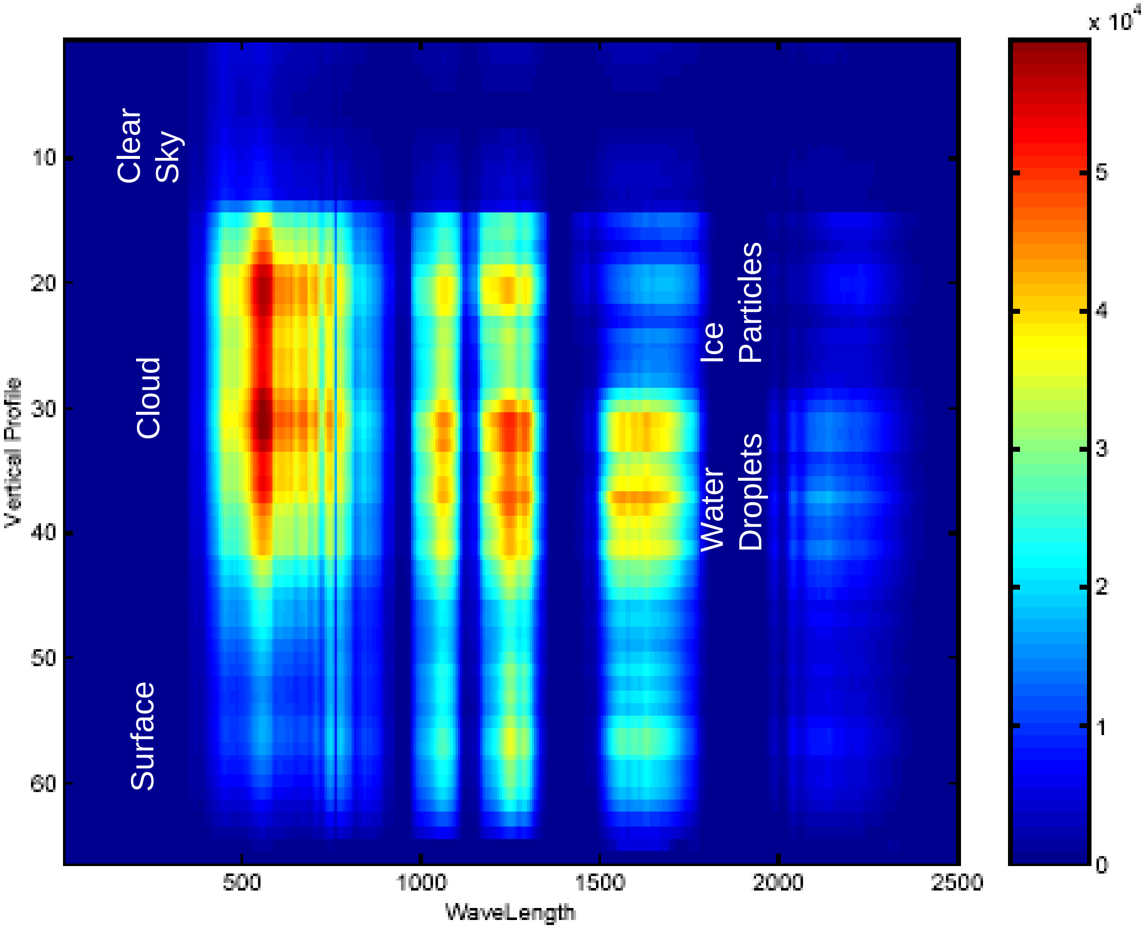


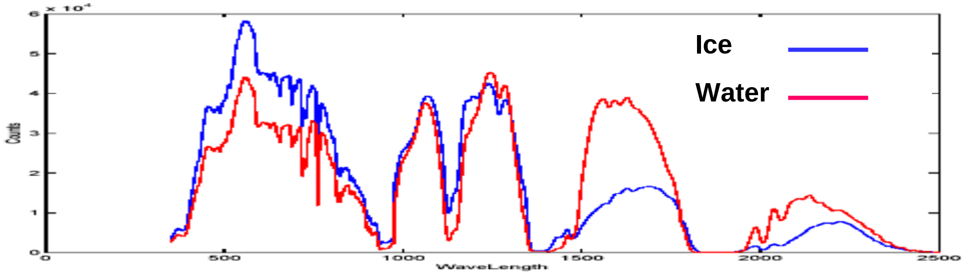
Water and Land



Average Spectral Profile of the Scanned Cloud







UMBC

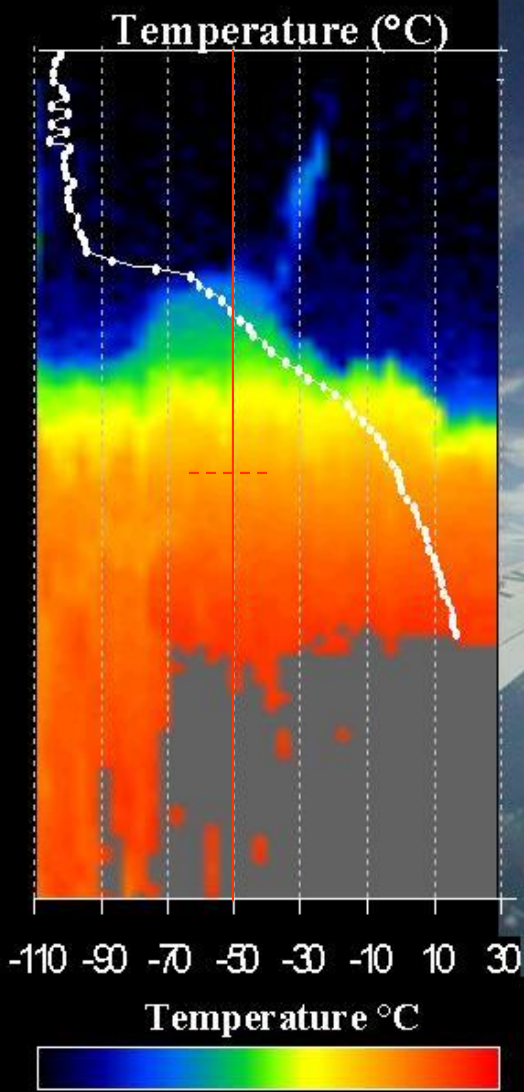
www.umbc.edu/laco

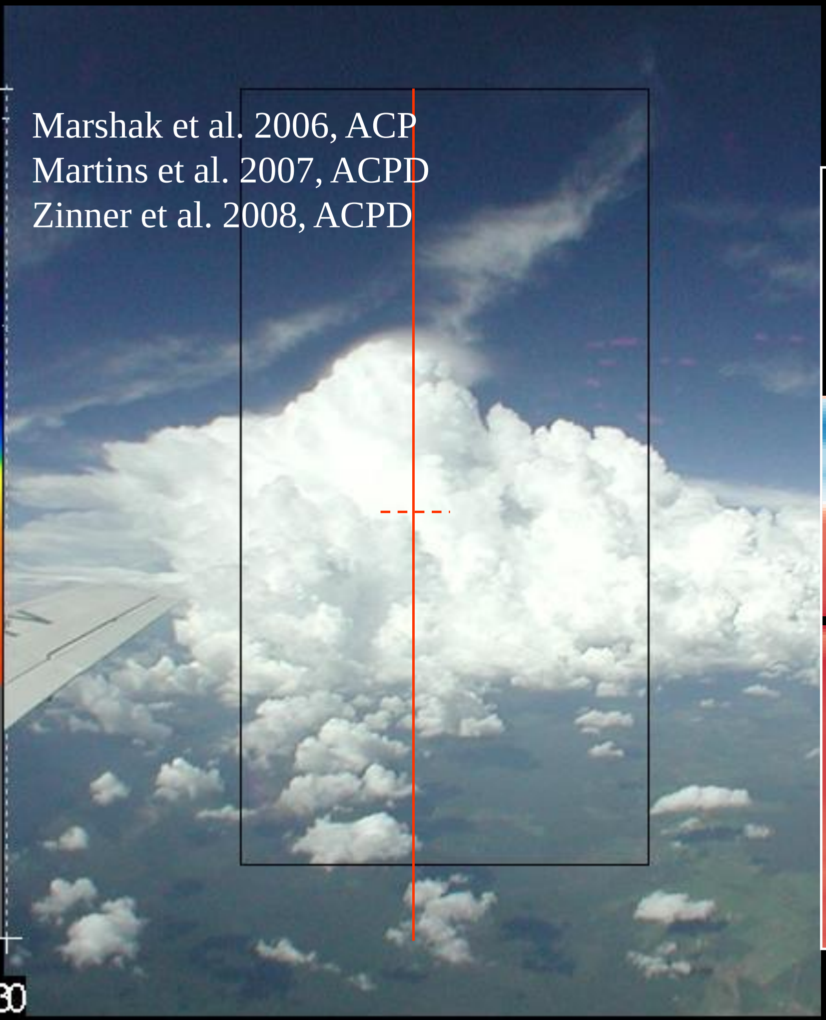
LACO

Physics Department

JCET

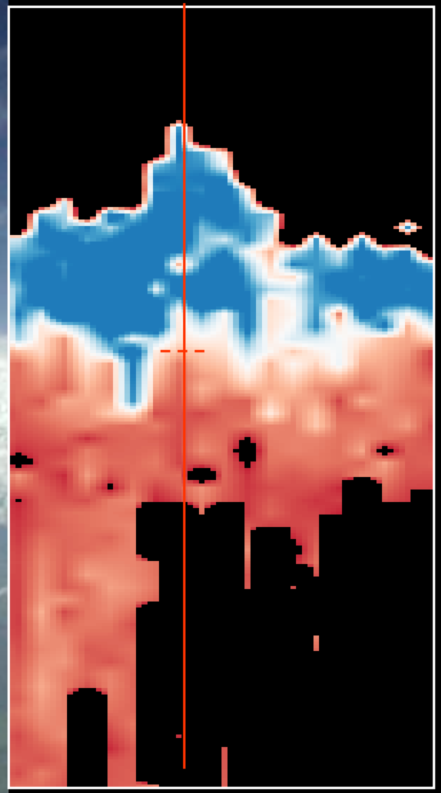
Laboratory for Aerosols, Clouds and Optics





