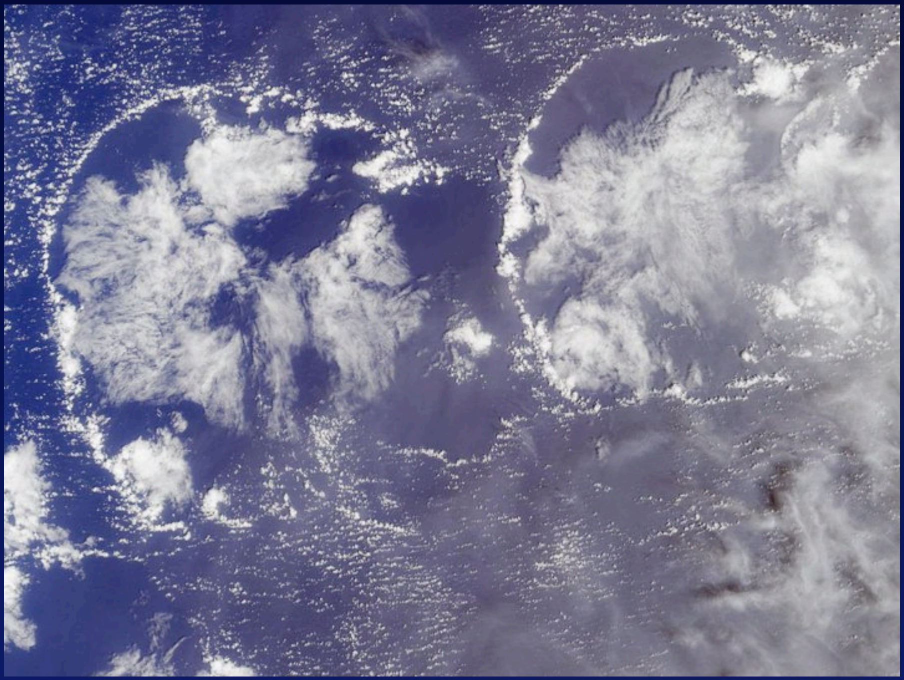
Advances in multiangular and polarimetric imaging: Application to boundary layer clouds and aerosols

KISS Symposium, Caltech
Innovative Satellite Observations to Characterize the Cloudy Boundary Layer
September 22, 2010



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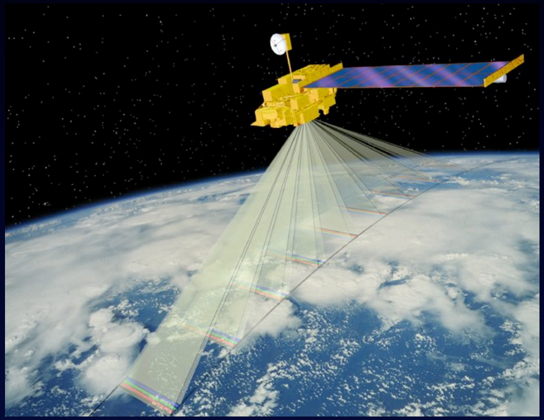
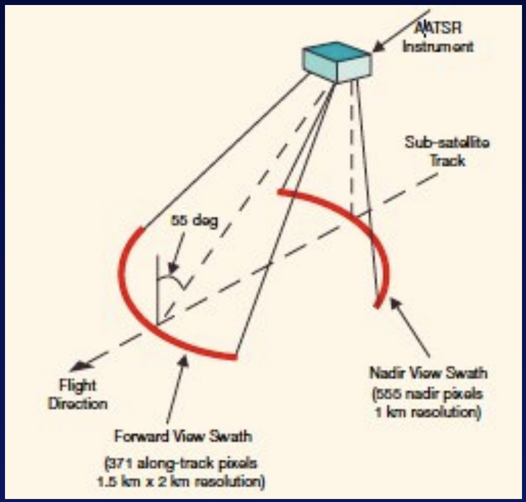
Introduction

- IPCC AR4: "The shortwave impact of changes in boundary-layer clouds, and to a lesser extent midlevel clouds, constitutes the largest contributor to inter-model differences in global cloud feedbacks."
- IPCC AR4: "There remain large uncertainties in both measurements and modelling of [aerosol-cloud interaction] processes."
  Issues with satellite observations:
  - Insufficient spatial resolution
  - Cloud heterogeneity
  - Particle type sensitivity
- Observations aided by multiangular and polarimetric imagery:
  - Cloud-top heights
  - Dynamical environment (horizontal winds)
  - Aerosol and cloud microphysical properties
  - Cloud 3D structure

Current multiangle satellite sensors

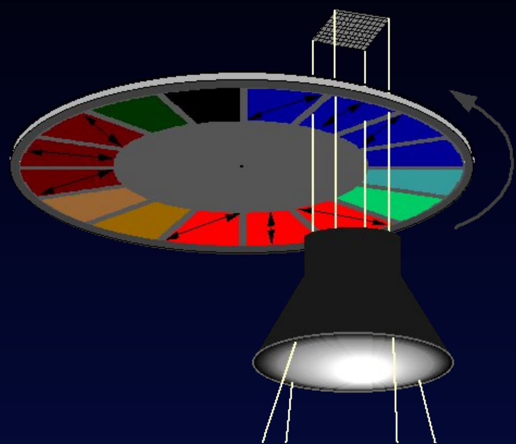


- MISR
  - 9 view angles
  - 275 m spatial resolution, 400 km swath
  - 4 VNIR spectral bands

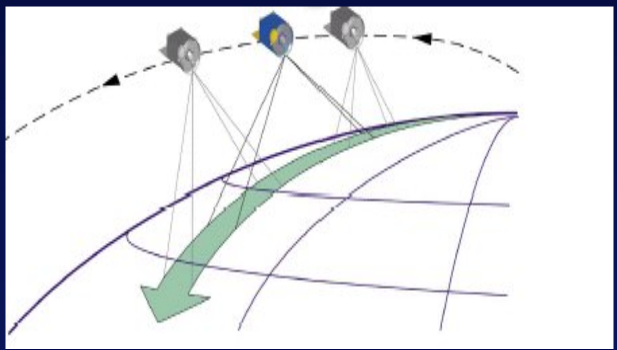


- ATSR-2/AATSR
  - 2 view angles
  - 1 km spatial resolution, 512 km swath
  - 3 VNIR, 1 SWIR, 3 TIR spectral bands

Current/near-term polarimetric satellite sensors



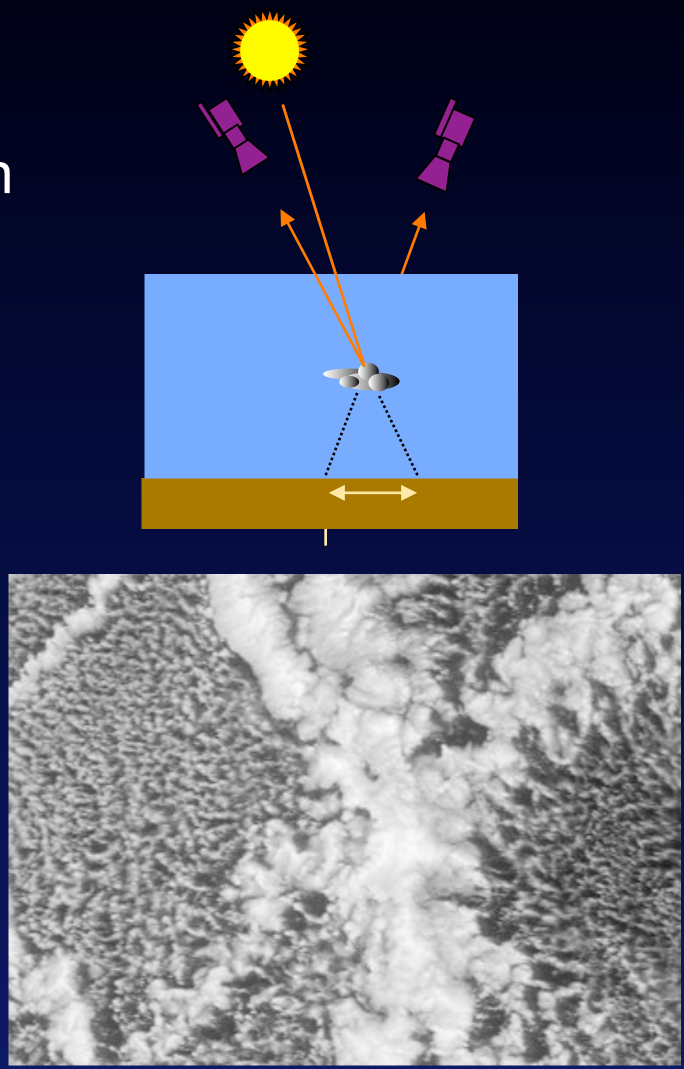
- POLDER/PARASOL
  - Up to 14 view angles
  - 7 km spatial resolution, 2400 km swath
  - 9 VNIR spectral bands (3 polarimetric)



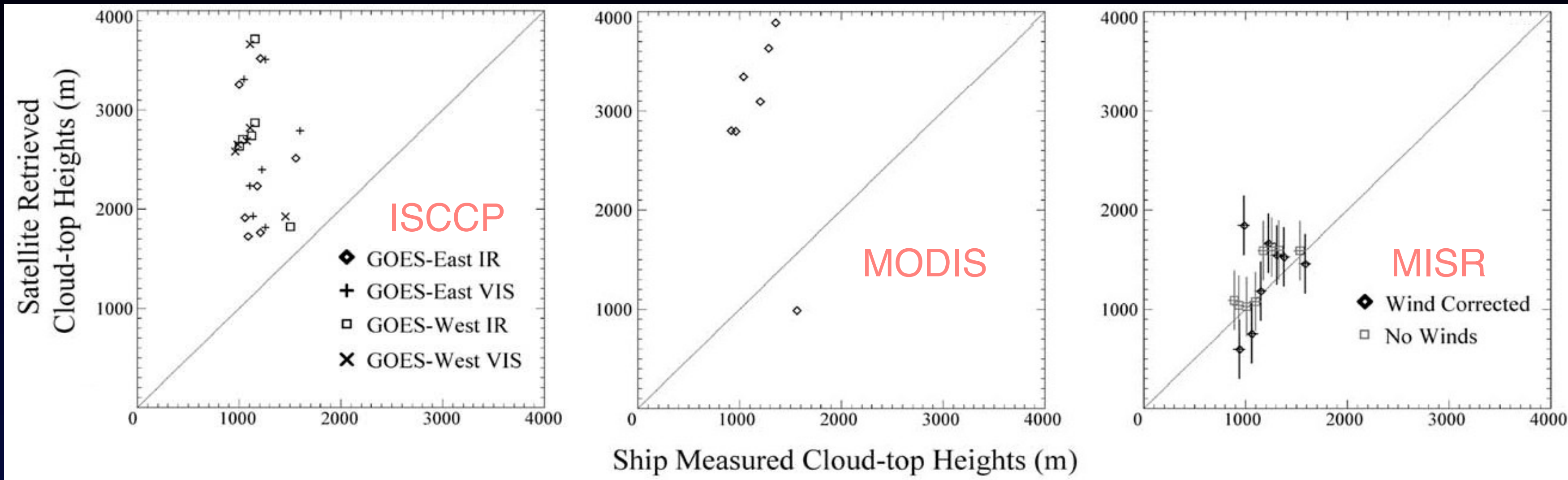
- Glory APS
  - Hundreds of view angles
  - 6-20 km spatial resolution, non imaging
  - 6 VNIR, 3 SWIR spectral bands (all polarimetric)

“Geometric” multiangle measurement approach

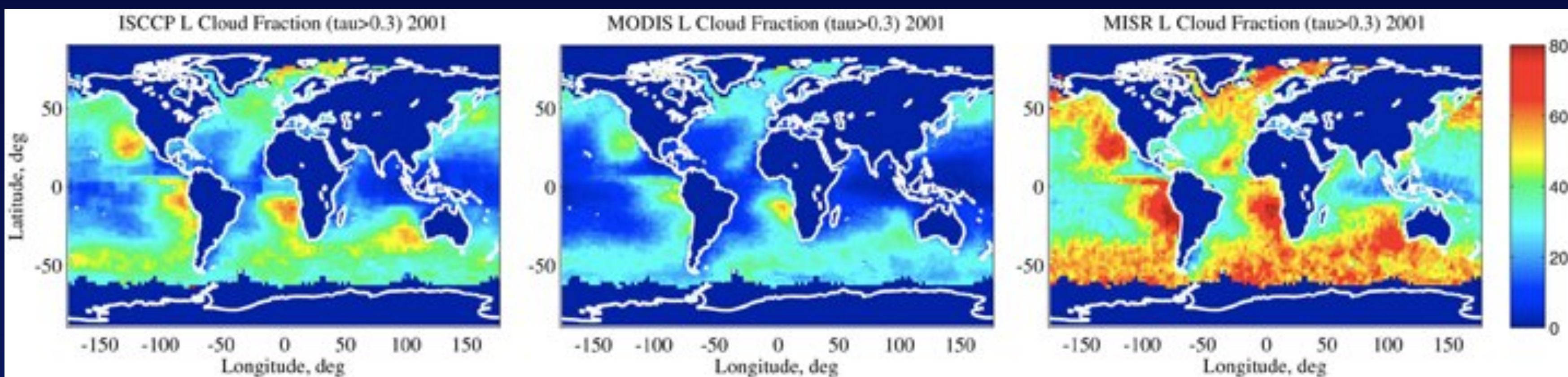
Geometric (stereoscopic) approach keys on parallax and time lapse



Stereo heights are independent of temperature…

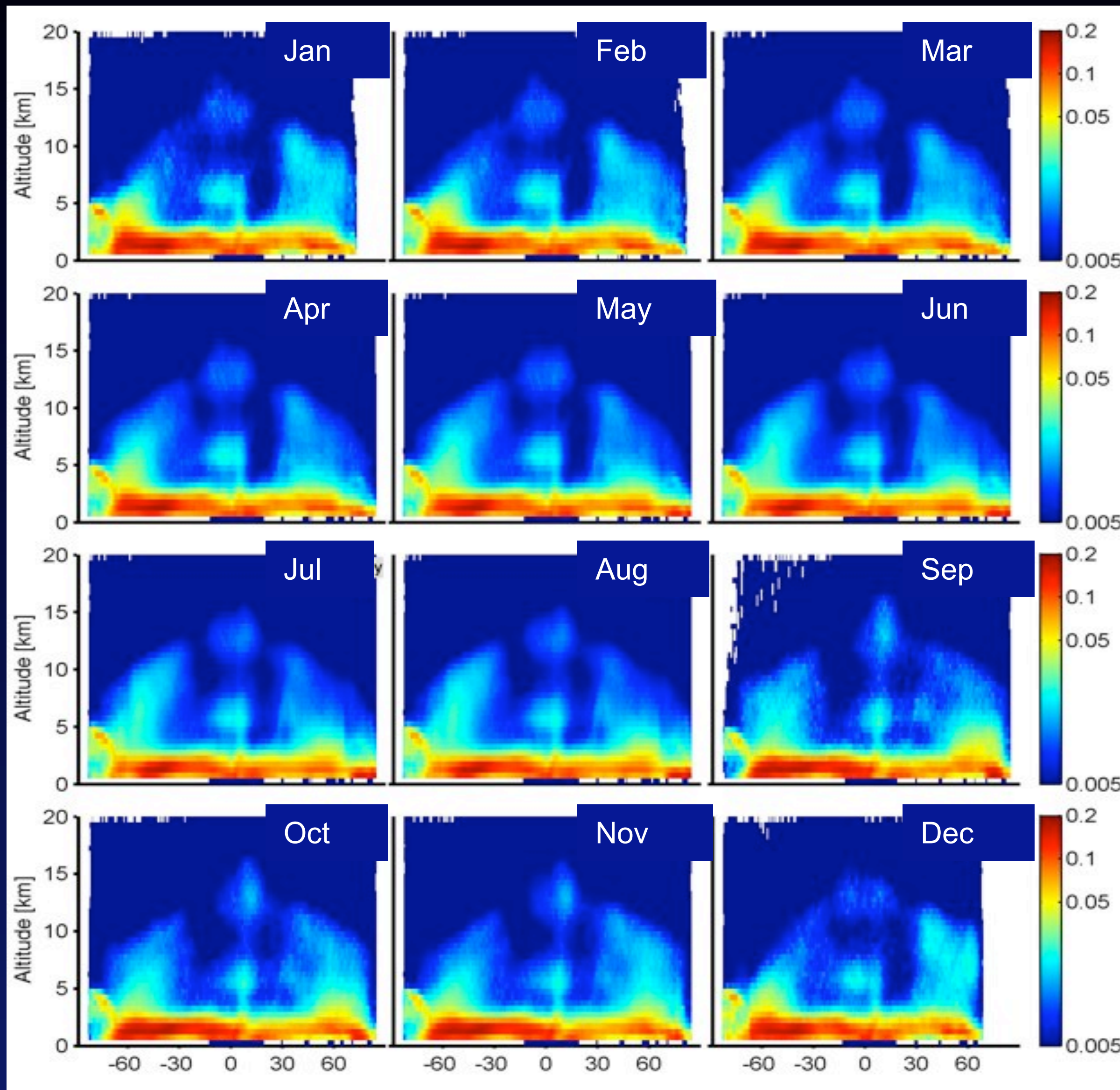


Marine stratocumulus off western coast of S. America (2001, 2003, 2006 data)



Garay et al. (2008), *JGR* **113**; Harshvardan et al. (2009), *TGARS* **47;**
Marchand et al. (2010), *JGR* **115**

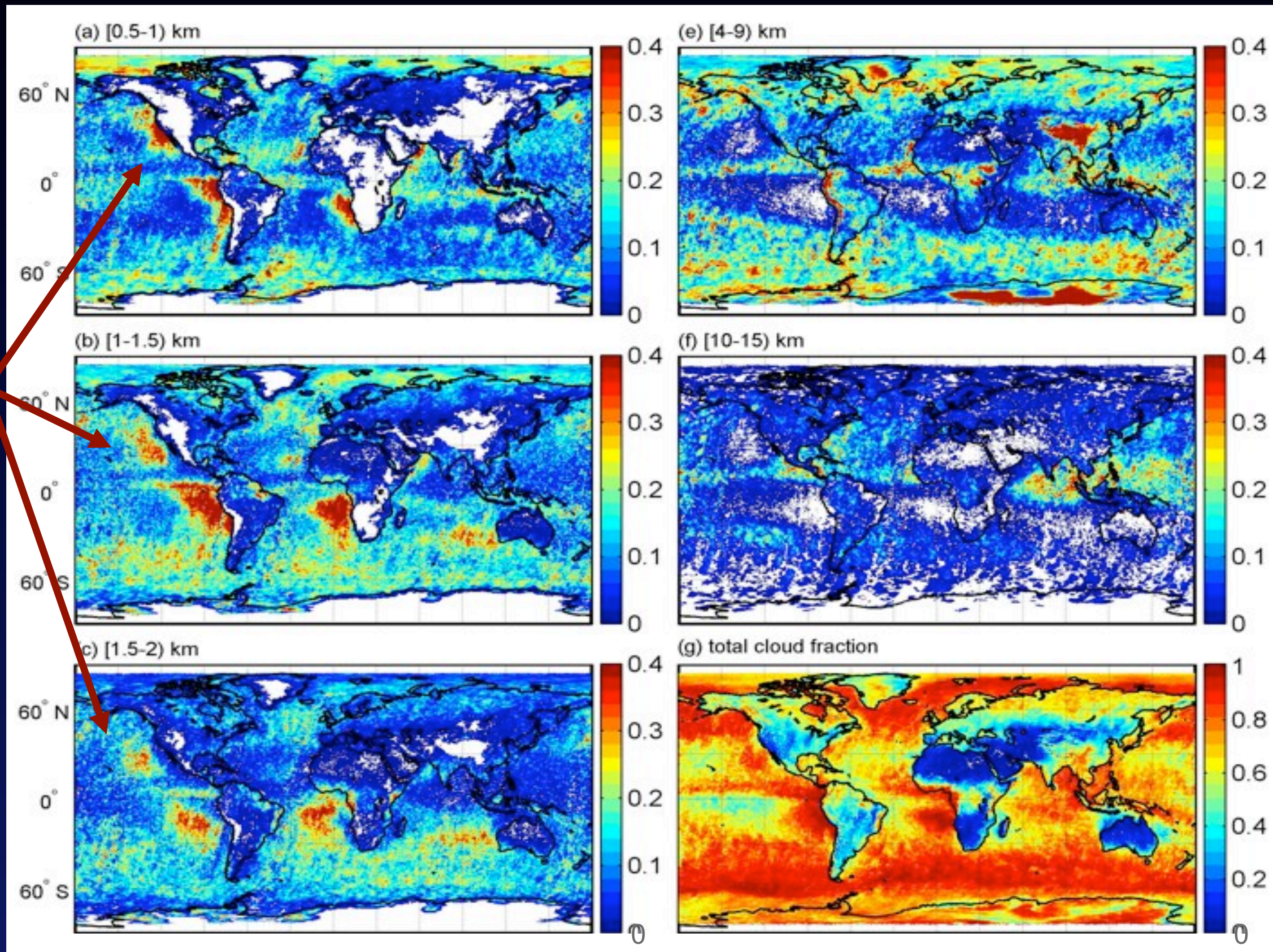
…and very sensitive to low- and mid-level clouds



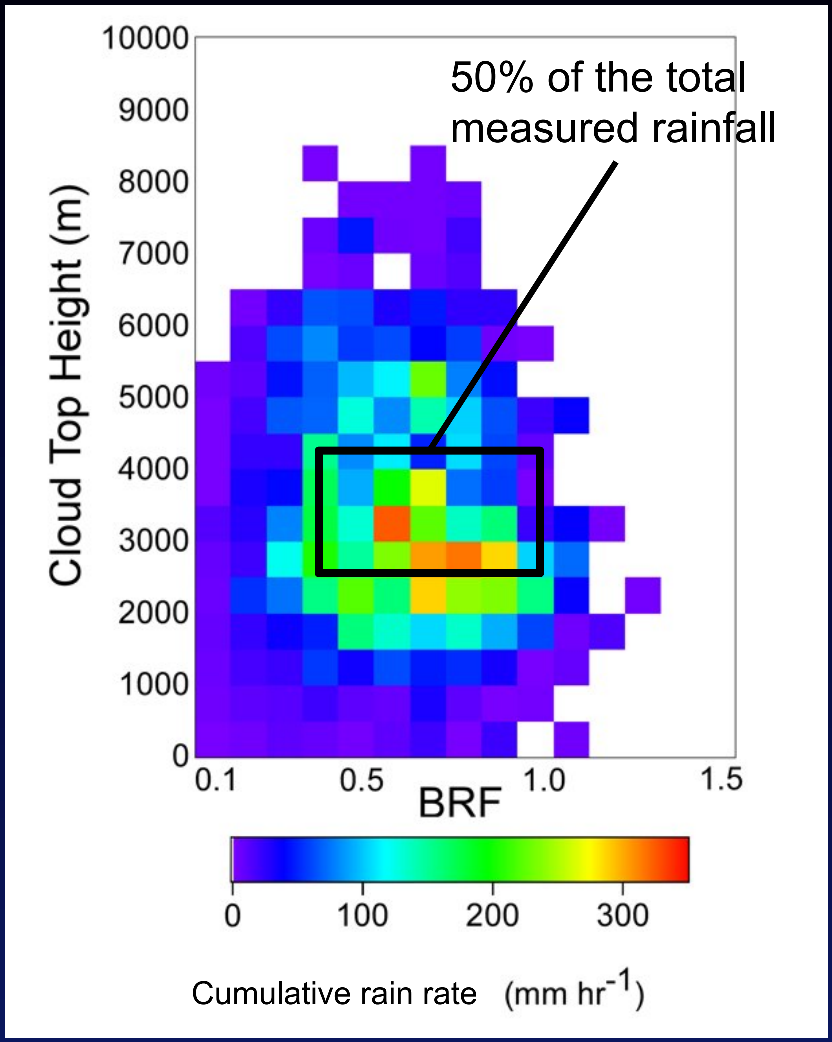
MISR zonal mean cloud(-top) fraction vs. altitude

MISR cloud fraction by altitude

Stereo recovers increase in cloud heights associated with SST increase and deepening of the boundary layer



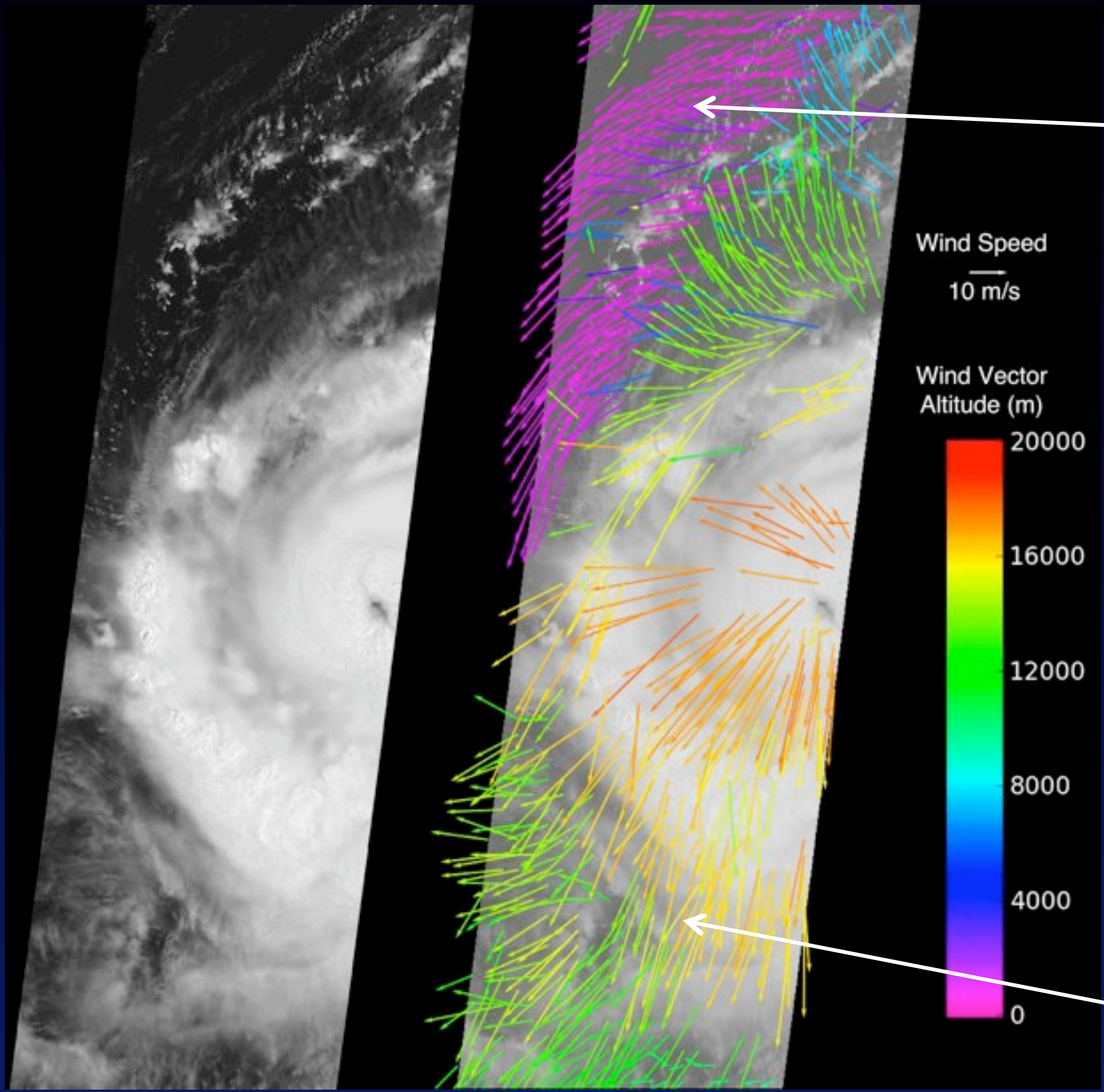
Cloud height and precipitation during RICO