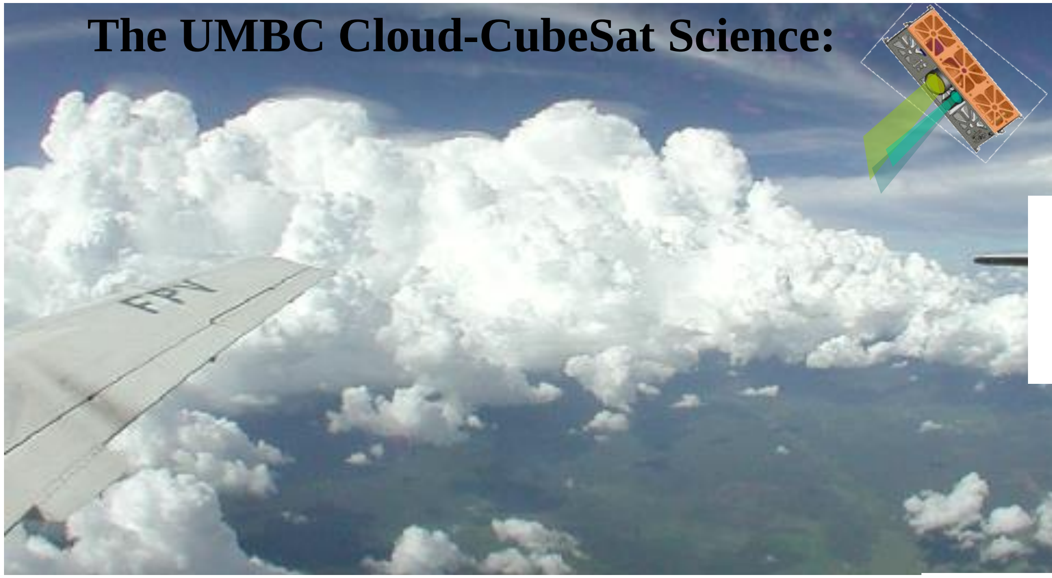
Brazil, Jan-Feb. 2005

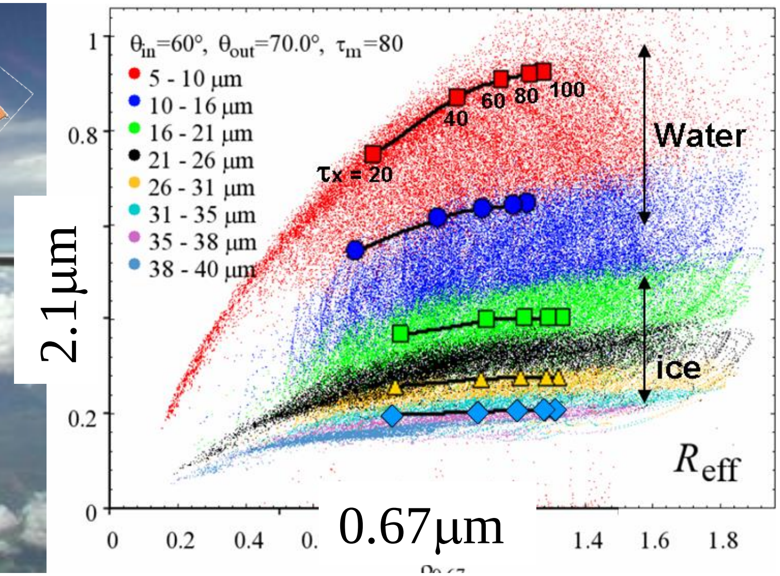
Ratio $\rho_{2.1}/\rho_{2.25\mu m}$
Proxy for ice/water separation

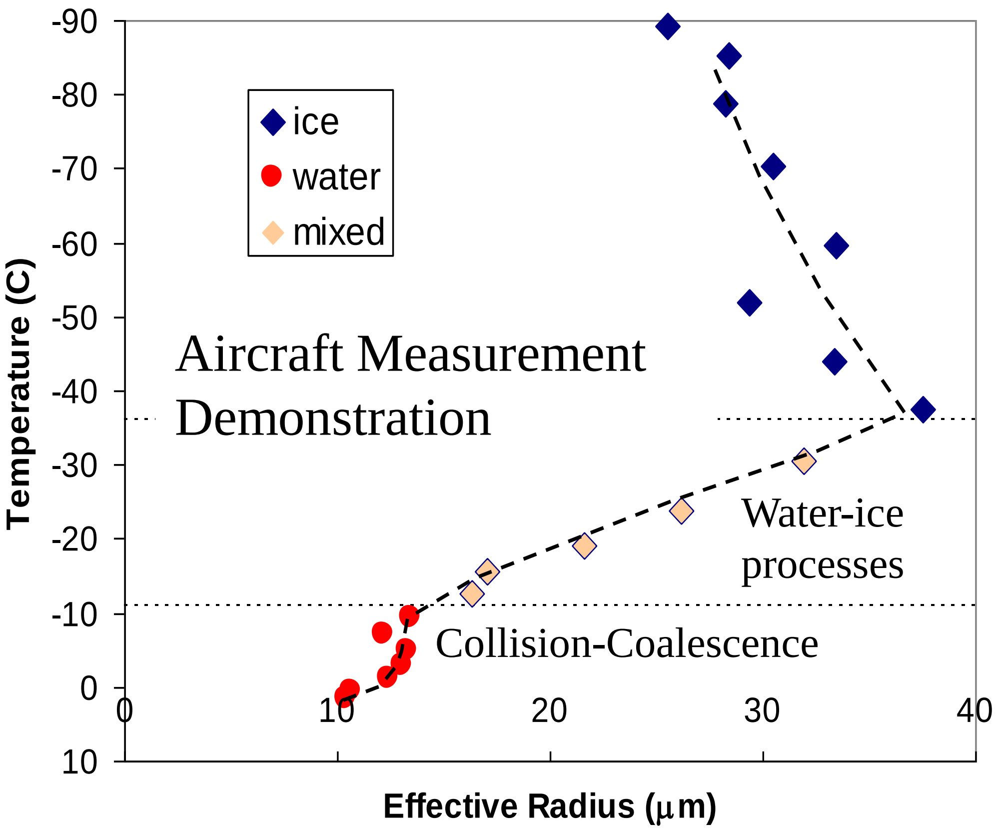


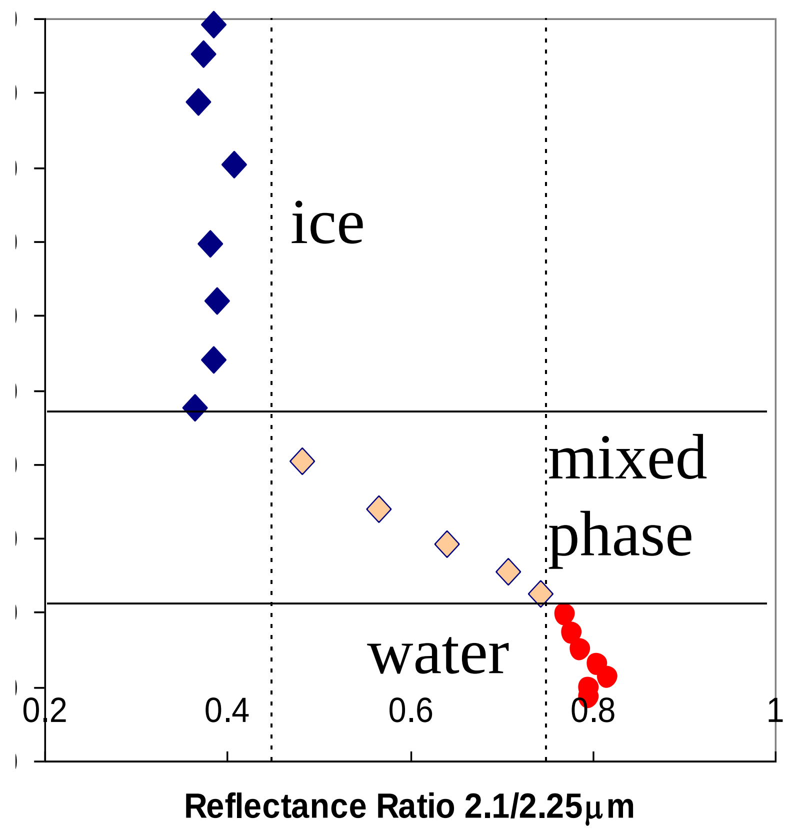
Prof. J. Vanderlei Martins
martins@umbc.edu

The UMBC Cloud-CubeSat Science:

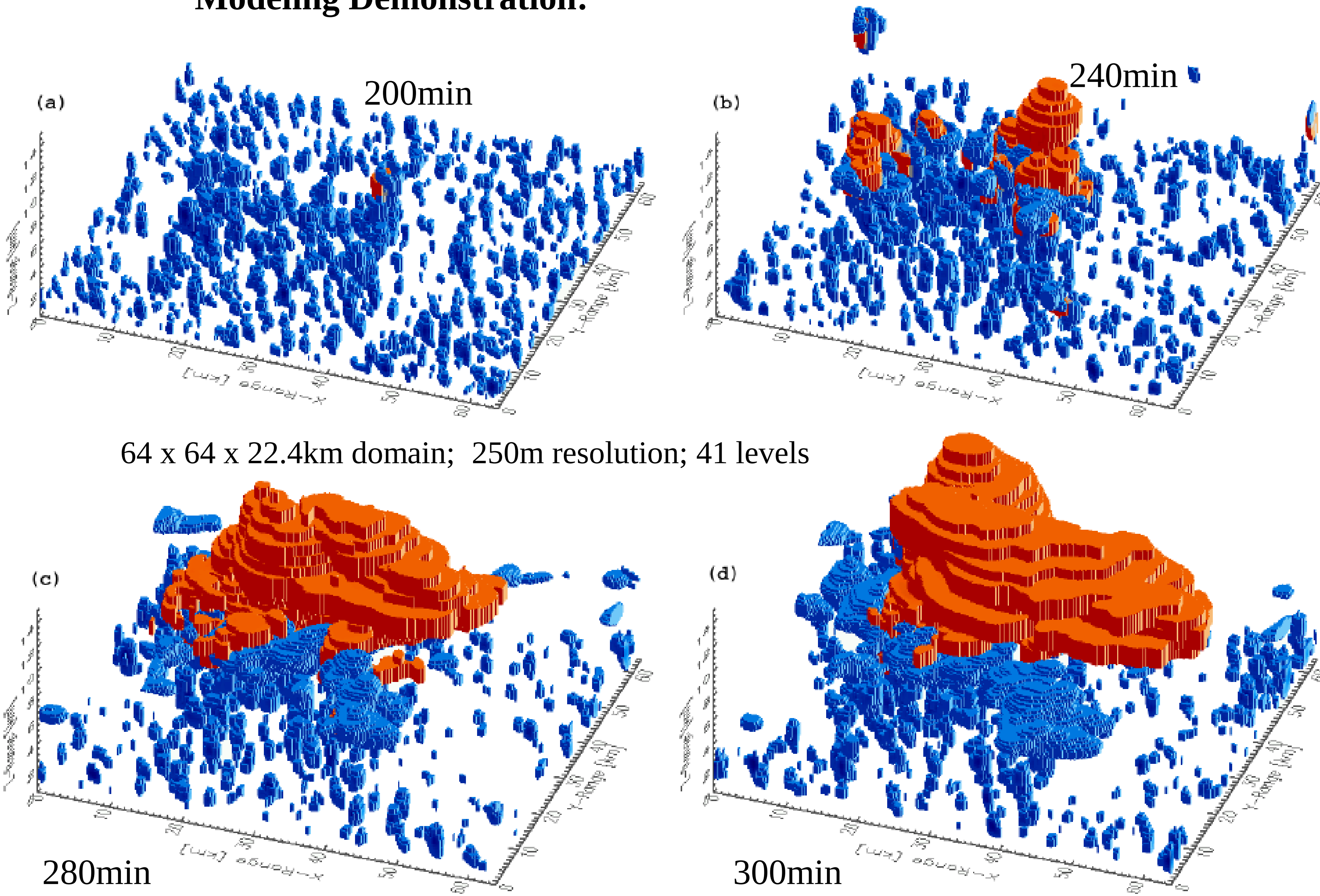








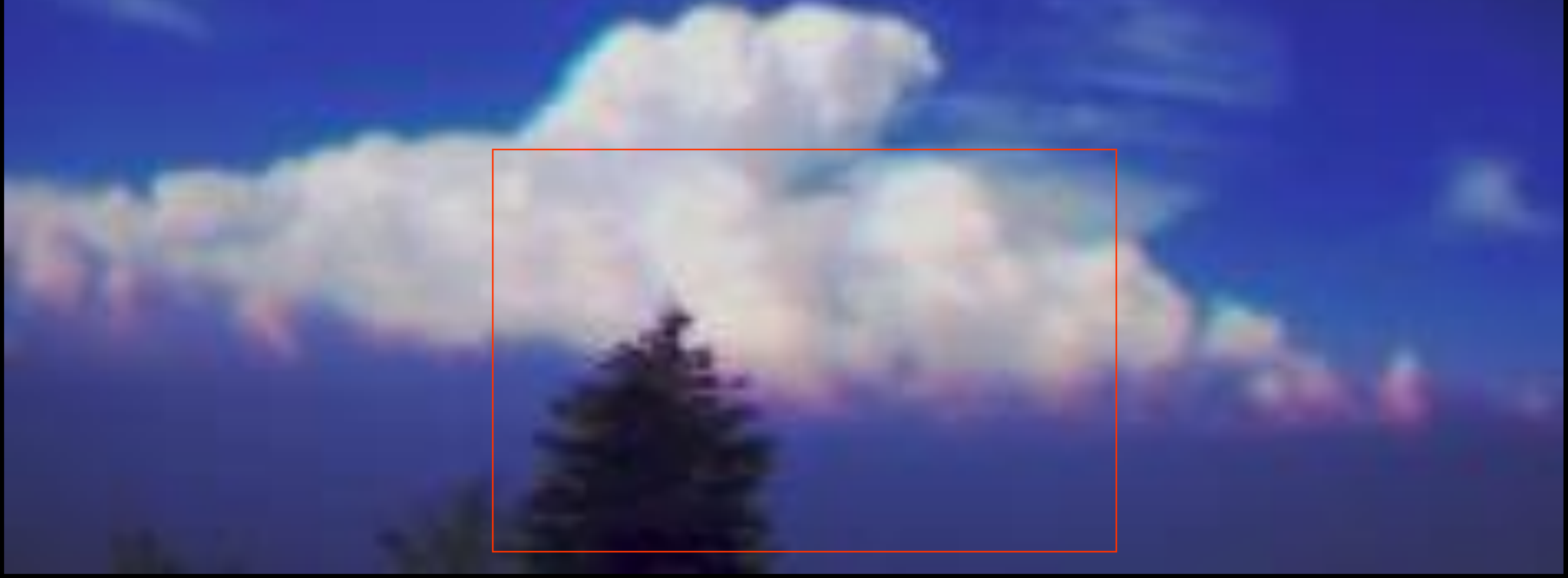
Modeling Demonstration:

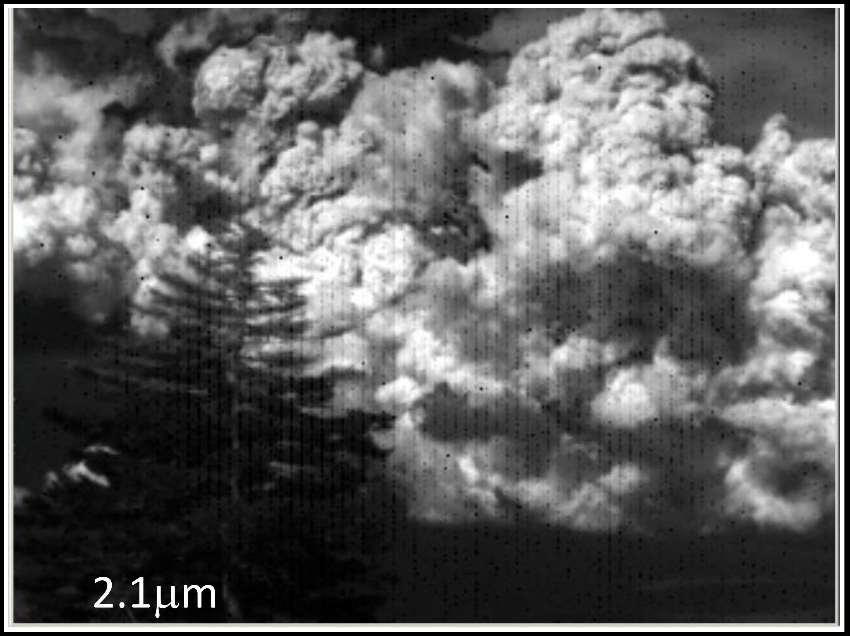


T. Zinner, A. Marshak, S. Lang, J. V. Martins, and B. Mayer, Atmos. Chem. Phys., 8, 4741–4757, 2008

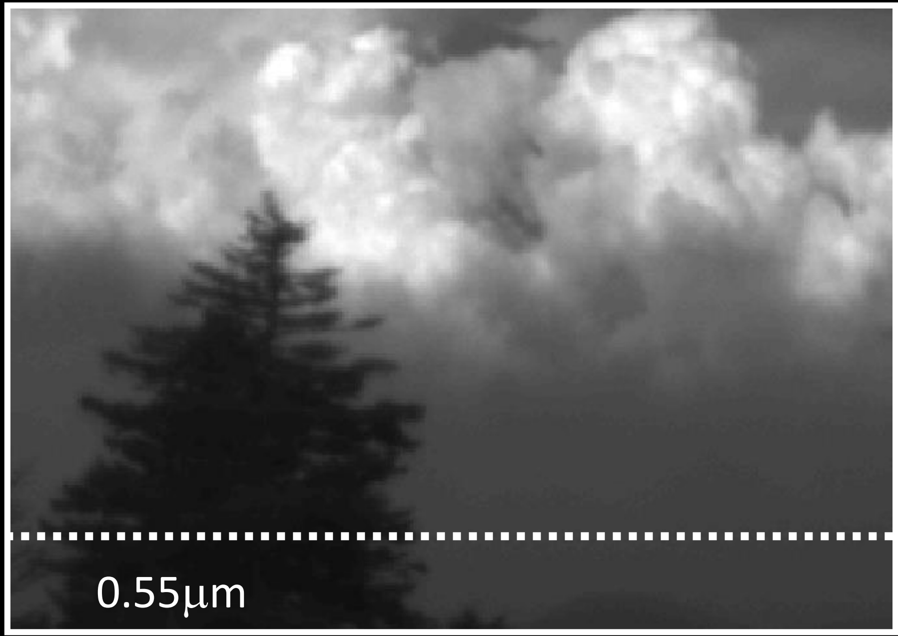
Cloud side Measurements from Mount Mitchel – North Carolina

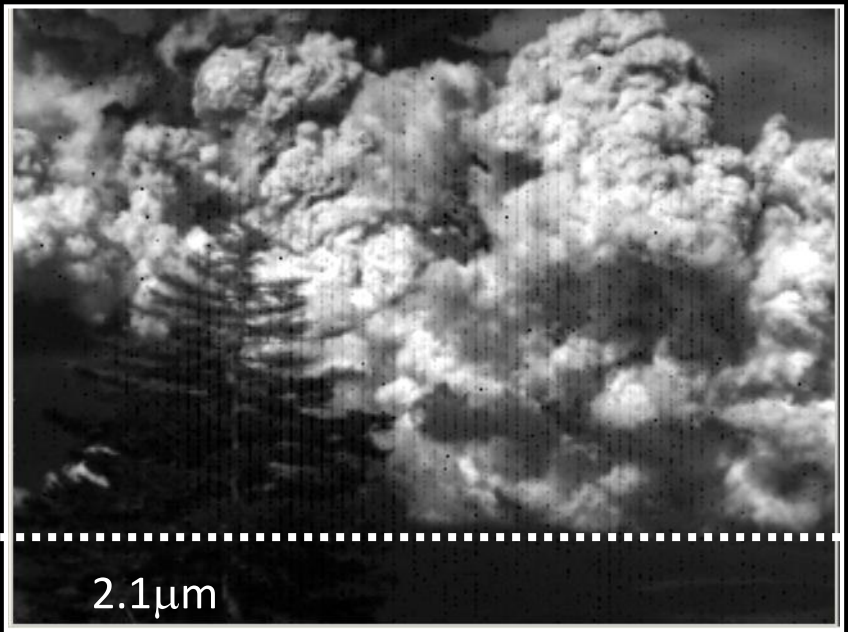
Cloud side Measurements from Mount Mitchel – North Carolina





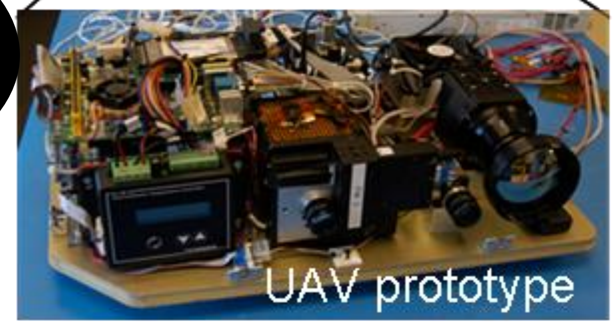
Cloud side Measurements from Mount Mitchel – North Carolina