Fusion of MISR and ground-based radar data localize the type and altitude of dominant rain-producing trade wind cumuli

Snodgrass et al. (2009), *JAMC* **48**

Height-resolved stereo wind retrievals from MISR

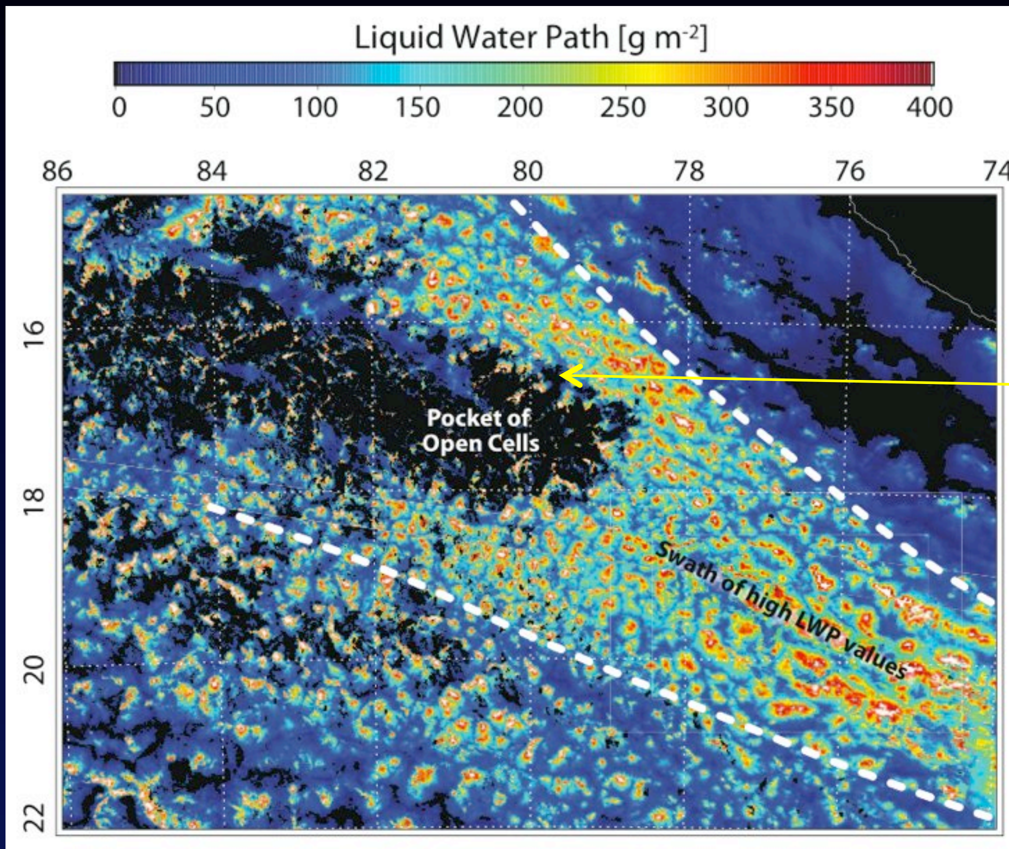


Boundary layer wind field

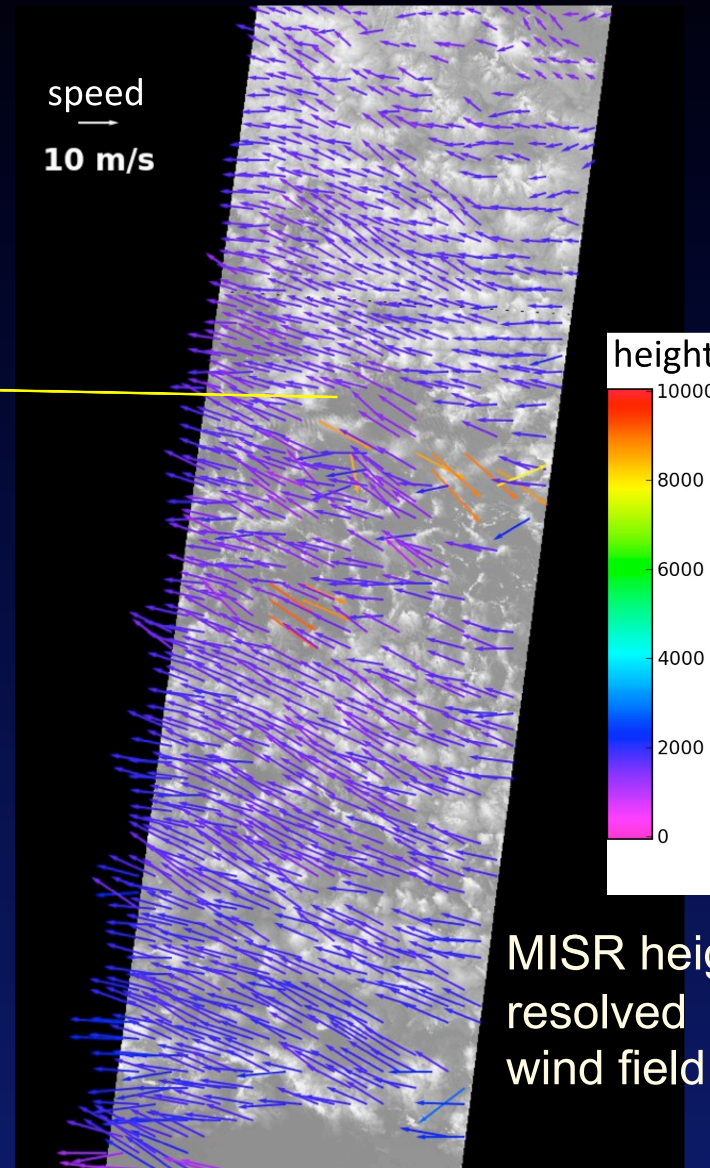
High-level outflow

Hurricane Earl 8/30/2010

Marine stratocumulus winds



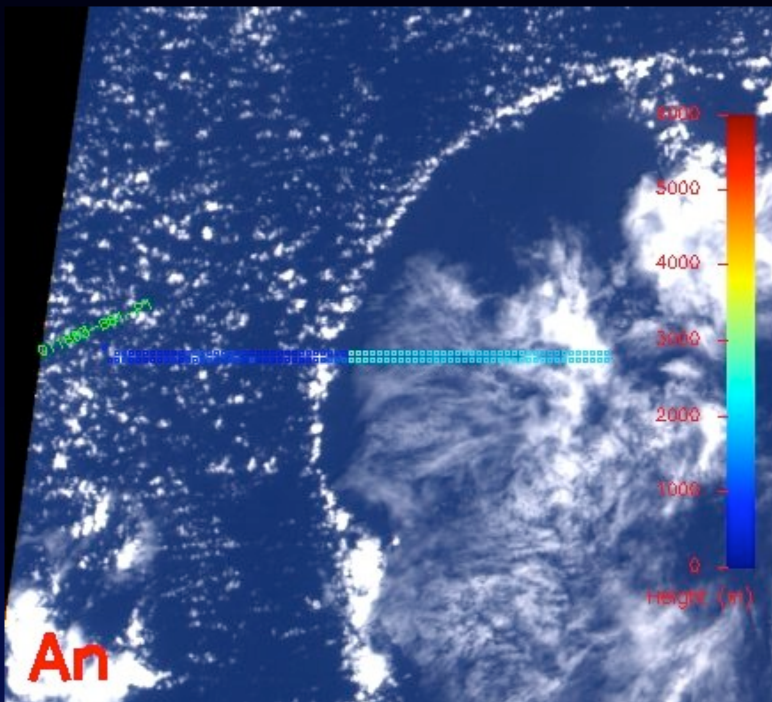
MODIS LWP for stratocumulus in Southeast Pacific during VOCALS, Oct. 2008

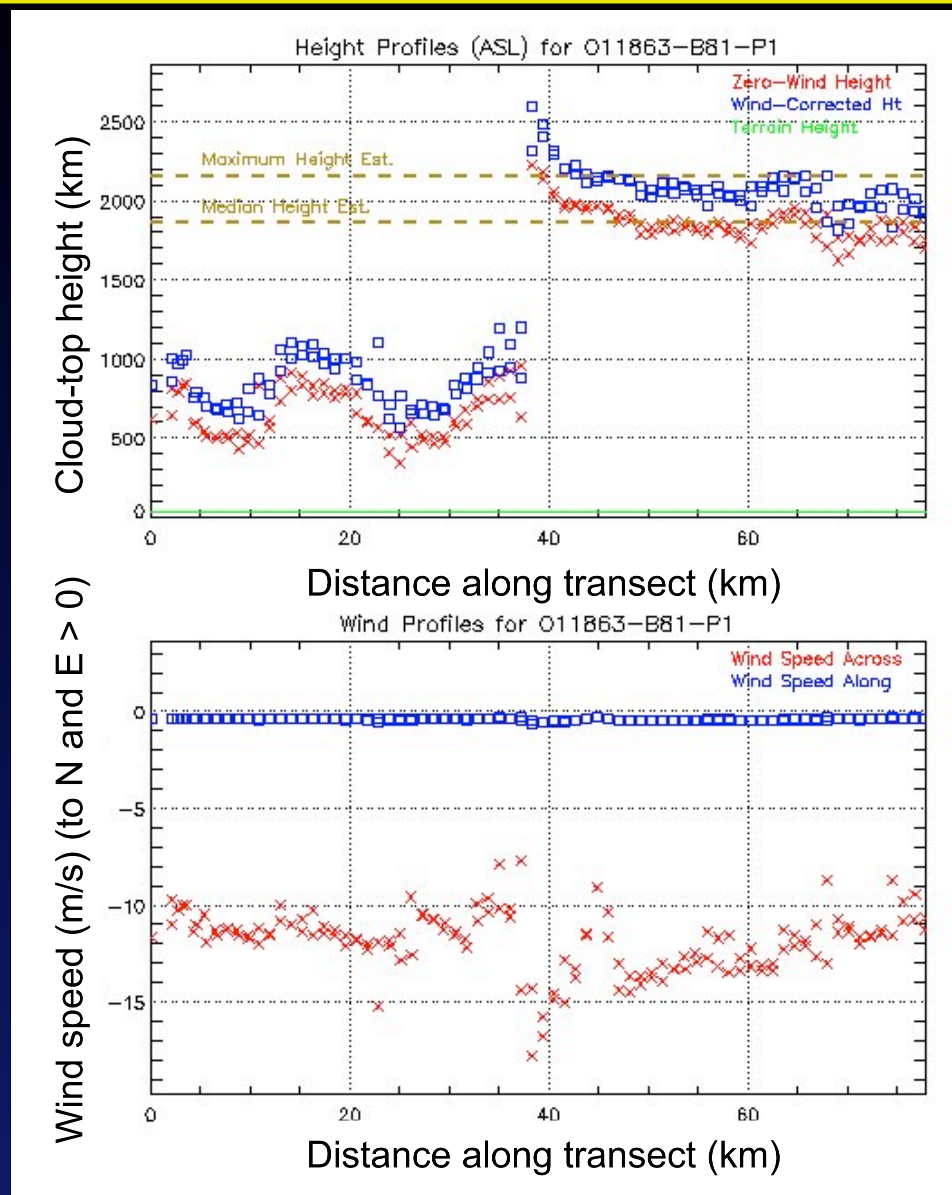


MISR height-resolved wind field

Wood et al. (2010), *ACPD* **10;** K. Mueller, JPL

Boundary layer dynamics at high resolution

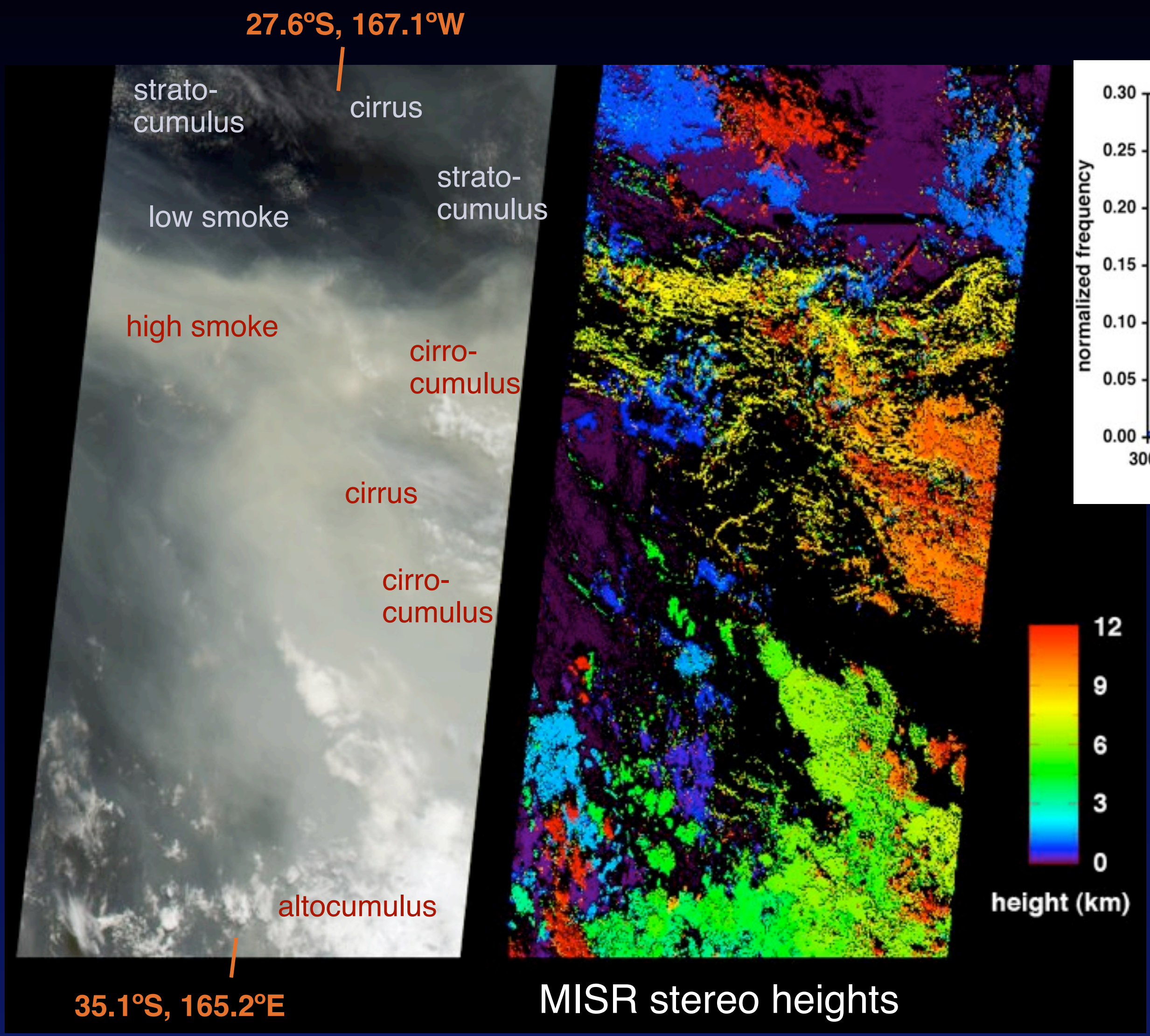


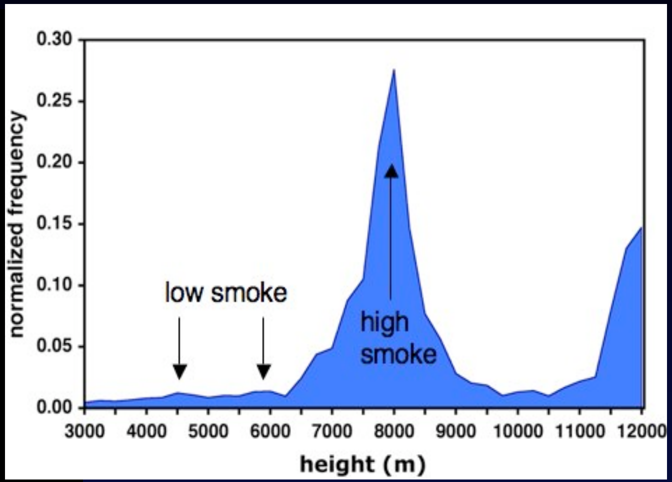


MISR heights and winds retrieved at 1.1 km resolution

Precision:
- height: ~100 m
- wind: ~0.3 – 1.0 m/s

Stereo also retrieves aerosol heights





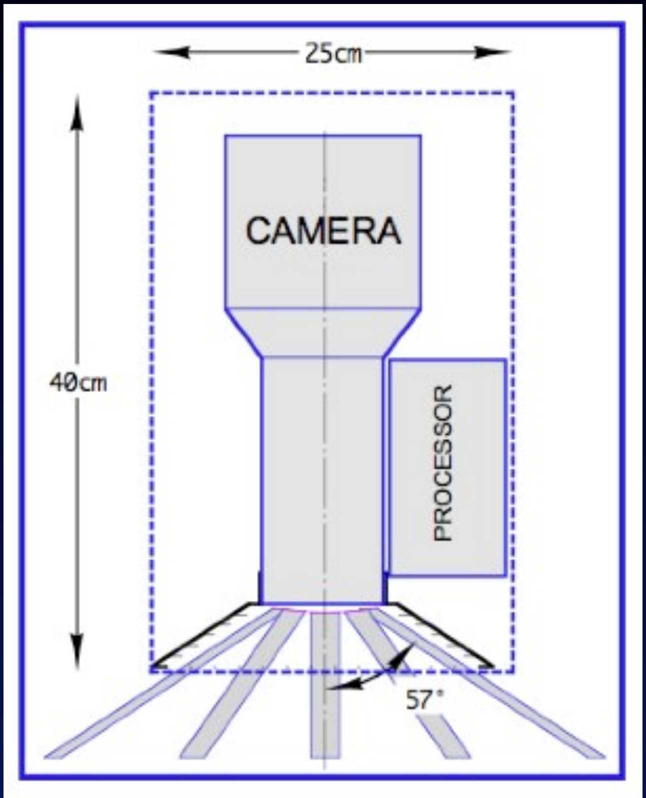
19 January 2003, 2306Z

Technique is limited to aerosols with discernible spatial structure

WindCam multi-stereo camera

MISR	WindCam
9 narrow angle cameras, 4 VNIR bands	1 wide angle camera, 1 red band
View angles: Nadir, 26º, 46º, 60º, 70º	View angles: Nadir, 40º, 60º, 70º
Mass: 150 kg Power: 75 W Data rate: 7 Mbps	Mass: 17 kg Power: 23 W Data rate: <3 Mbps
Spatial resolution: 275 m 400 km swath Global coverage - 9 days	Spatial resolution: 250 m or less 1000 km swath Daily global coverage from 3 platforms

WindCam

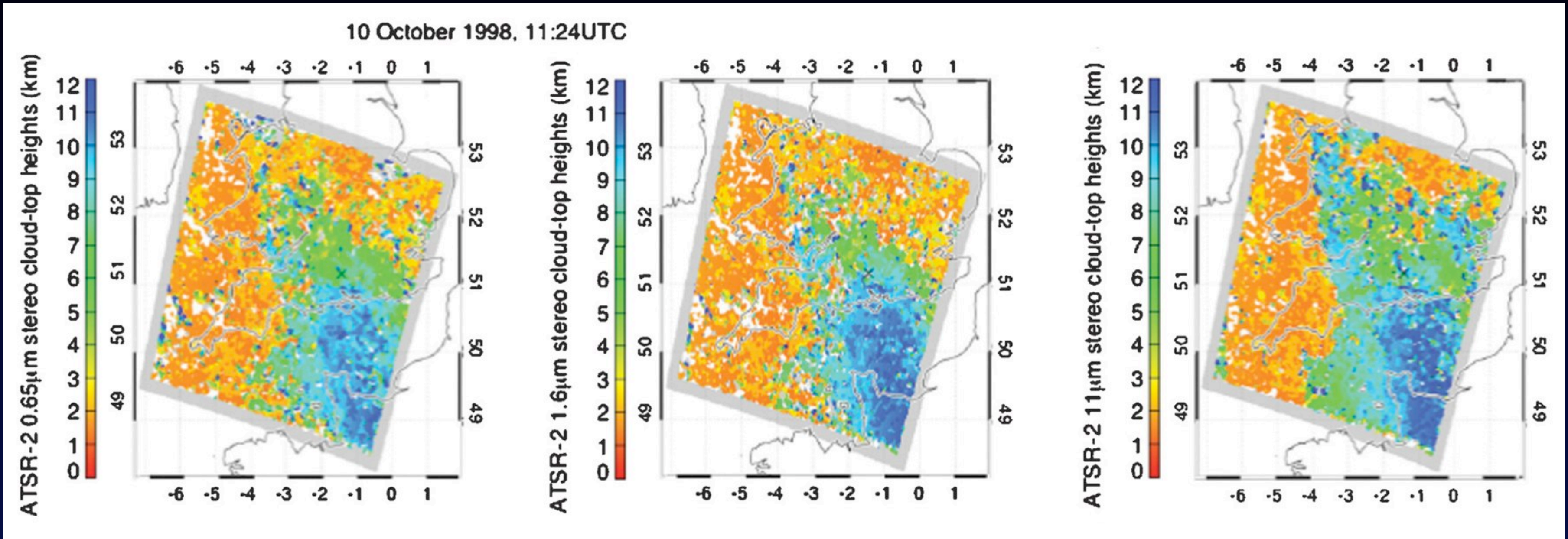


Flight direction →

Use of multiple angles and subpixel image matchers will provide ~100 m vertical resolution

Long focal length will improve resolution further

Multiwavelength stereo from ATSR-2



650 nm 1.6 µm 11 µm

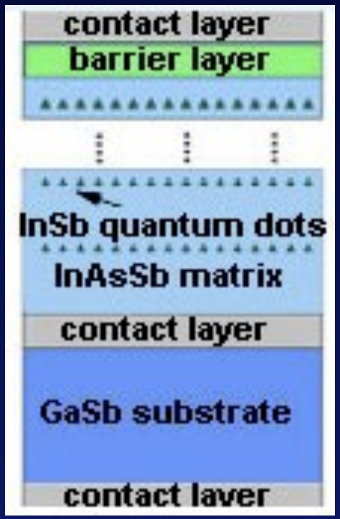
- As a geometric technique, stereo can operate at many wavelengths
  - Midwave/thermal IR provides day/night coverage
  - Currently spatial resolution from ATSR-2 is ~1 km

Naud et al. (2007), *IJRS* **28**

Technology challenge: high-resolution IR stereo

- Initial look at 3.7 μm multi-stereo camera with 250 m resolution
  - Optics 2-3 larger than visible camera
  - Heavy lens elements with complex prescription
  - Optics cooled to 200ºK
  - Large format focal plane cooled to 120ºK

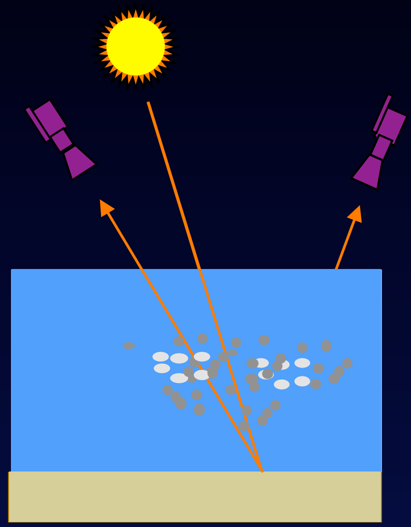
- Technology needs
  - Higher temperature detectors with low noise in appropriate pixel layouts, e.g., Barrier Infrared Detector (BIRD) technology
    - Eliminates one source of dark current (generation-recombination noise) without impeding the photocurrent
    - Achieves similar SNR at warmer temperatures than conventional photodetectors such as HgCdTe
    - Active area of research at JPL's Microdevices Lab

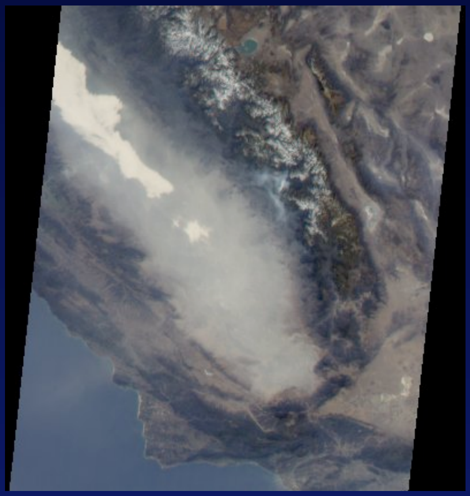


Hill et al. (2010), *Electron. Lett* **46**

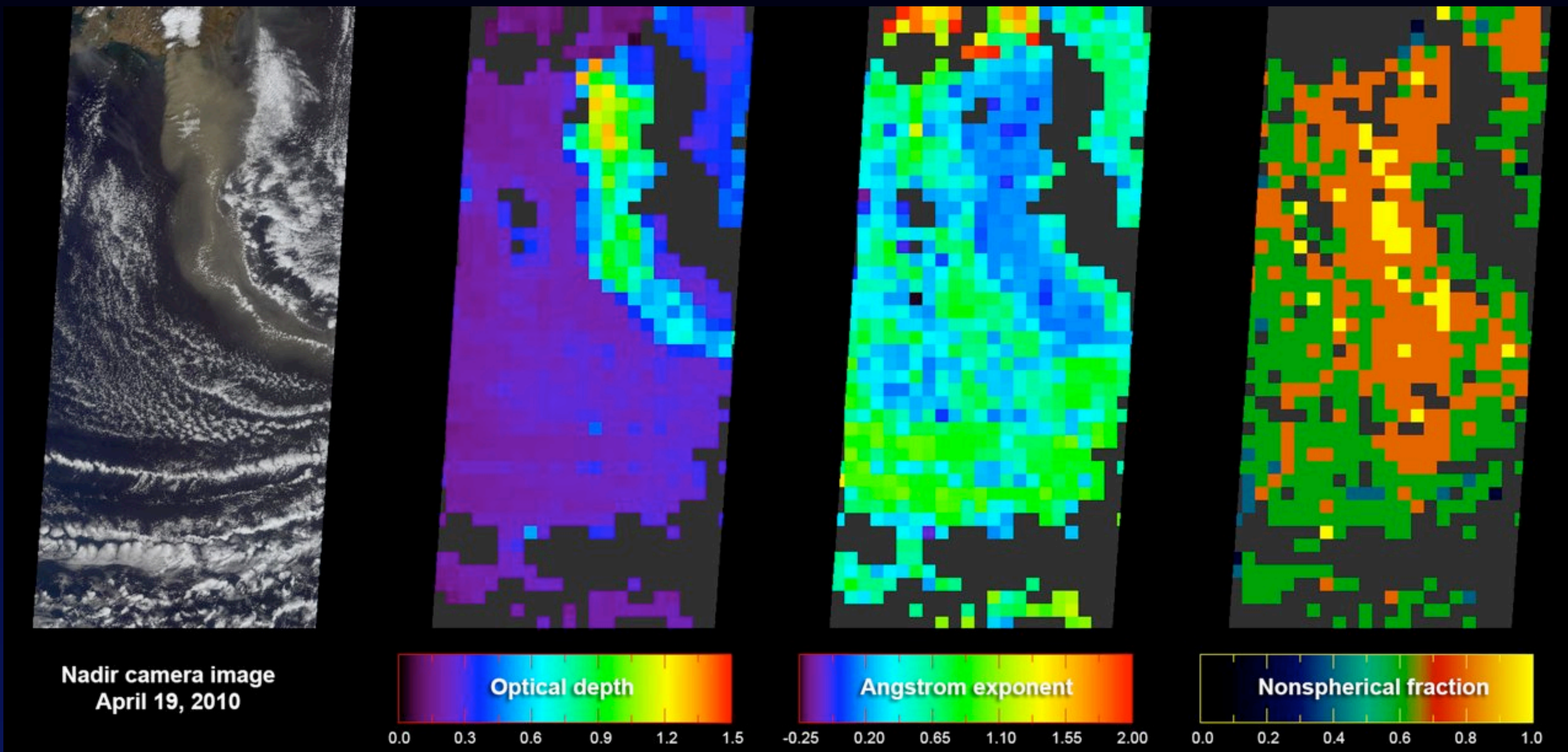
“Radiometric” multiangle measurement approach