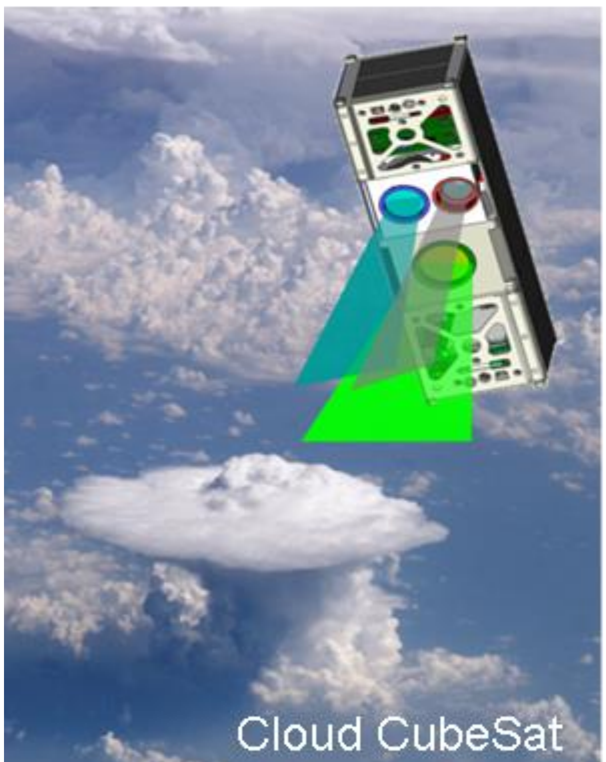


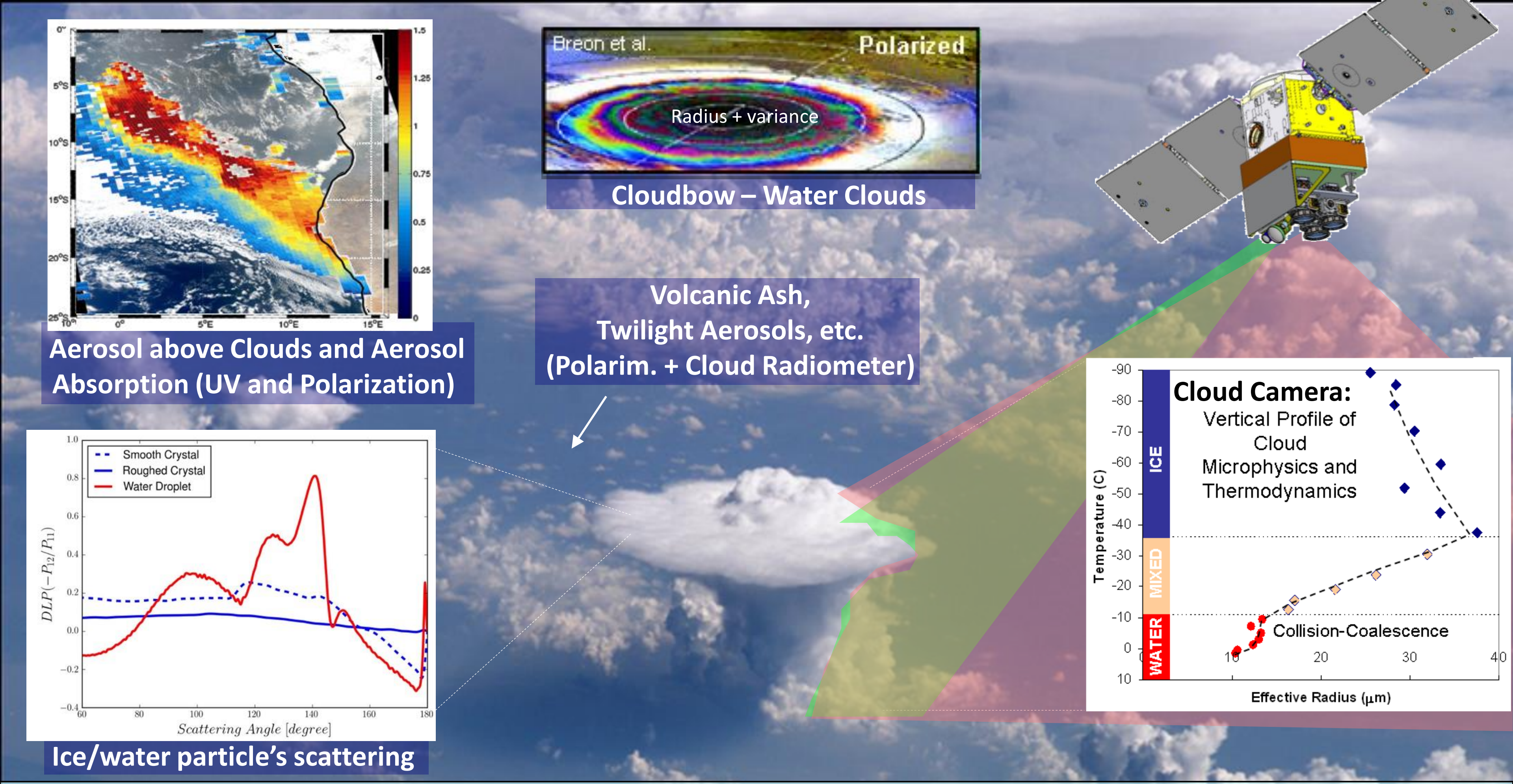


Many ideas, no funding…

Cloud Scanner







CLAIM-3D

PI: J. Vanderlei Martins (UMBC – JCET / 613)

Project Scientist: A. Marshak (GSFC 613)

- *The interaction between aerosol and clouds carry the largest uncertainty in climate forcing*
- *CLAIM-3D will determine how cloud evolution, droplet sizes, lifetime, vertical structure, thermodynamic phase, and ice particle structure vary as a function of aerosol type and amount*

- *CLAIM-3D has unprecedented combination of mature instruments and algorithms to address the interaction between aerosols and clouds*
- *CLAIM-3D is designed to provide a full court press characterization of the interactions between aerosol and clouds*

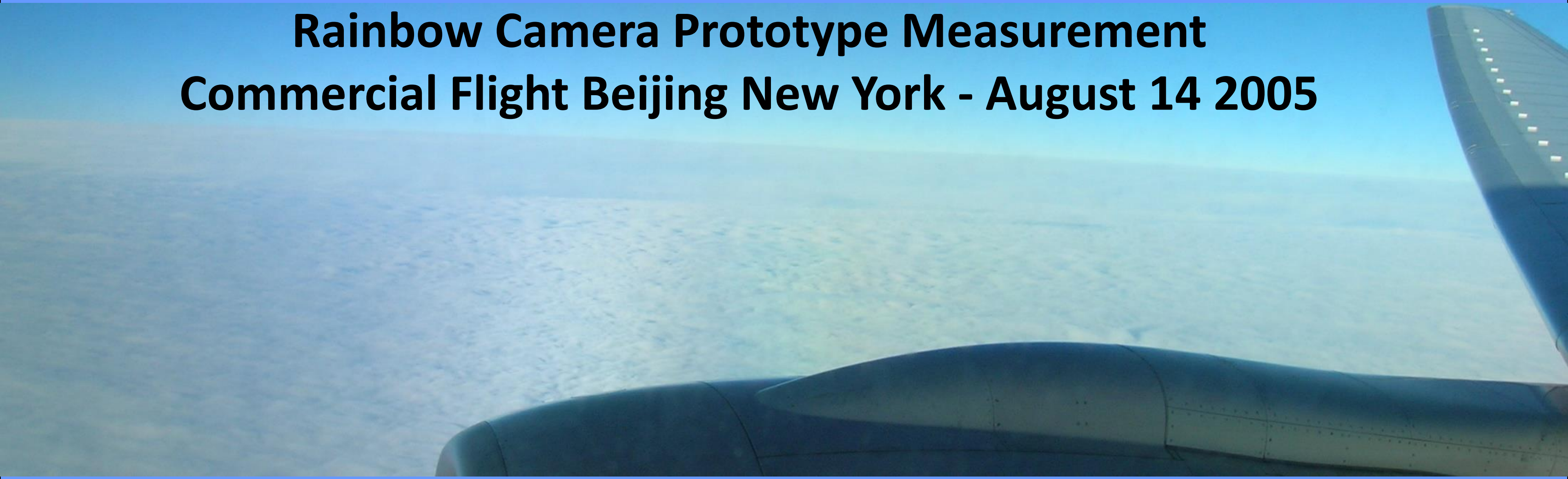
Back to the Lab!!!

What a Physicist carries on its Pocket?

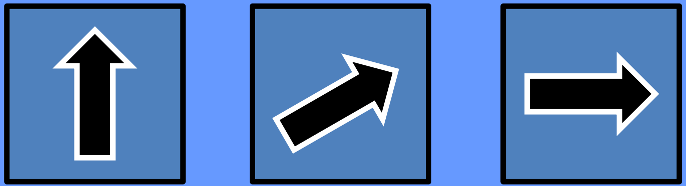
- Polarizer sheets led to my first experience flying in first class:
  - Measuring rainbows in a trip back from China.

- 600 pictures later, the flight attendant asked:
  - **“Sir, we are all wondering, it is so cloudy, why are you taking so many pictures?”**

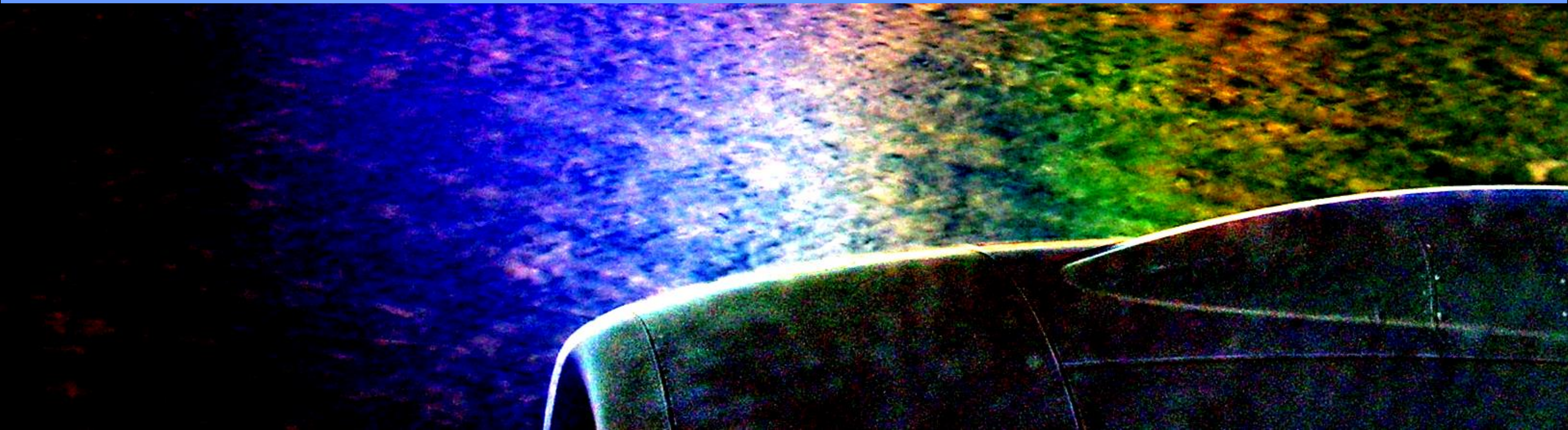
Rainbow Camera Prototype Measurement
Commercial Flight Beijing New York - August 14 2005



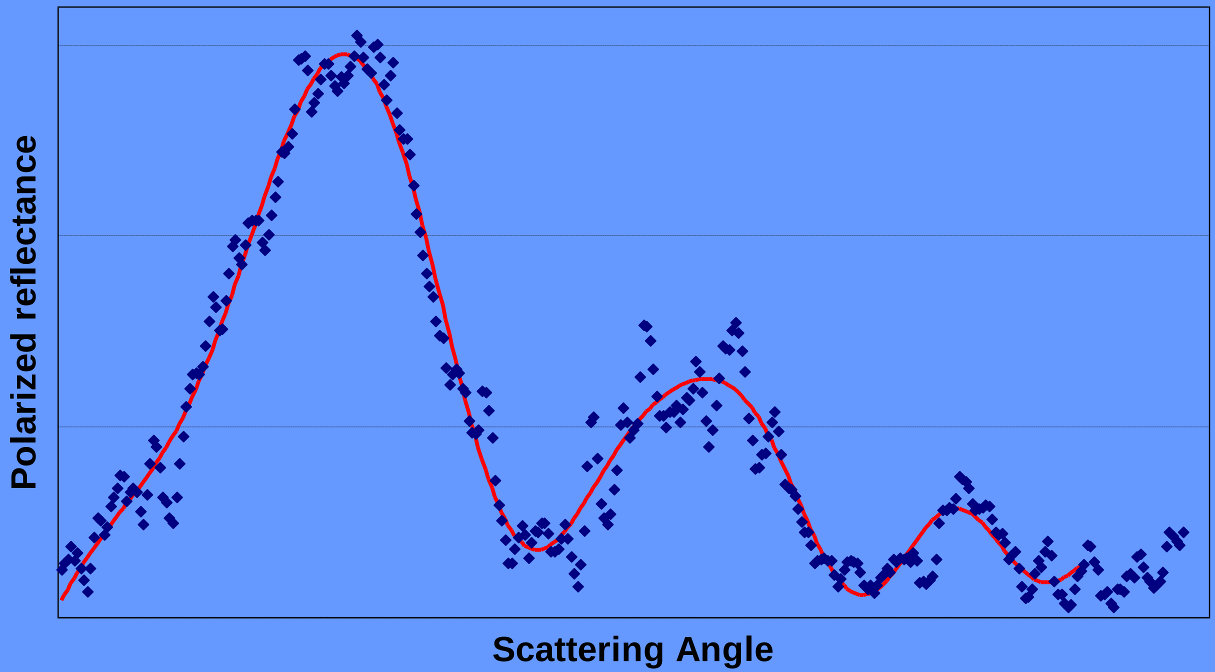
Pictures with 3 orientations of the polarizers



Recombined image:



Rainbow Camera Prototype Measurement
Commercial Flight Beijing New York - August 14 2005



My first cloudbow profile.

What a Physicist carries on its can get you in trouble!!!

- My second experience flying in first class
  - Trying to measure rainbows in a trip to Germany.
- TSA security did not like the wires and battery coming out of the polarizing camera that Dominik put together for me
  - I was escorted out of the plane by the police
  - Back to the plane to fly with 2 flight marshals
- On the way back:
  - **"Sir, you have been selected for a random check…";** the most thorough check I ever had.