Radiometric (non-polarimetric or polarimetric) approach keys on variation of radiance with view angle



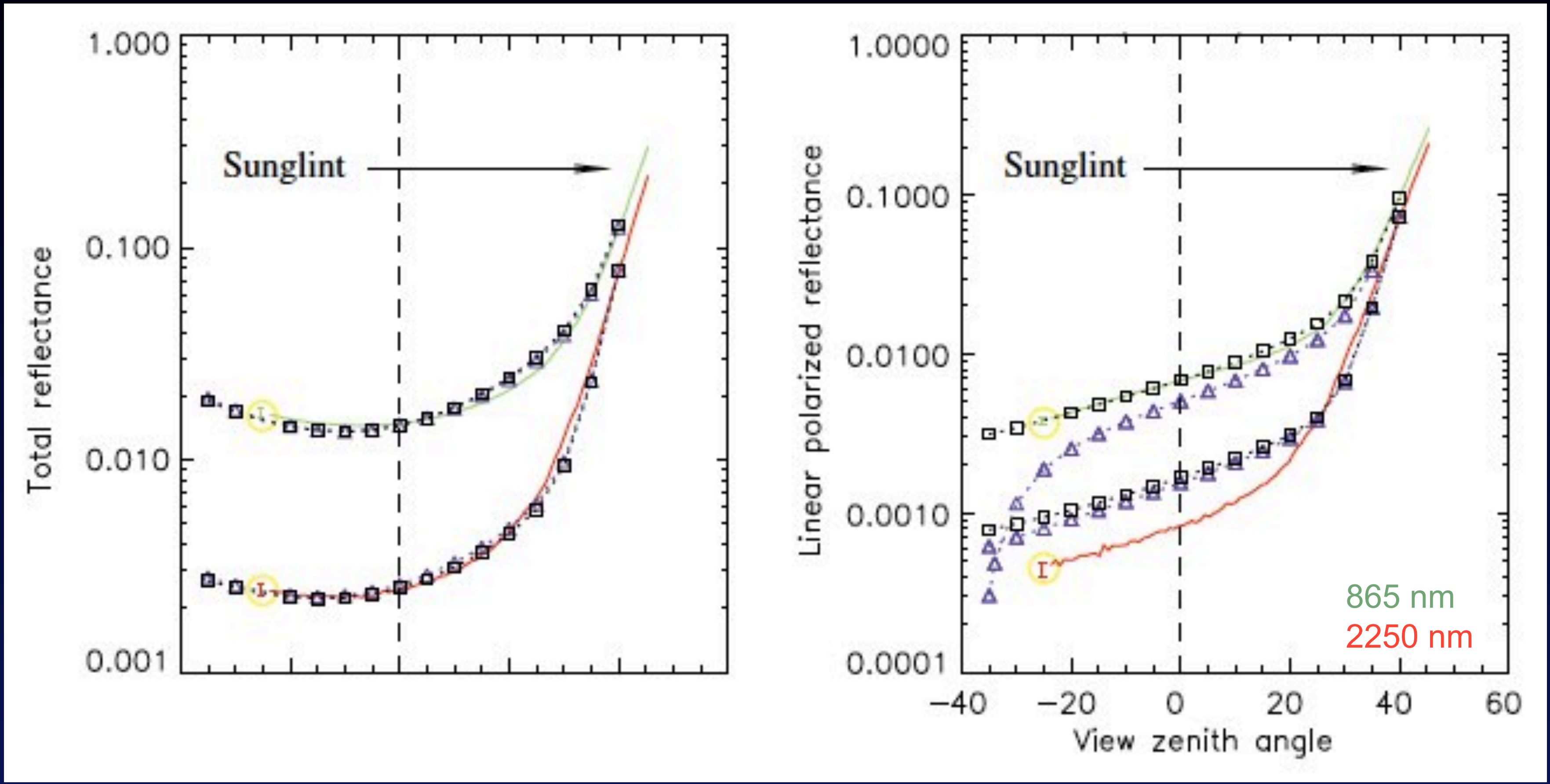


Aerosol particle properties



MISR views of Eyjafjallajökull – 4/19/2010

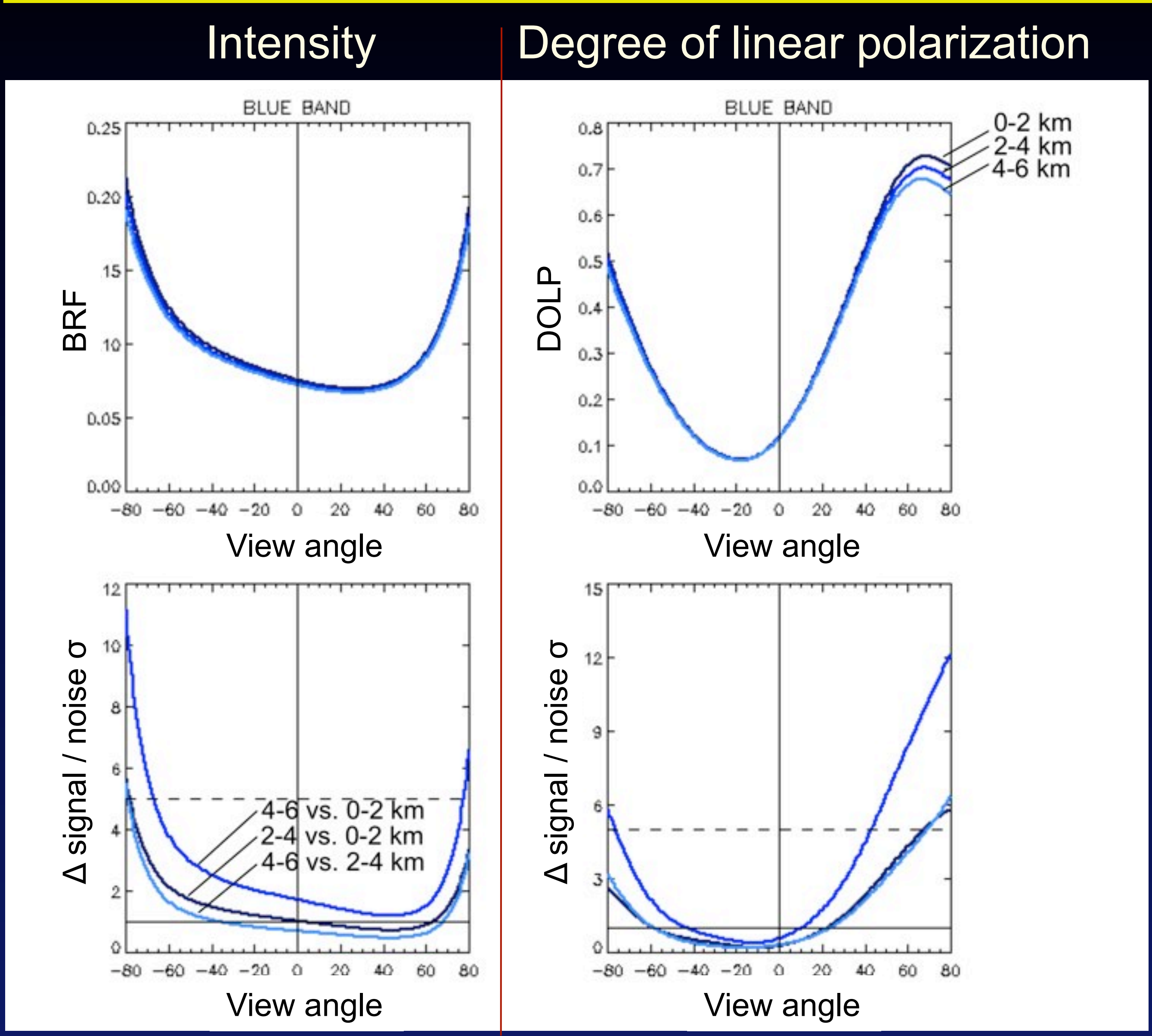
Polarimetry helps distinguish aerosol type



	r_{eff} (μm)	v_{eff}	m_{2250}	m_{865}
□	0.25	2.0	1.32	1.39
△	0.35	1.5	1.37	1.48

Chowdhary et al. (2001), *GRL* **28**

Sensitivity to aerosol height

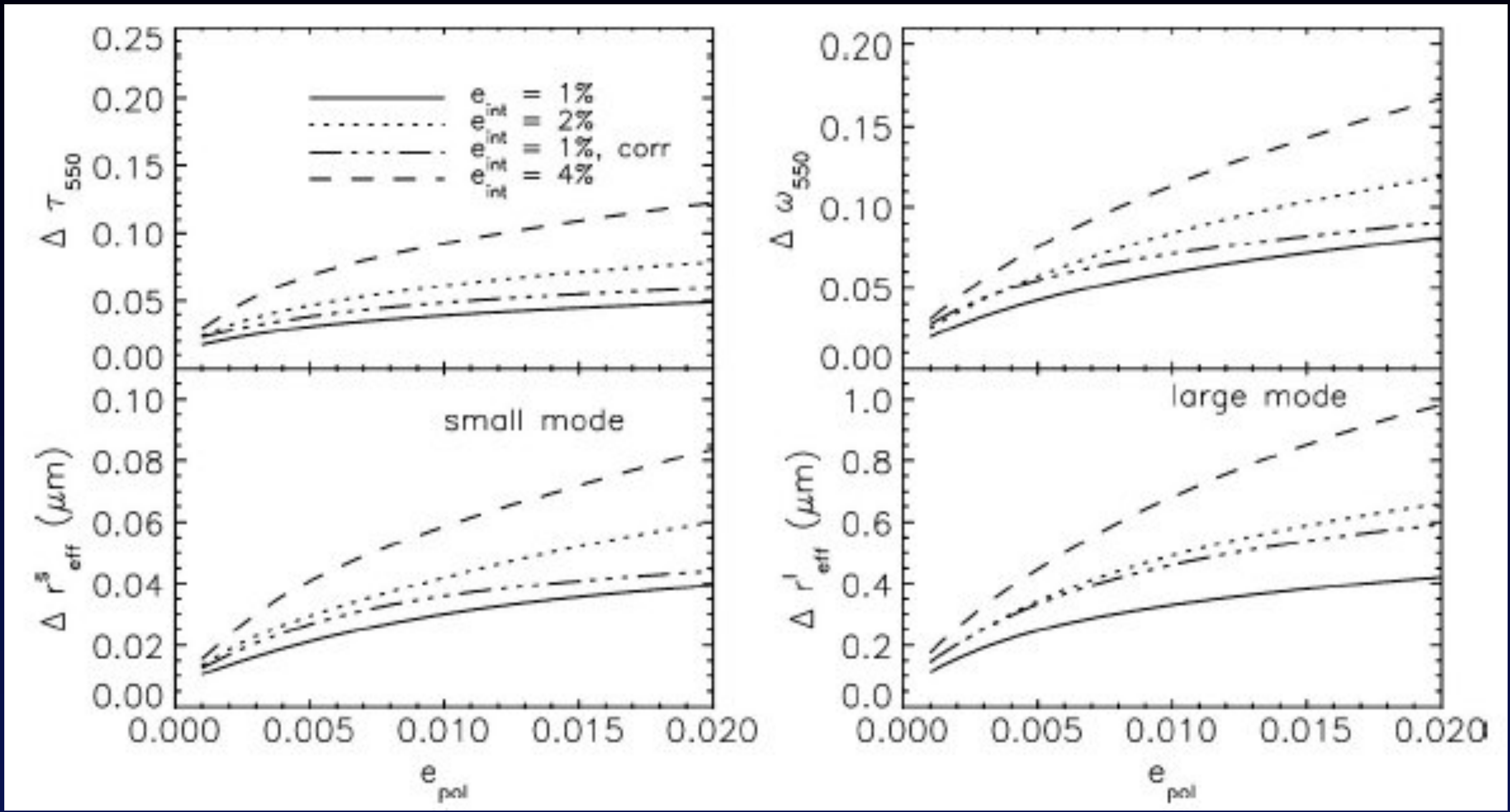


AOD= 0.3

Black surface

Dust aerosol at different heights

Particle properties sensitivity

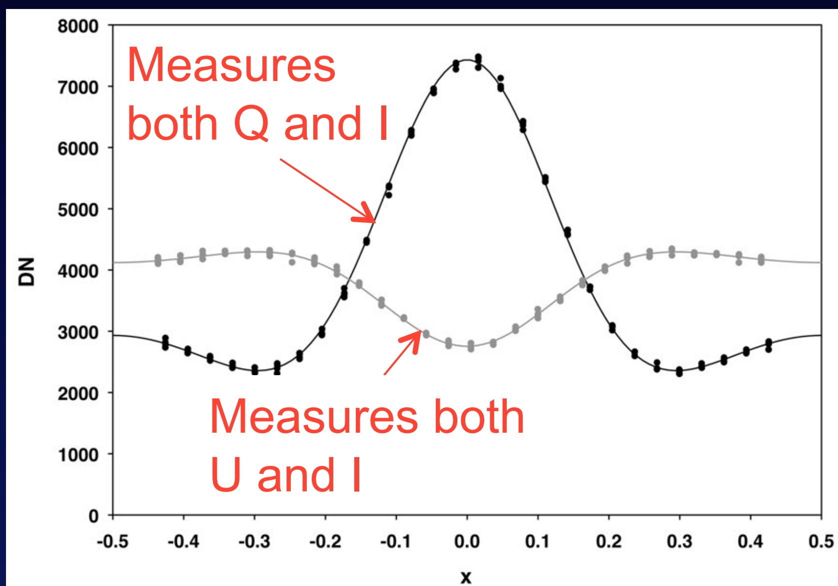


To add high-accuracy information content to multiangle intensity data, uncertainty of 0.005 or better in degree of linear polarization is required

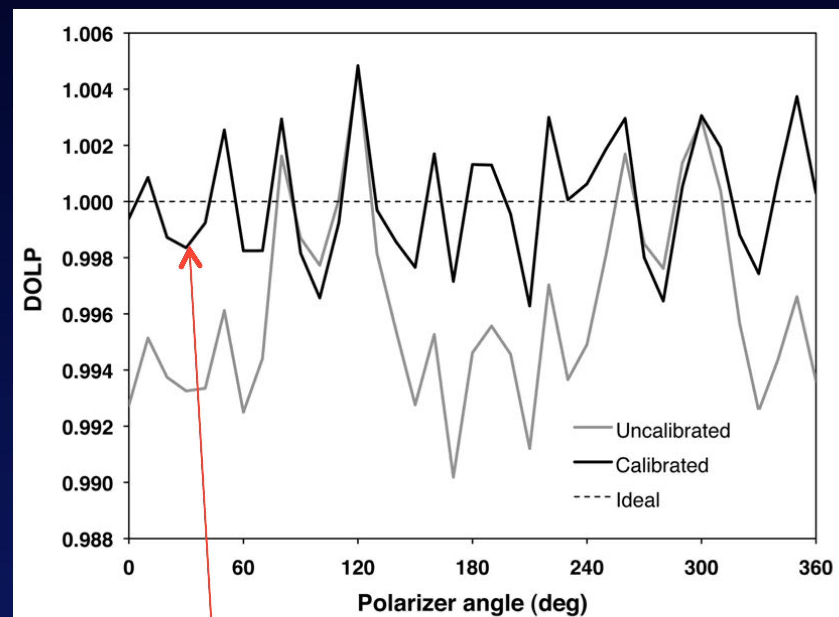
Hasekamp and Landgraf (2007), *Appl. Opt.* **46**

Polarimetry using temporal modulation

- We have developed a design that rapidly modulates the input polarization using photo-elastic retardance modulators (PEMs)
  - Enables retrieval of $q = Q/I$ (and $u = U/I$) as *relative* measurements, providing high sensitivity and accuracy



1 frame ~ 40 msec

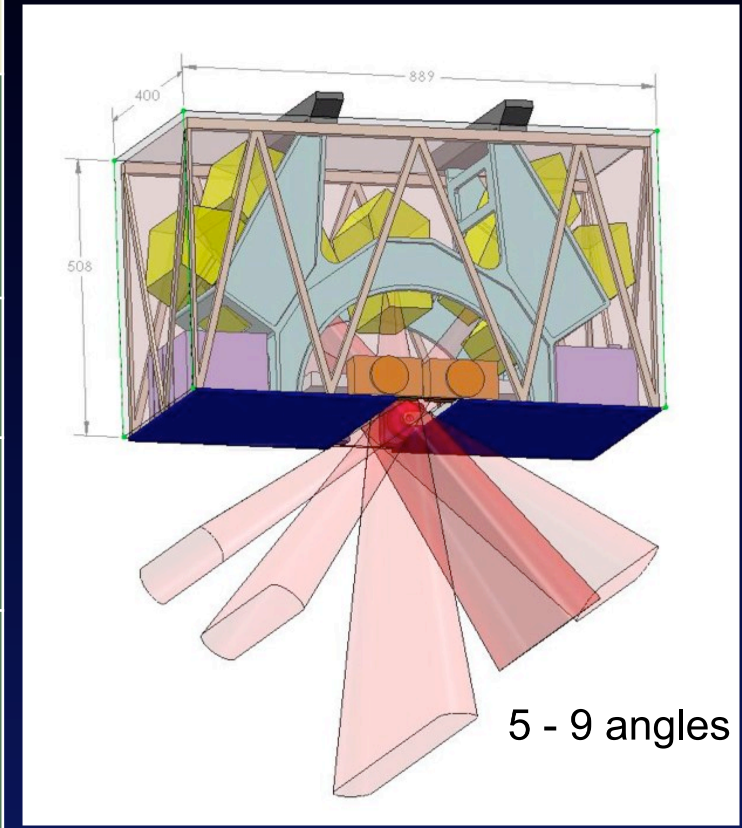


Calibrated DOLP = 1.0000 ± 0.0022

Diner et al. (2010), *Appl. Opt.* **49**

Mutiangle SpectroPolarimetric Imager (MSPI)

MISR	MSPI
9 cameras, 4 VNIR bands	5 - 9 cameras, UV-VNIR-SWIR bands Polarimetry in selected bands
View angles (9): Nadir, 26º, 46º, 60º, 70º	View angles (7): Nadir, 38º, 60º, 70º
Mass: 150 kg Power: 75 W Data rate: 7 Mbps	Mass: ~140 kg Power: ~100 W Data rate: 15 Mbps
Spatial resolution: 275 m 400 km swath Global coverage - 9 days	Spatial resolution: 275 m, less at nadir 700 km swath, 1800 km at nadir (depends on orbit) Global coverage - 4 days



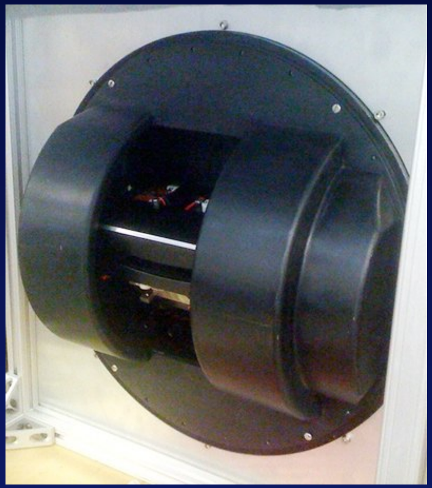
Two prototype UV/VNIR cameras are built

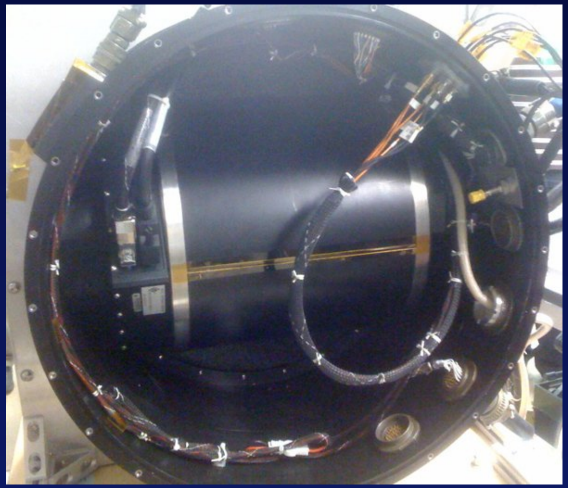
- GroundMSPI is operating in the field

Spectral bands

355, 380, 445, 470*, 555, 660*, 865*, 935 nm (*polarimetric)

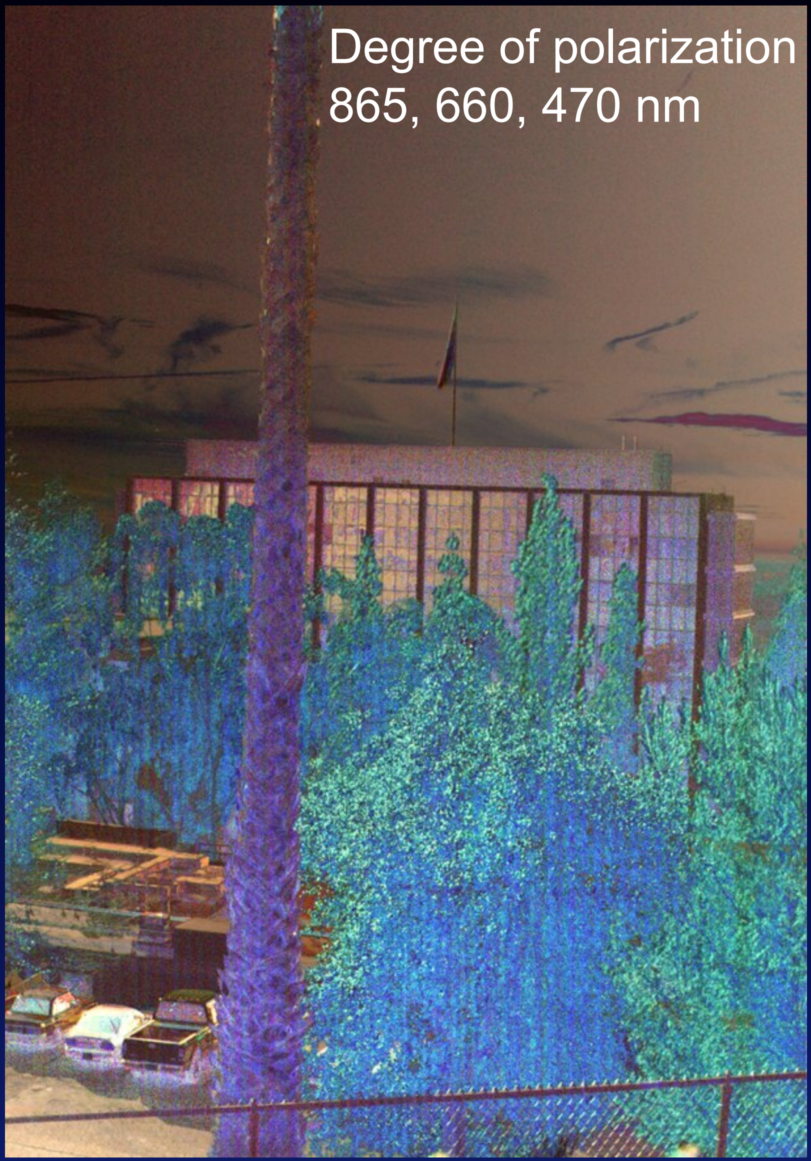
- AirMSPI is operating and flight ready, awaiting ER-2 availability