Aerosols, Clouds, Rainbows and X-Rays: A Partnership between Earth and Space Sciences in Lean Times

J. Vanderlei Martins – JCET/UMBC, NASA GSFC - 613.2
Keith Gendreau – NASA GSFC - 662

The Earth Sciences Motivation:

- Aerosols from the Bodele Region
- The optical properties of Dust and the paradox of the Bodele dust
- The need for Chemical composition and mineral identification

A New X-ray Analysis Technique:

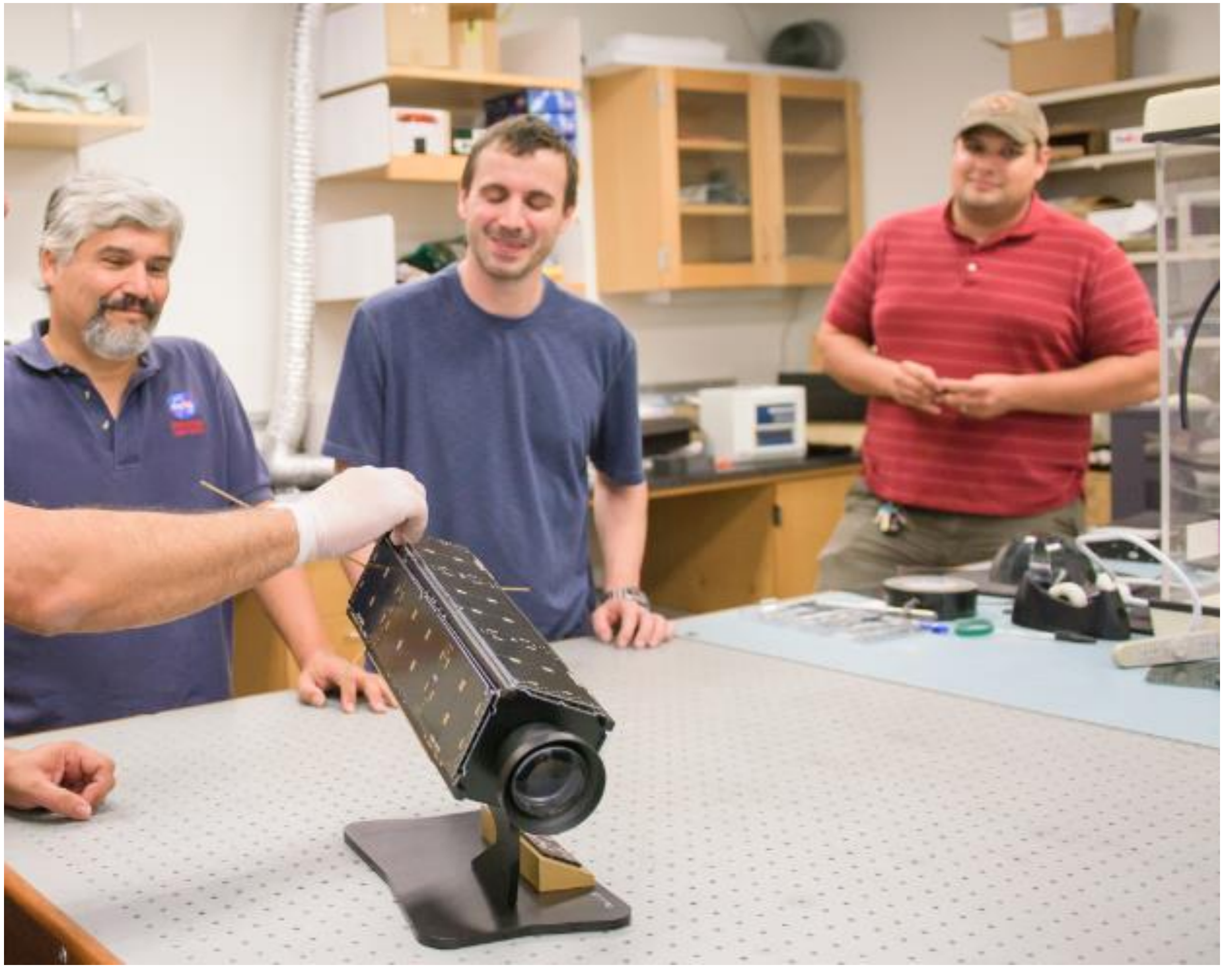
- X-Ray Astrophysical Instrumentation and Analysis Applied to Material Analysis
- A new type of X-Ray Diffractometer: Overview and General Applications
- Measurements of Bodele Aerosols

What this whole thing have to do with Clouds and Rainbows

- New measurements of Cloud Microphysics
- A Combination Rainbow x CXRDF system

Pictures by the BoDEx 2005 group

This team can build anything…



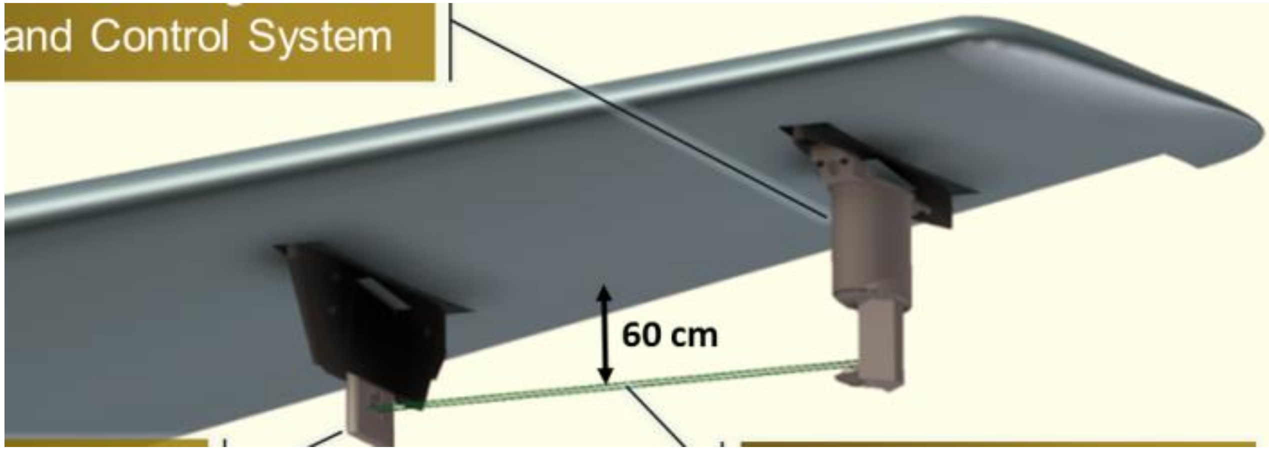
Roberto, Domink, Kevin and John

And in today’s environment, they could be out of job…

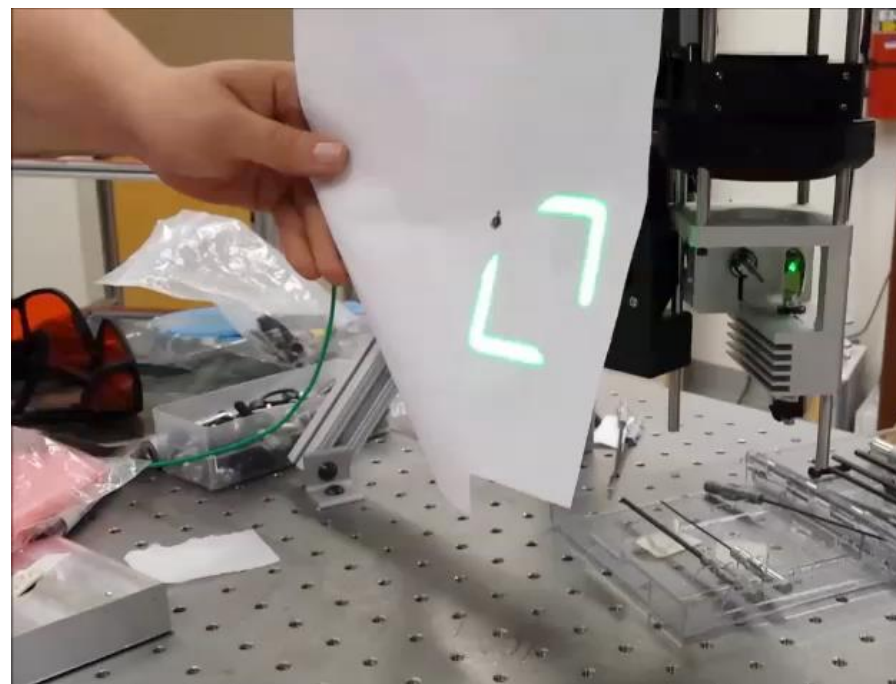
But then Ralph asked: **“Can they build a wall???”**

In situ measurements of Undisturbed particles:

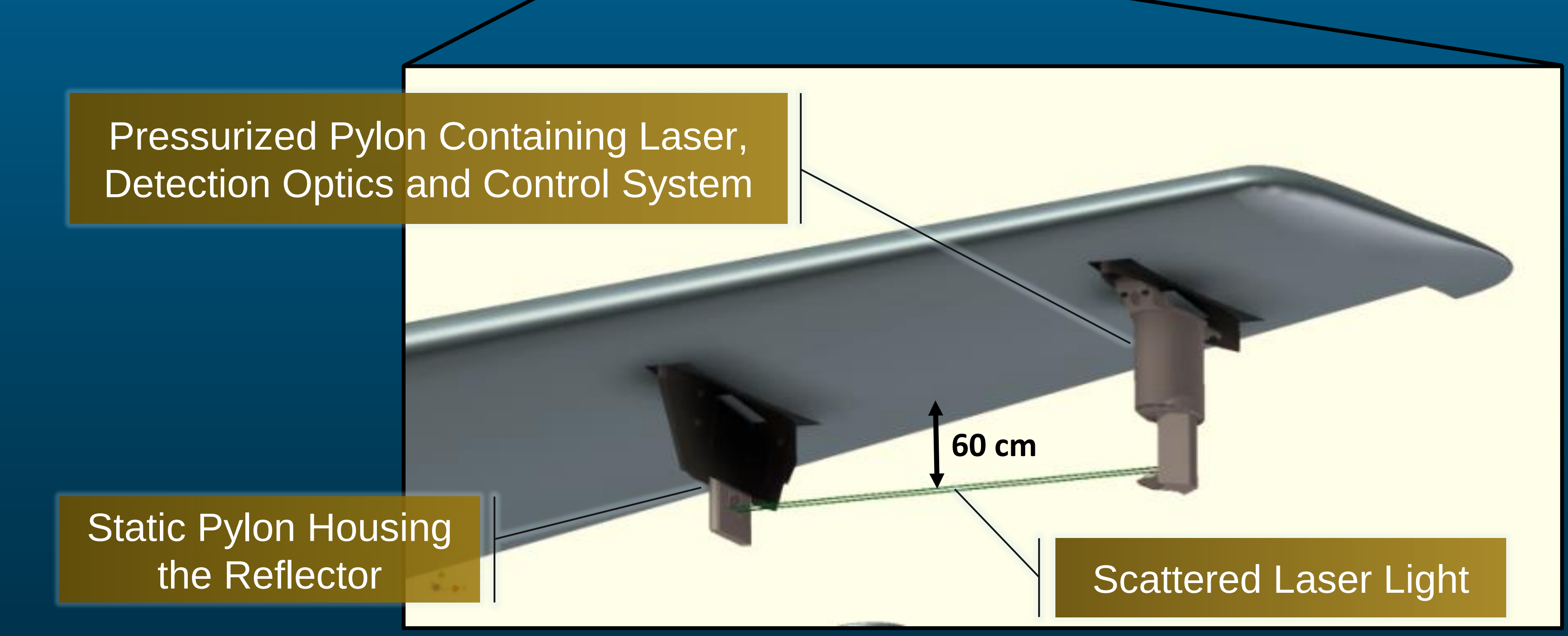
The Open Imaging Nephelometer

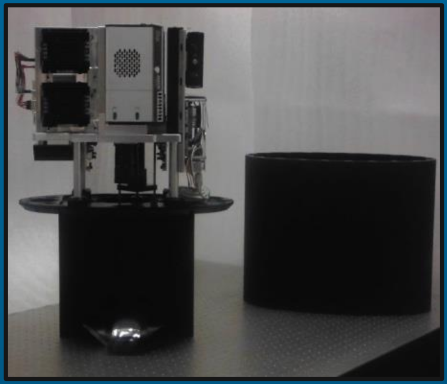


These people can build anything…

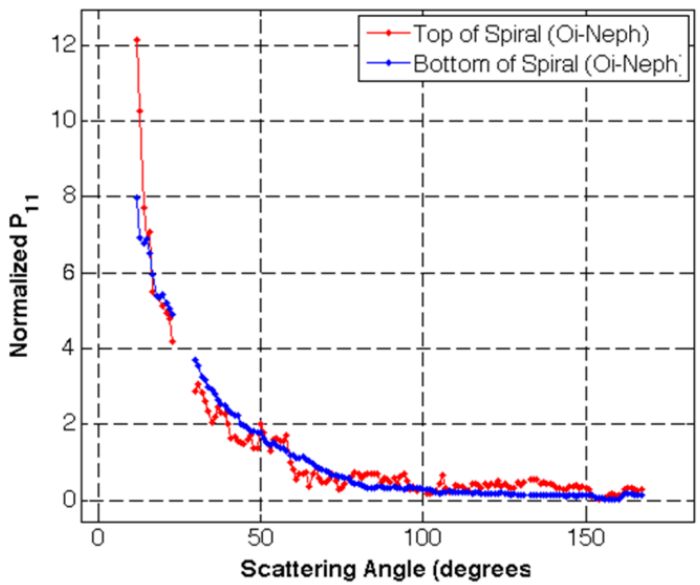


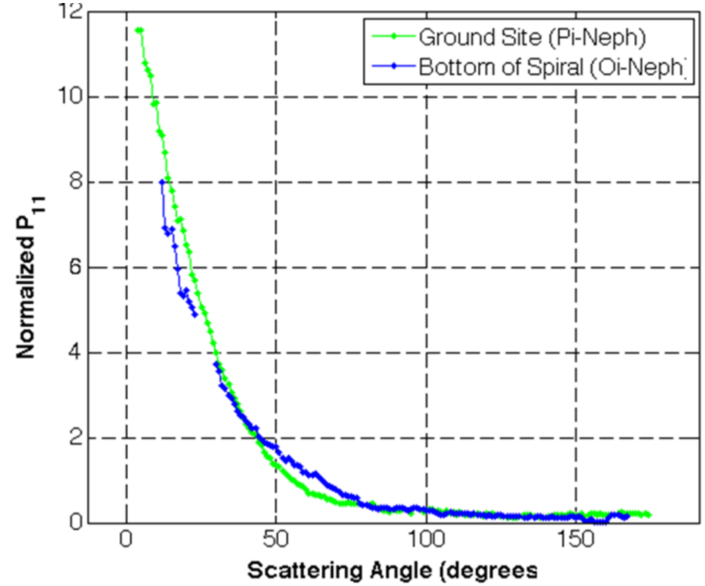
Open Imaging Nephelometer (OI-Neph)

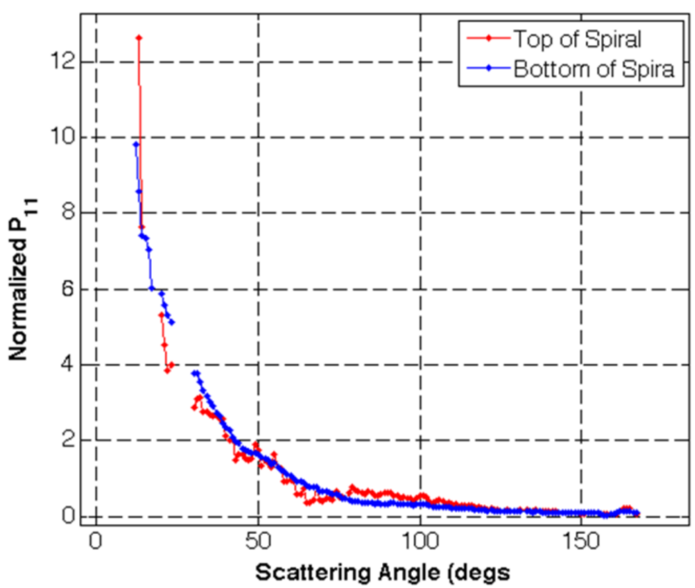


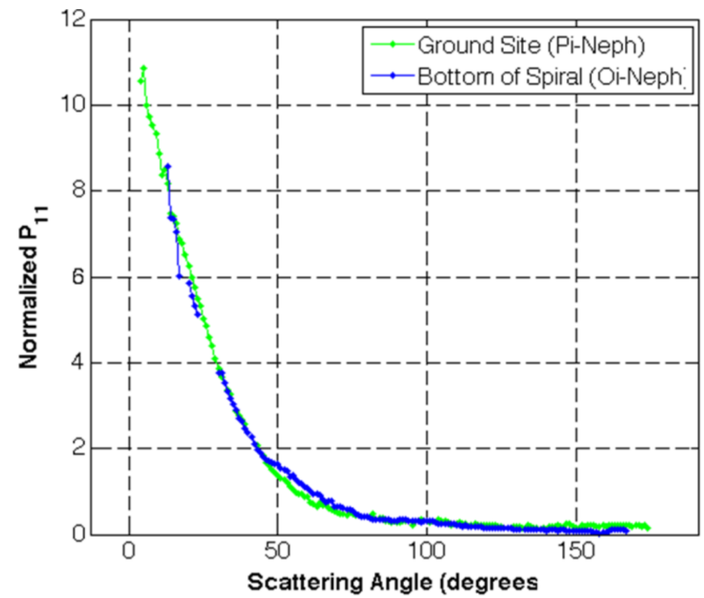


Open I-Neph First Results from DAQ

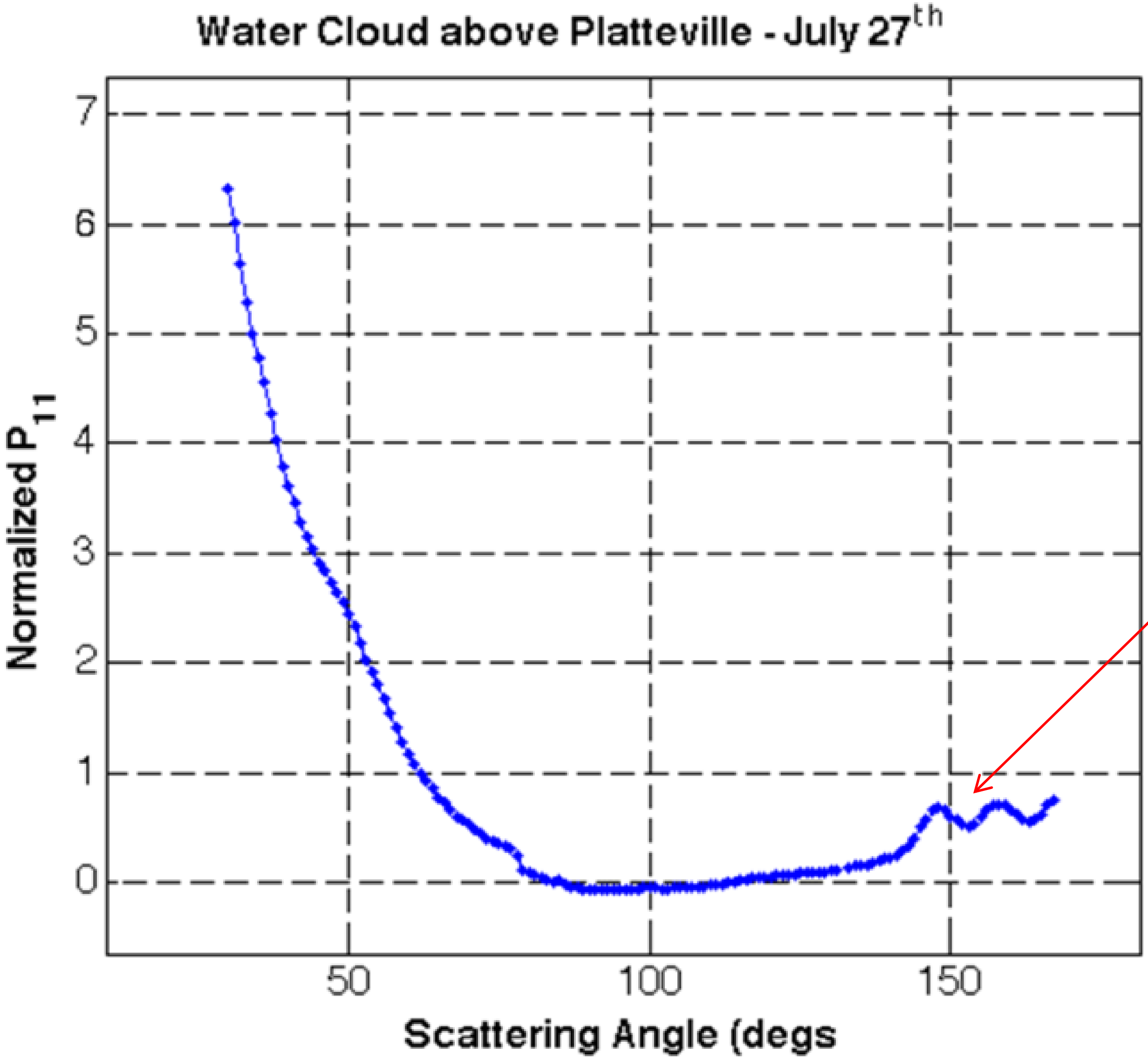








Open Ineph First Results from DAQ



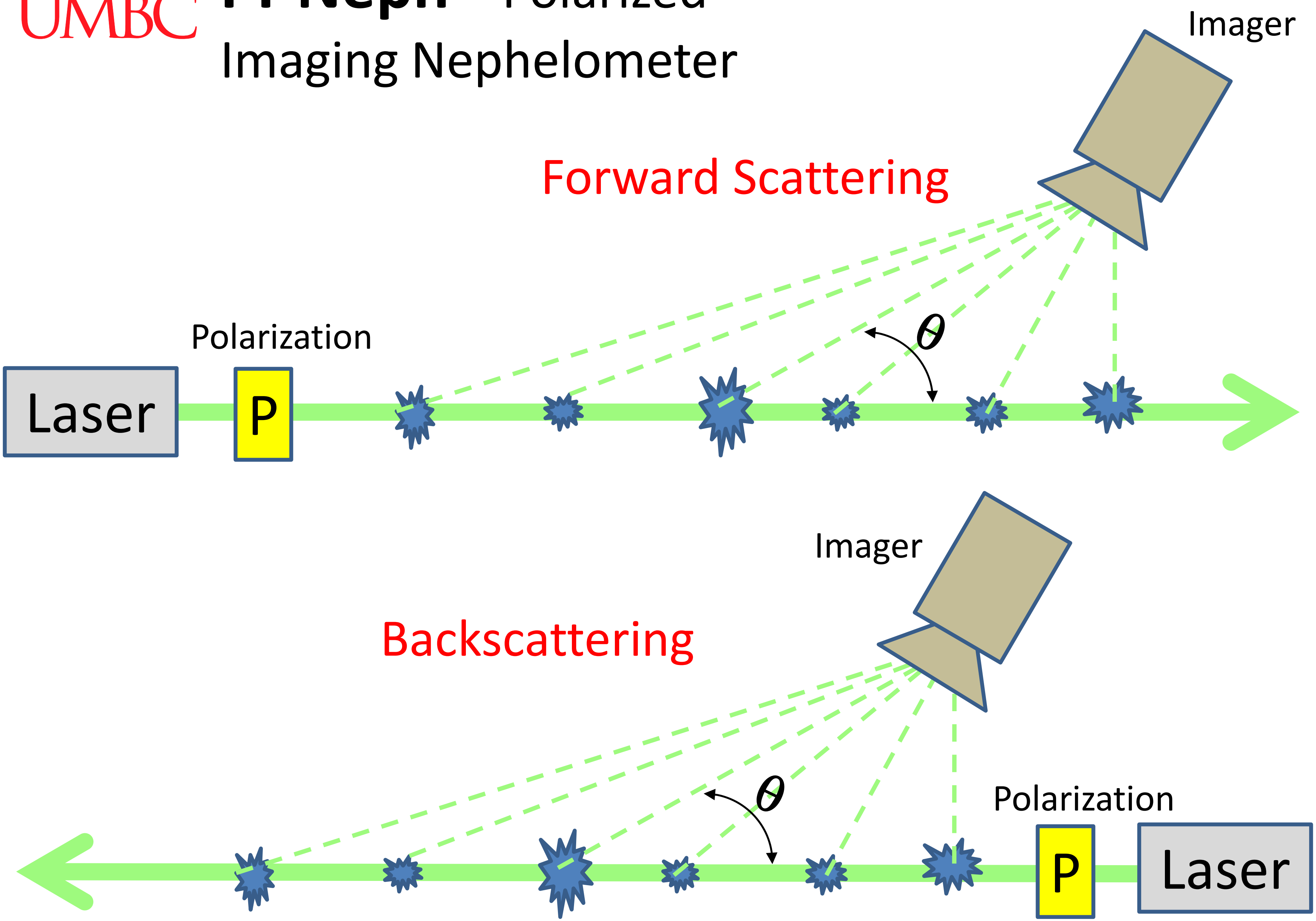
Measurement of the cloudbow inside a water cloud