Will fly in nose of ER-2, pointable to multiple angles

High polarimetric image quality - GroundMSPI



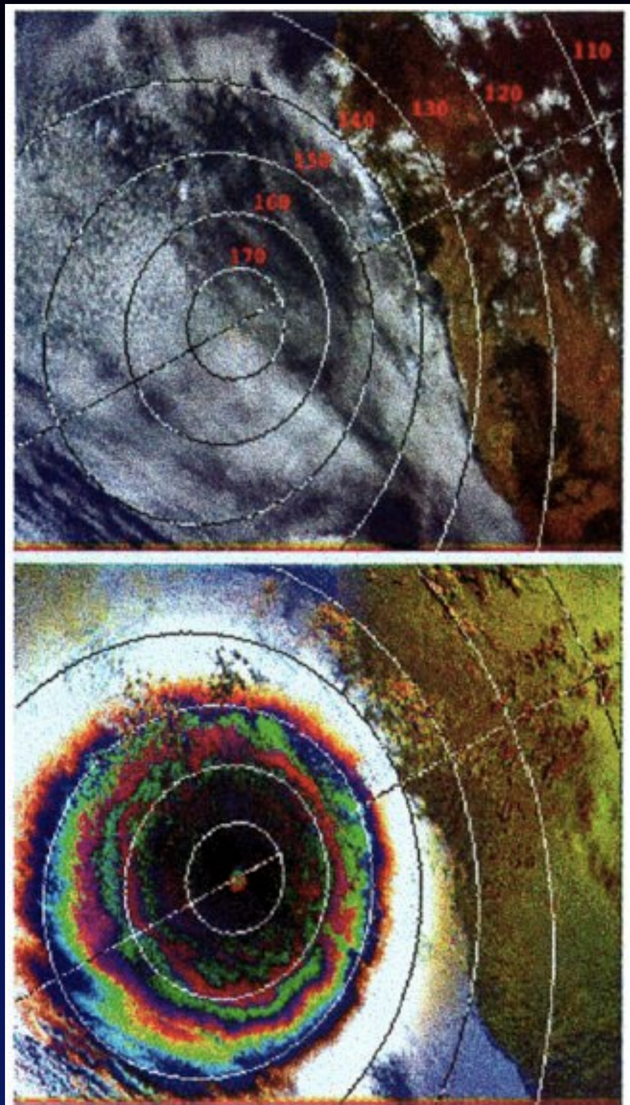
GroundMSPI cloud imagery

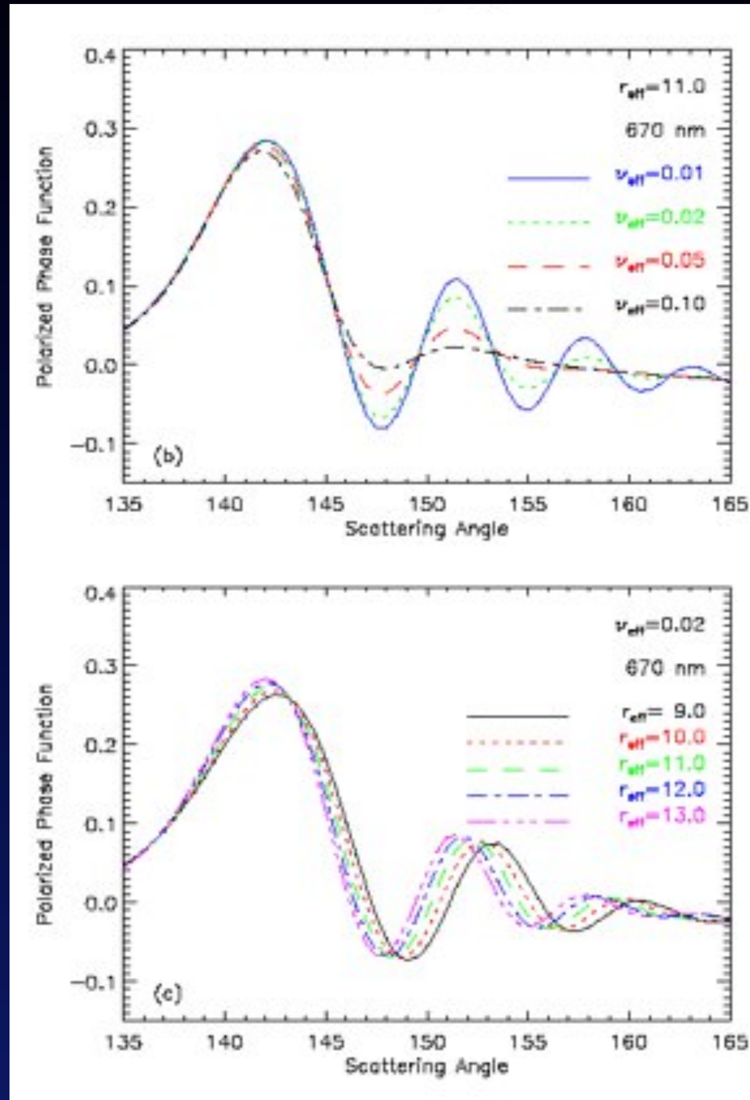
Intensity

DOLP

Polarization orientation

POLDER cloud drop size retrieval





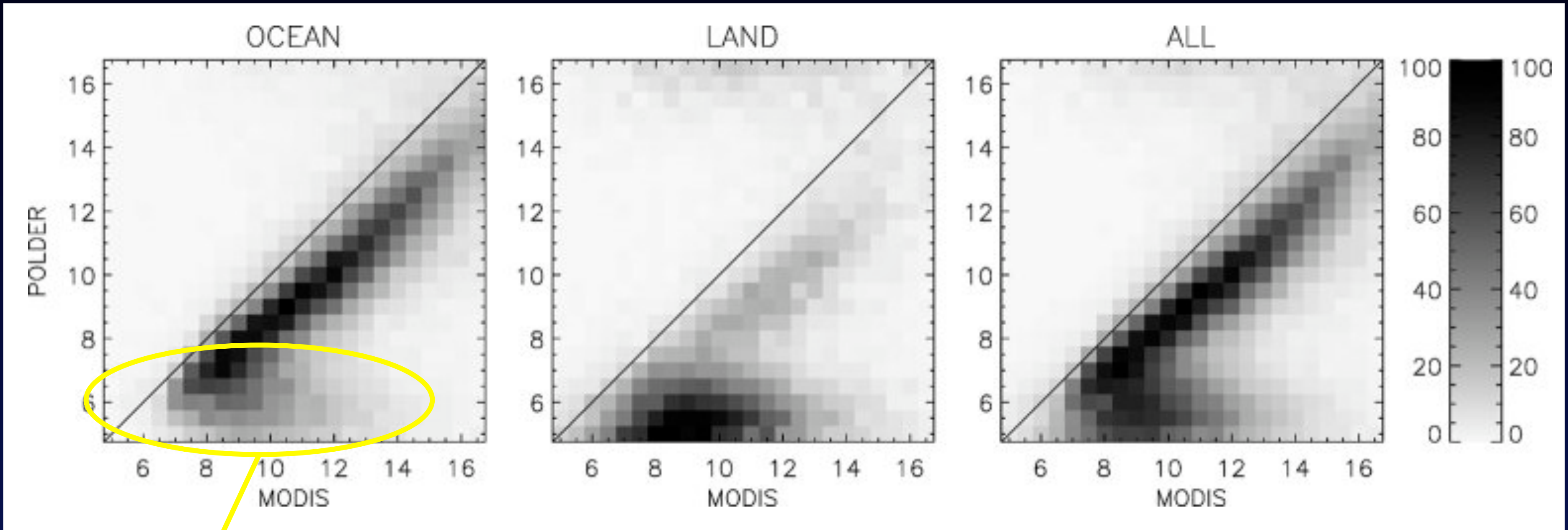
Polarimetry in cloudbow is sensitive to droplet size distribution

Angular density restricts technique to homogeneous clouds

Bréon and Goloub (1998), *GRL* **25**

Cloud droplet size retrieval comparison

POLDER (polarimetric) and MODIS (multispectral)



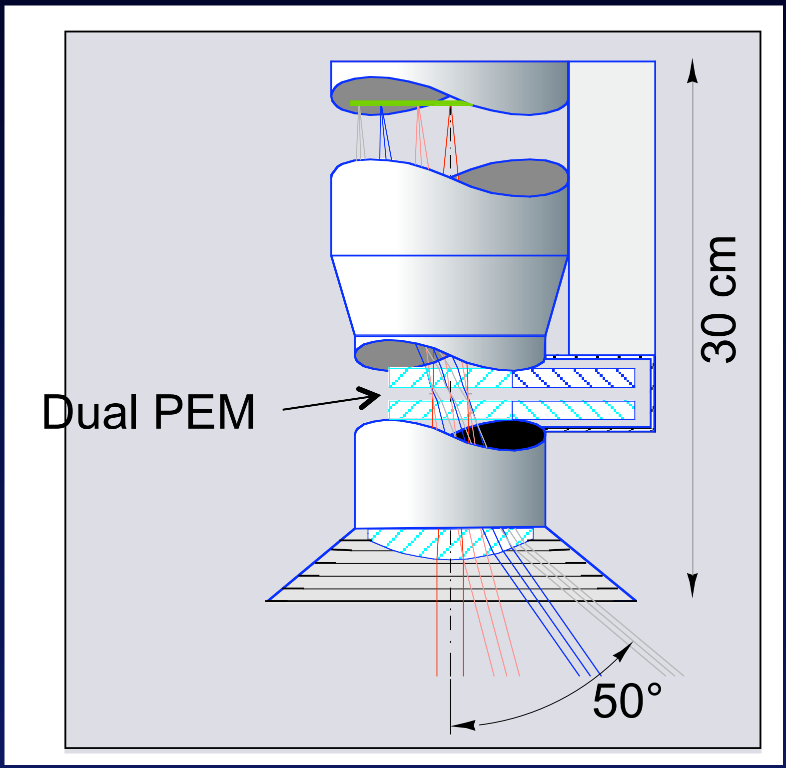
polluted areas

Requirement of homogeneity may bias POLDER results
Multispectral technique problematic for broken clouds

Bréon and Doutriaux-Boucher (2005), *TGARS* **43**; Rosenfeld and Feingold (2003), *GRL* **30**

Cloudbow imaging polarimetry concept

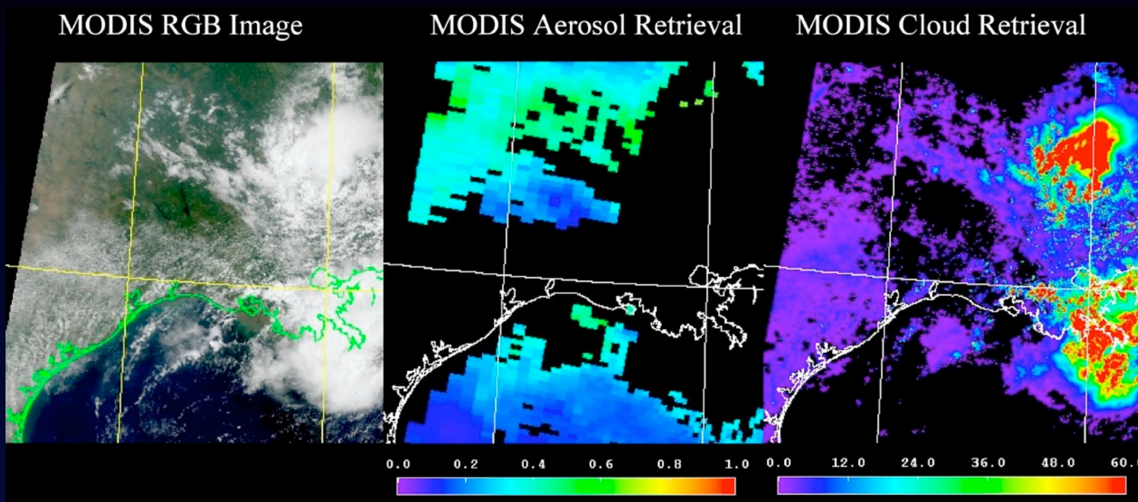
- Dual PEM technology enables a wide-angle polarimetric camera with dense angular coverage in a single spectral band, up to 1000-km swath, and ~250 m resolution
- Polarimetric adaptation of the visible wavelength WindCam concept



High angular density is possible by using many detector lines in the focal plane

This would permit applying the cloudbow technique at high spatial resolution, avoiding requirement of large-scale homogeneity

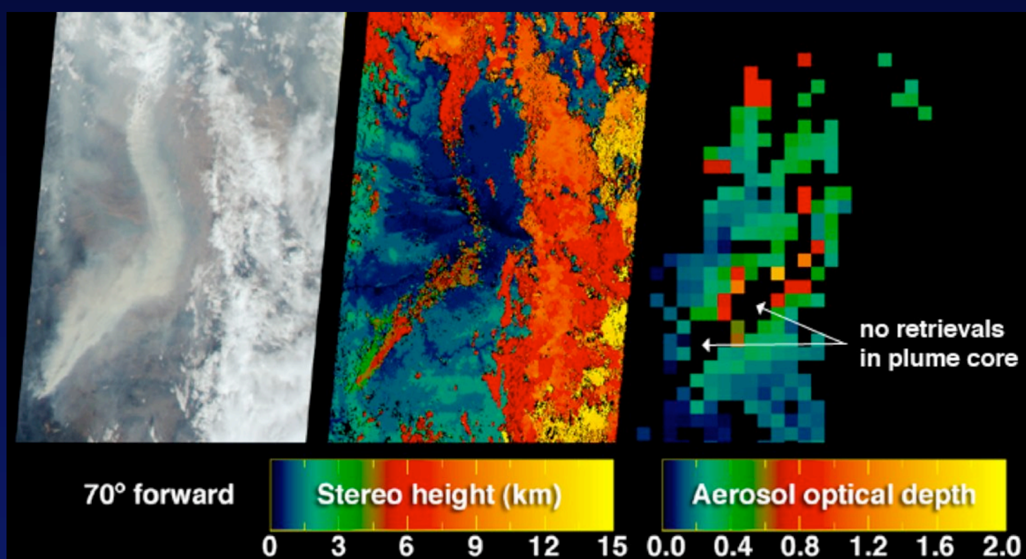
Current binary treatment of aerosols and clouds



MODIS example

Aerosols and clouds treated independently

Secondary illumination from clouds ignored

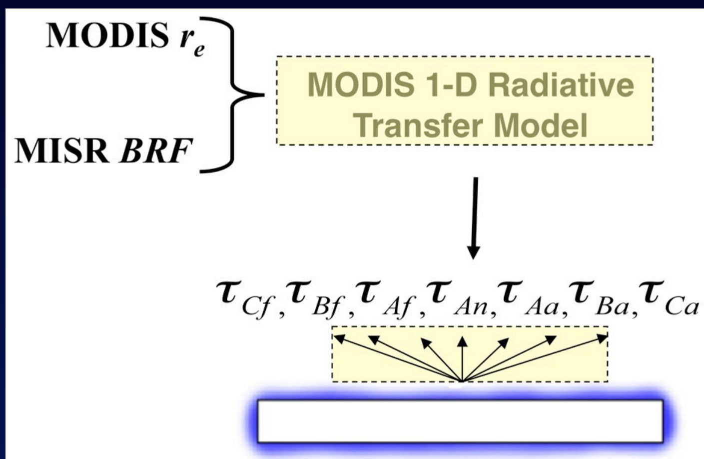


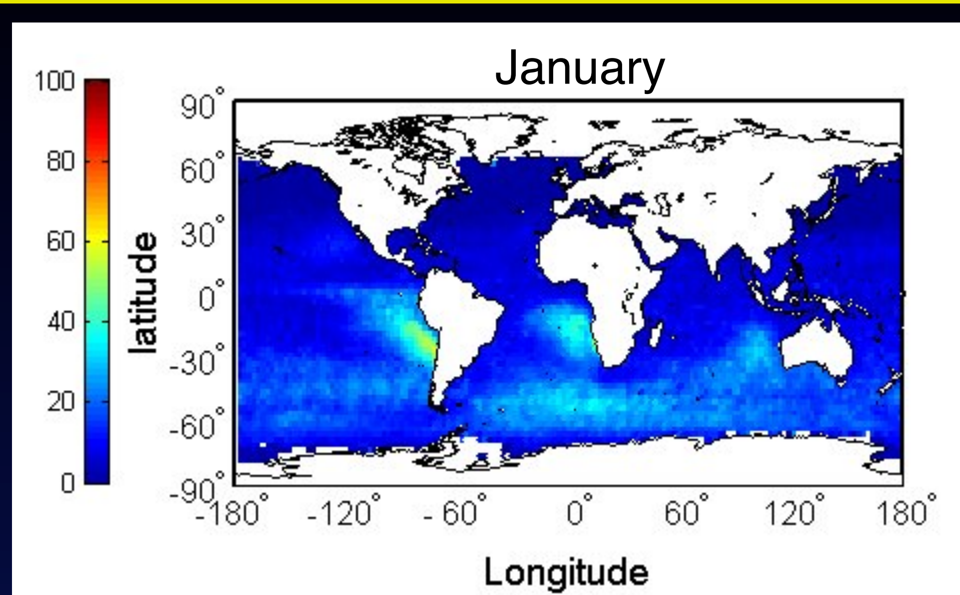
MISR example

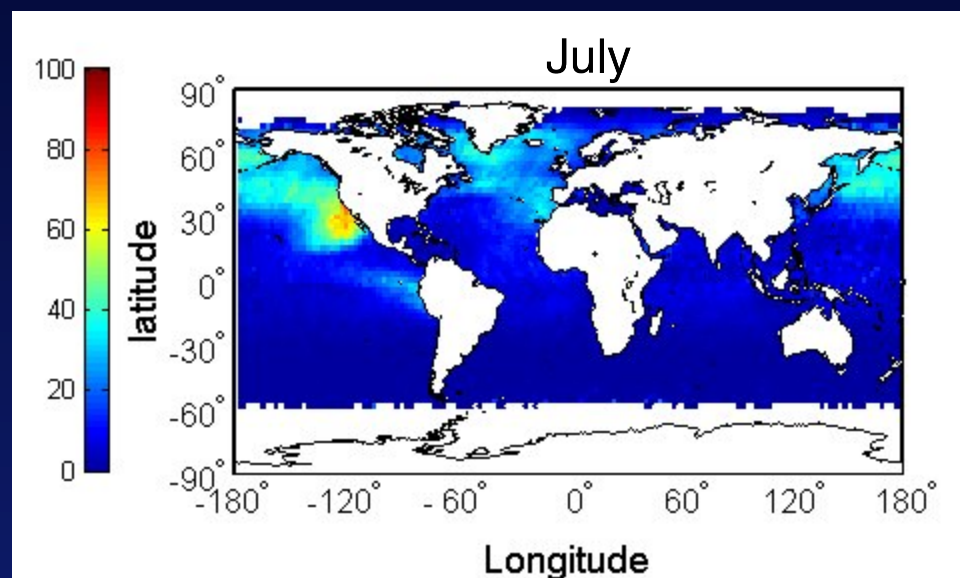
Plane parallel assumption violated in plume core; retrievals not performed due to spatial heterogeneity