Direct In situ measurements of the Optical Properties of Aerosols:

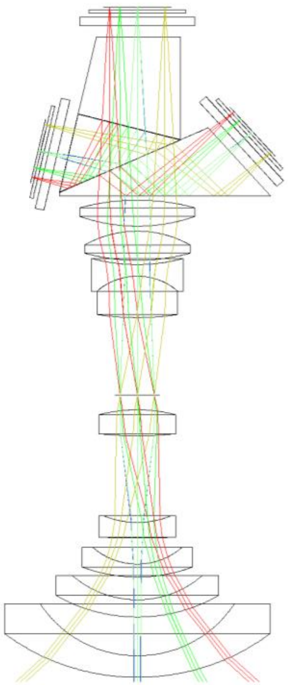
The Polarized Imaging Nephelometer: PI-Neph

UMBC

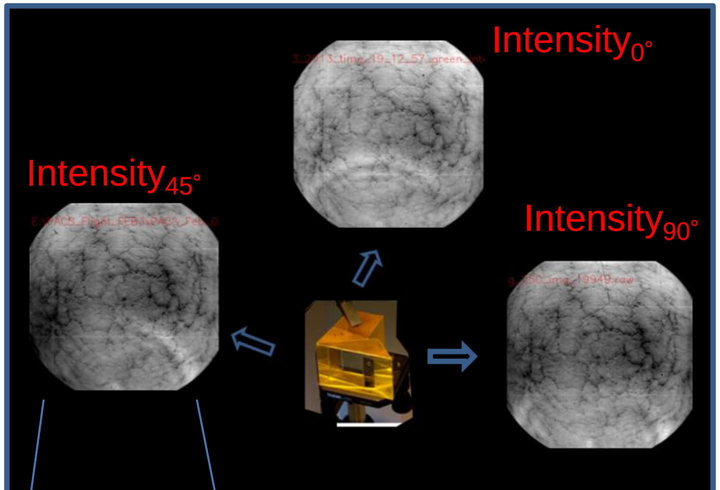
PI-Neph - Polarized Imaging Nephelometer



HARP Hyperangular Multi-Wavelength Polarization Images



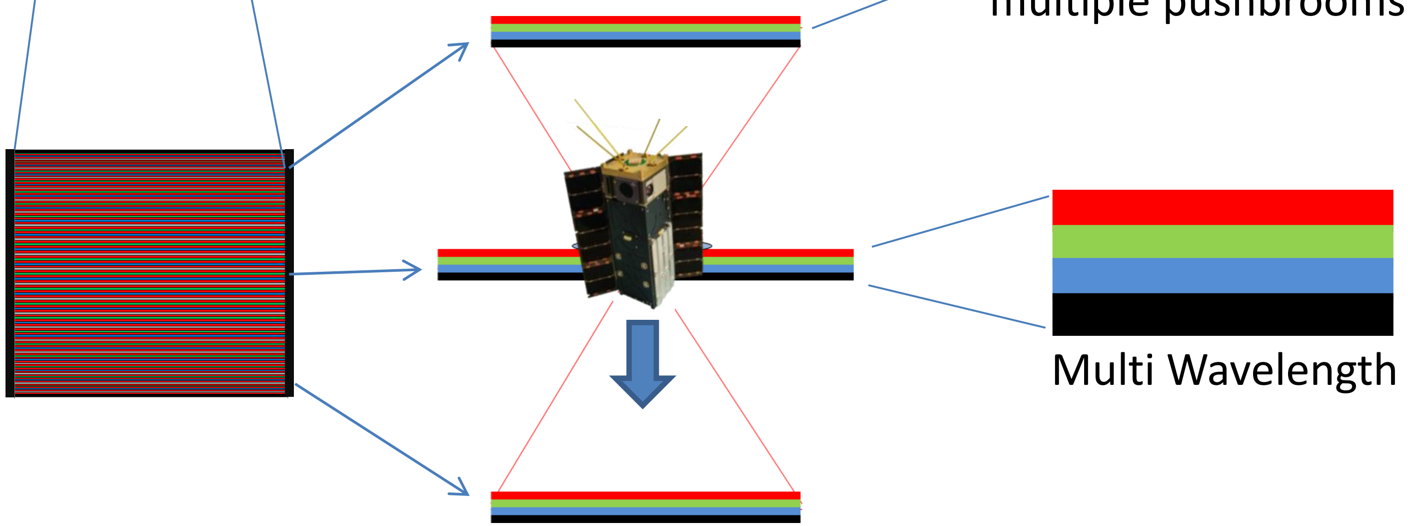
HARP Prism/Polarization Separation



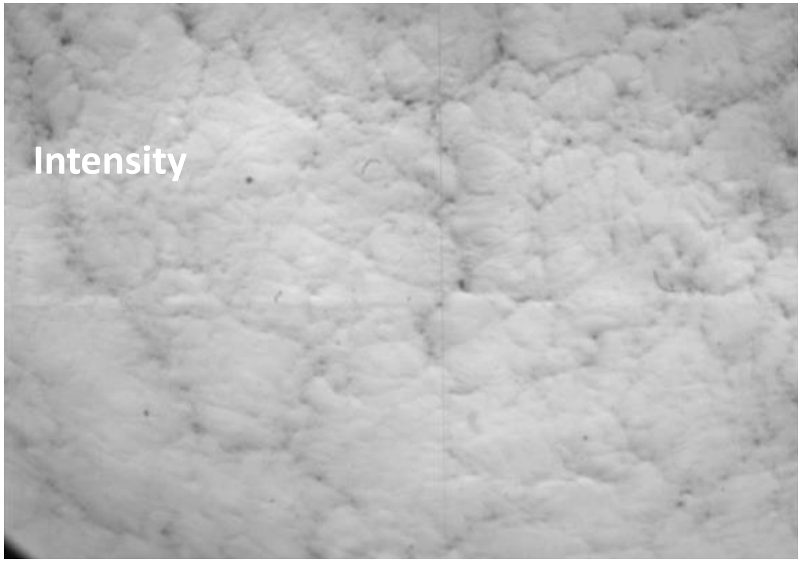
$$[I \;\; Q \;\; U]_{pixel} = [I_0 \;\; I_{45} \;\; I_{90}] \cdot M$$

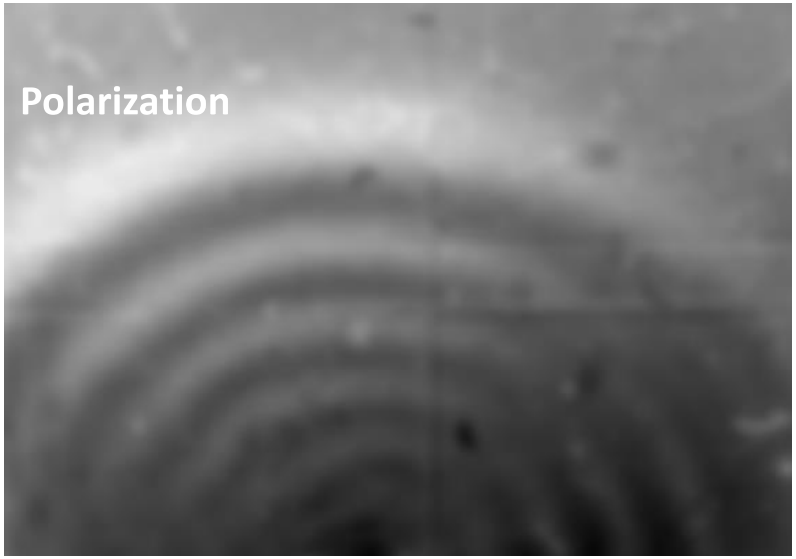
HARP

- Up to 60 viewing angles
- 440, 550, 670, 870nm
- 2.5km resolution
- 94 deg FOV X-track
- 110 deg FOV along track

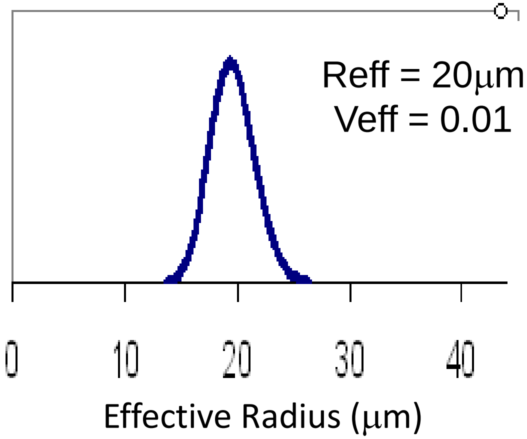


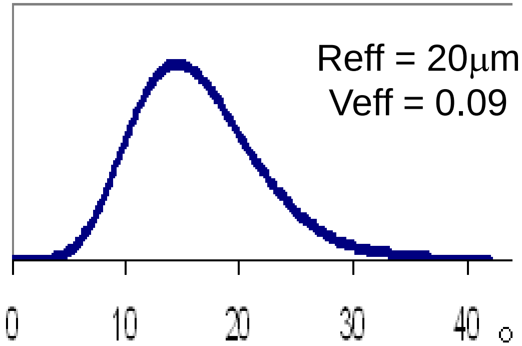
Hyper-Angular Polarization Retrievals of cloud droplet sizes provides effective radius and effective variance





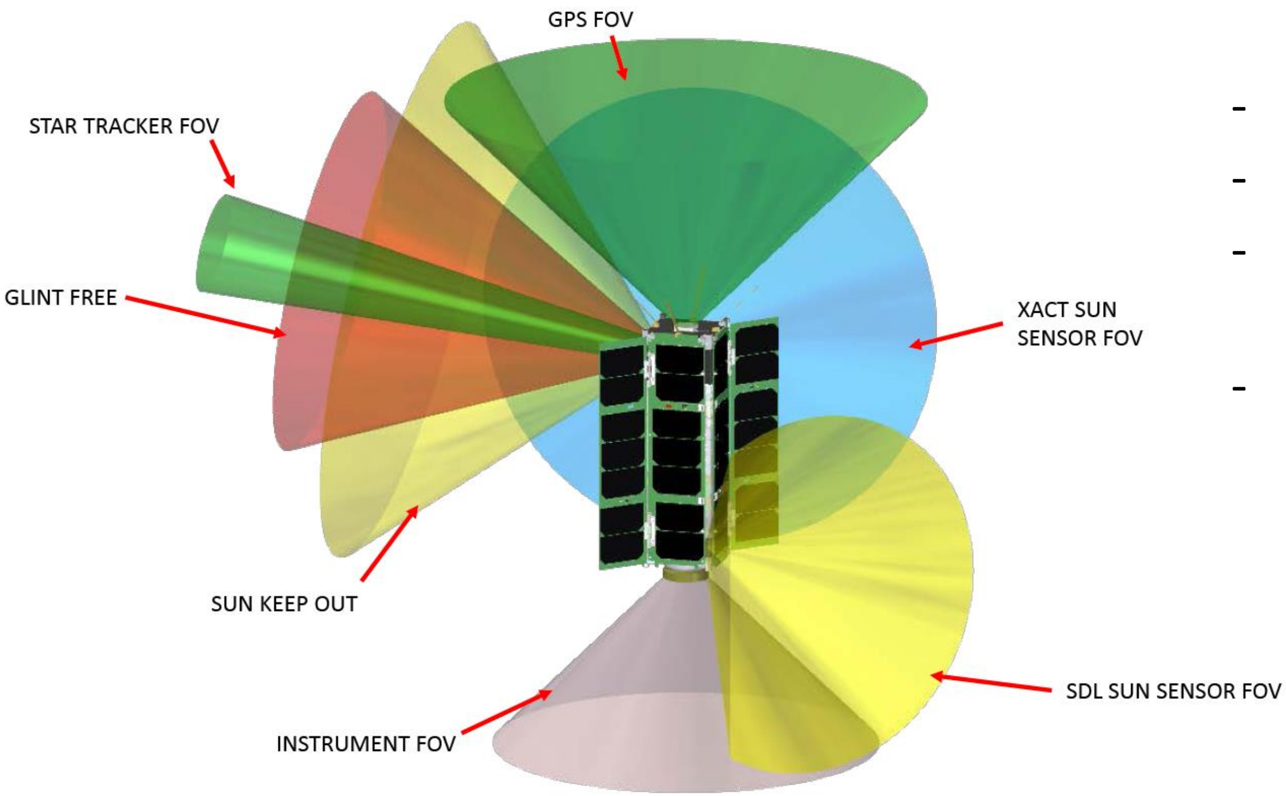
Water Droplet Distribution





These two cases are undistinguishable from Intensity measurements only (MODIS, VIIRS,…)

HARP – Full Feature Earth Sciences Satellite



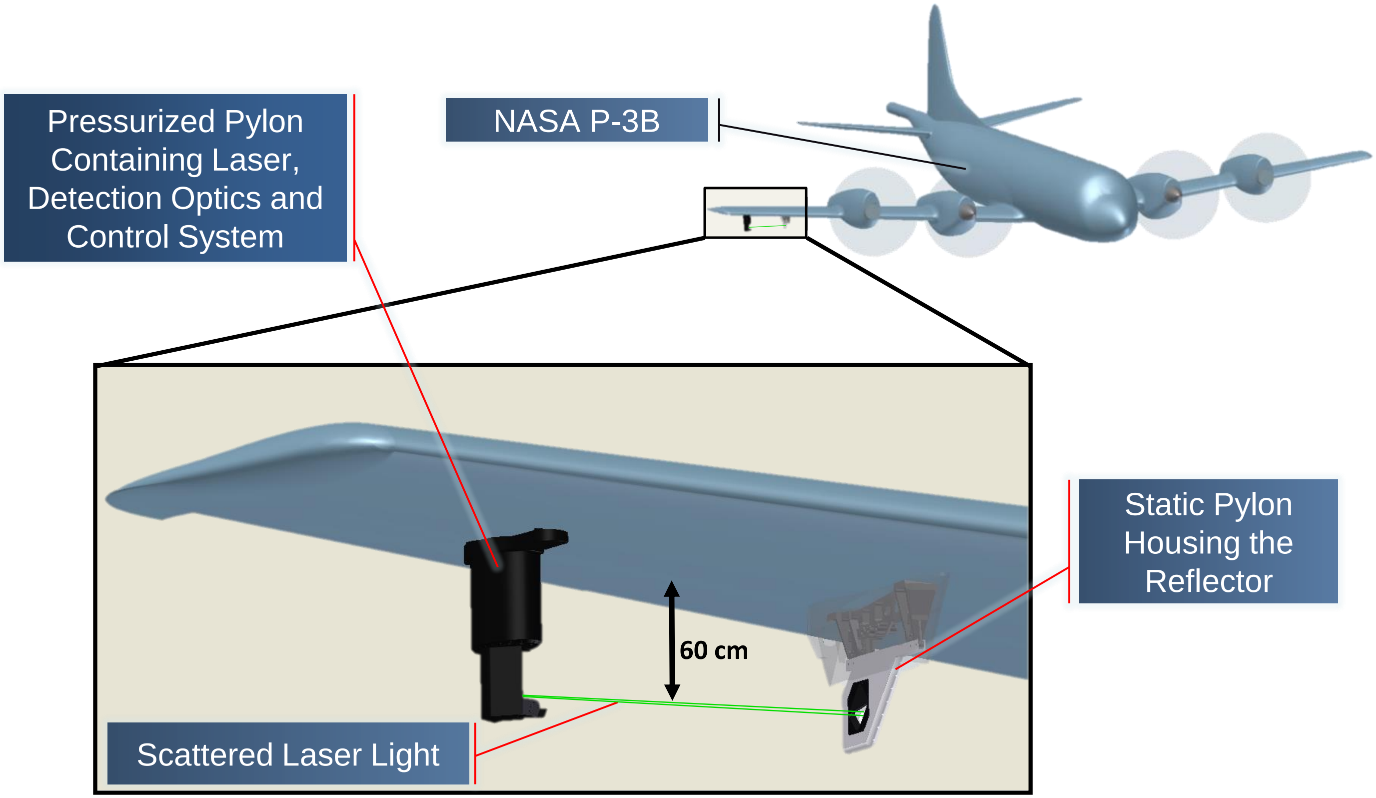
- Accurate ACDS
- Sun Sensor + Star tracker
- < 0.66km pointing knowledge/geolocation
- UHF radio up to 3Mbits/s

- Terra < 1 min
- NPP < 1min
- Aqua < 5 min
- Aqua < 5 min
- NPP < 5 min

ISS orbit crosses within minutes of other satellites several times a day (example: 13 Apr 2016):

UMBC

Inlet-Free Airborne Open Imaging Nephelometer (**O-INEPH**) for the Measurement of Atmospheric Particle's Phase Function



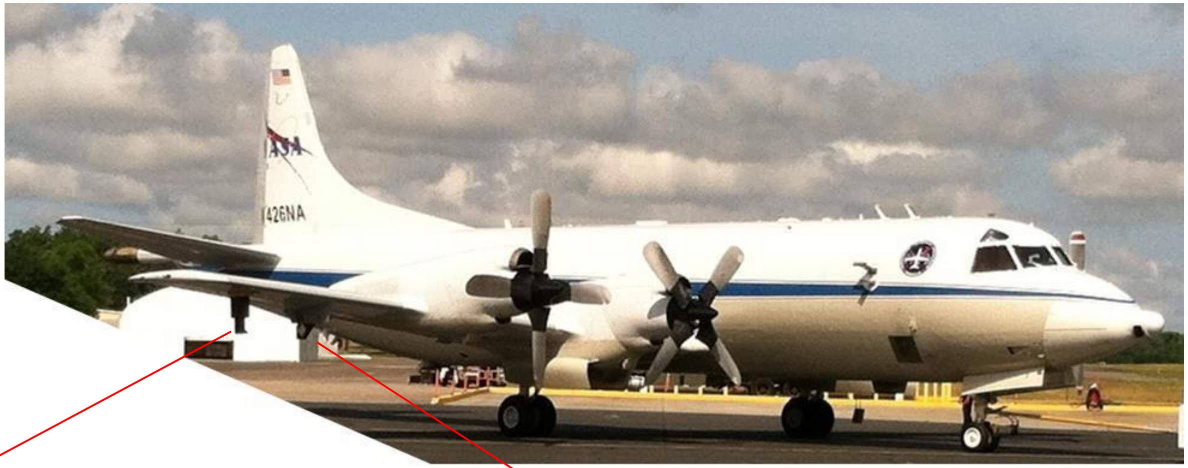


Photo credit: Dominik Cieslak

Open Imaging Nephelometer on NASA P3

UMBC LACO

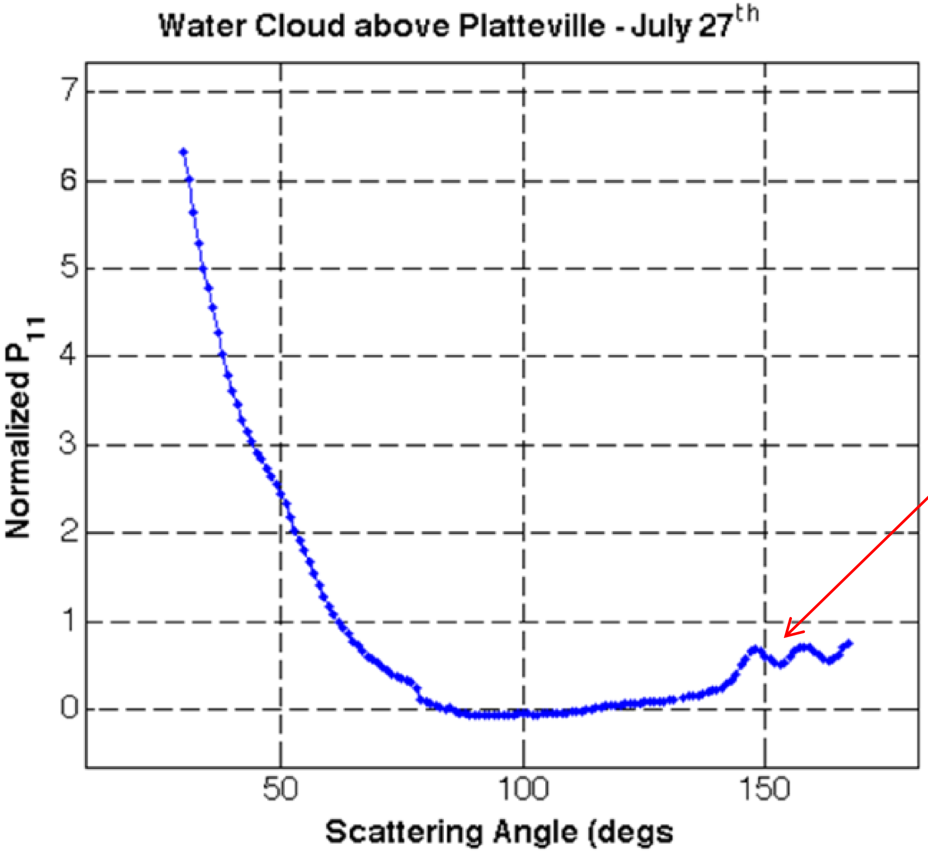
JCET The Joint Center for Earth Systems Technology

NASA

U.S. DEPARTMENT OF ENERGY

ASR Atmospheric System Research

Open Ineph First Results from DAQ



Measurement of the cloudbow inside a water cloud