Cloud optical depth inconsistencies with angle

Fraction of retrievals with angular consistency in COD within 5% of mean COD



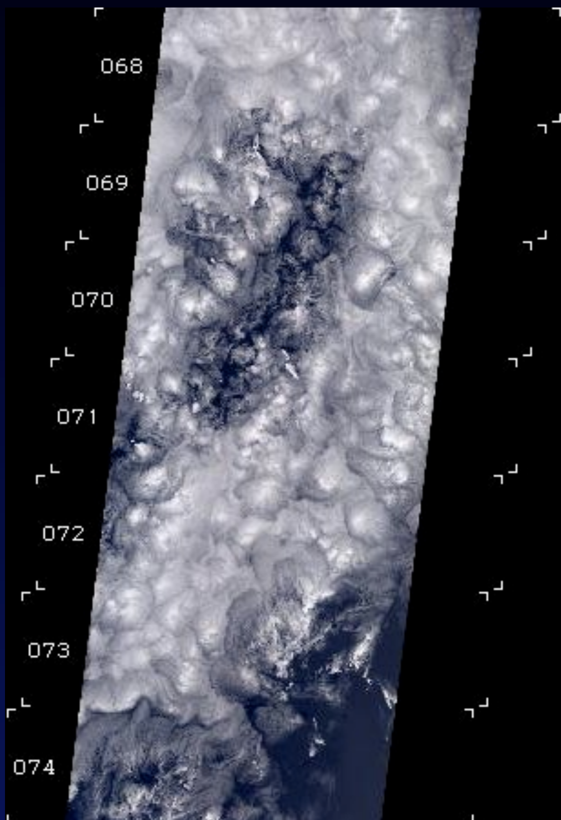




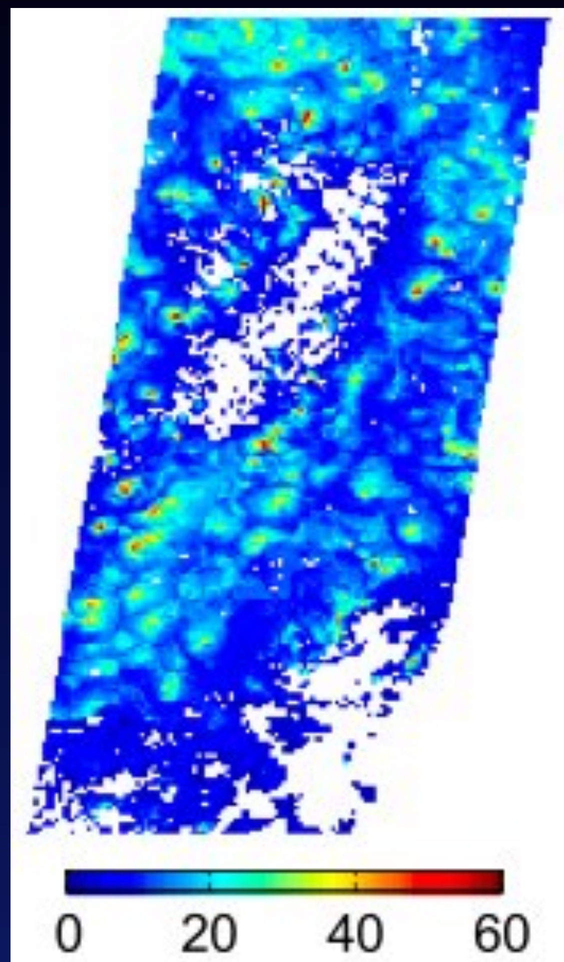
Di Girolamo et al. (2010), *GRL* **in press**

Specific example

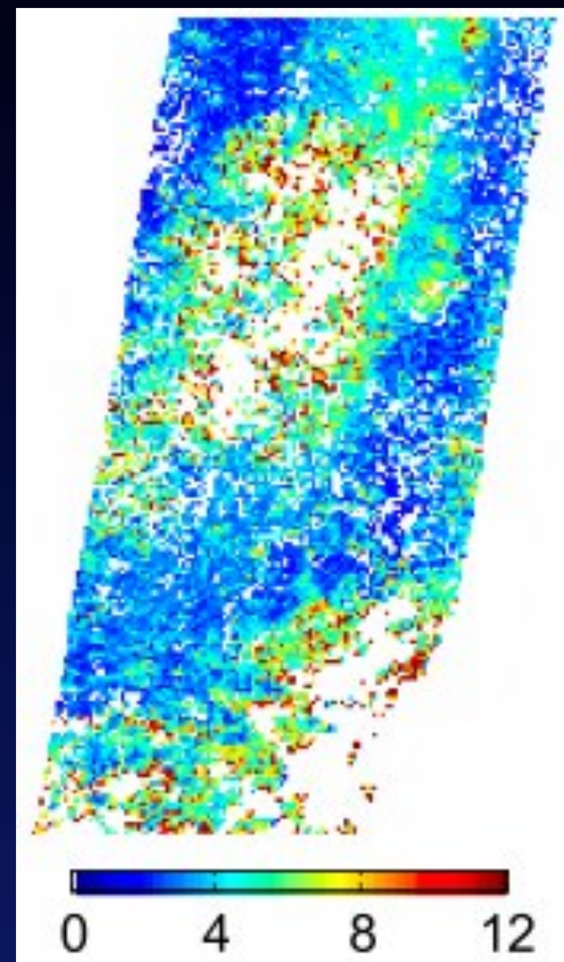
Marine water clouds in NE Pacific



Nadir image



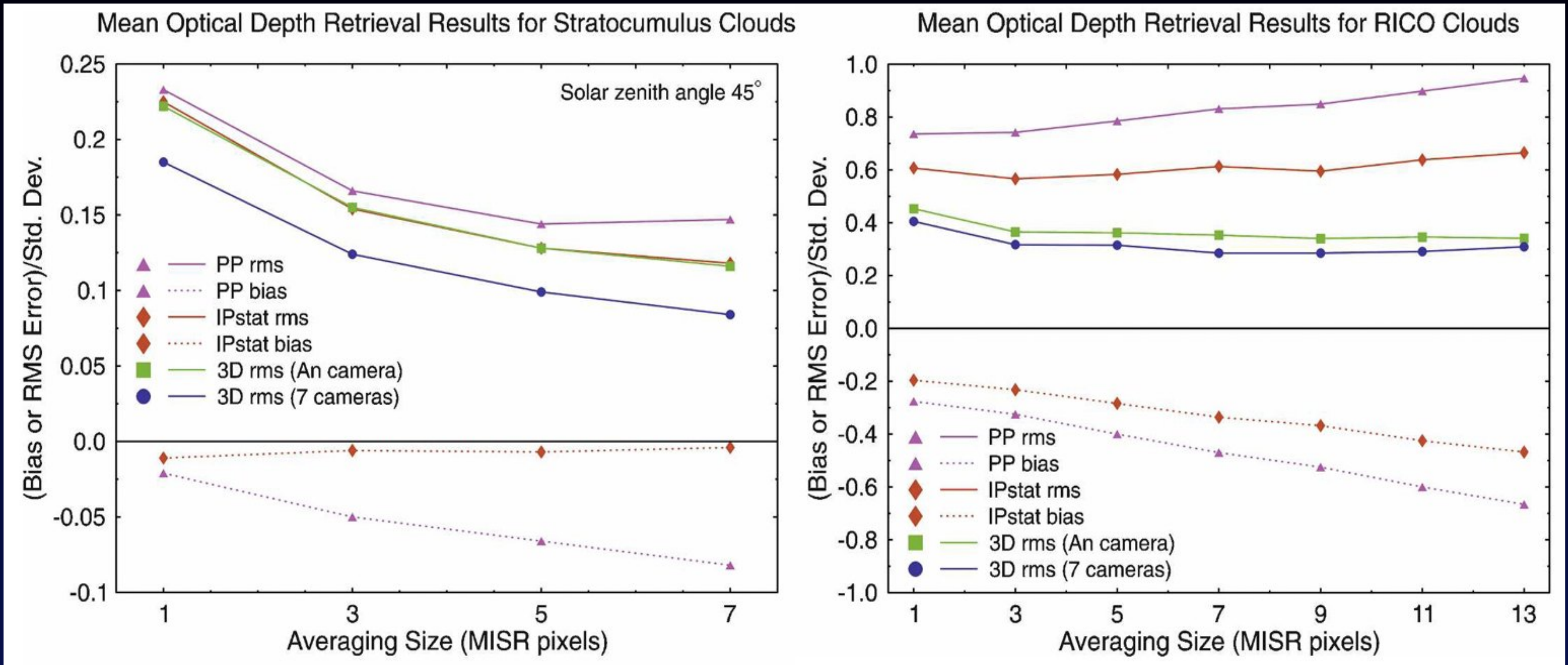
Mean cloud optical depth



Angular COD inconsistency (percent of mean COD)

Liang et al. (2009), *GRL* **36**

Plane-parallel biases and errors



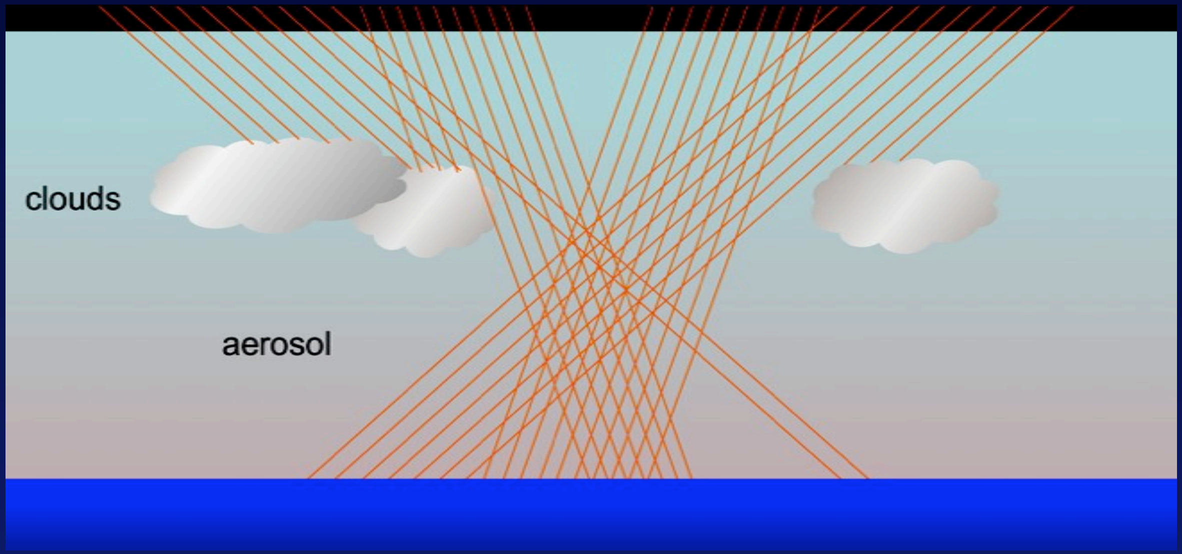
Cloud optical depth retrievals using LES models show significant reduction in bias and RMS error using 3D vs. 1D RT

Multiple view angles provide additional modest improvements to this statistical characterization – deterministic solutions need to be explored

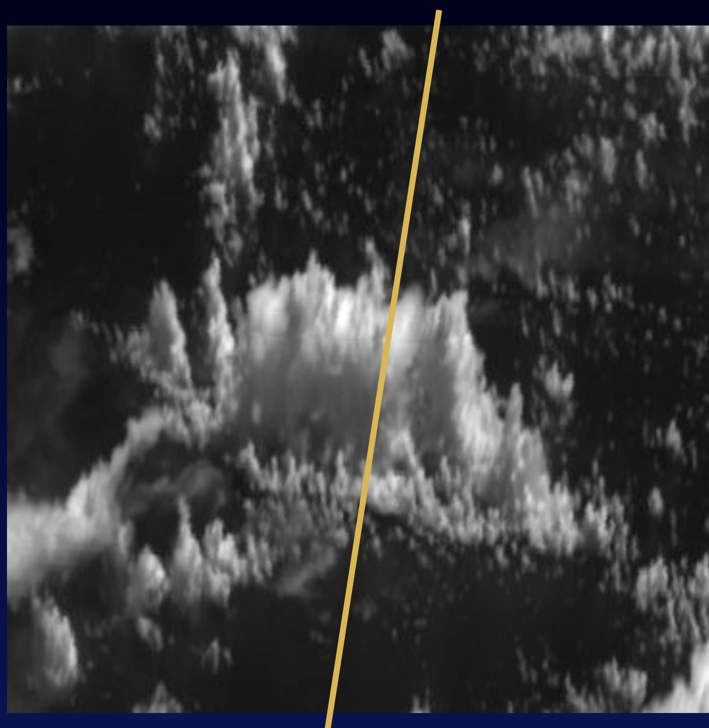
Evans et al. (2008), *JAS* **65**

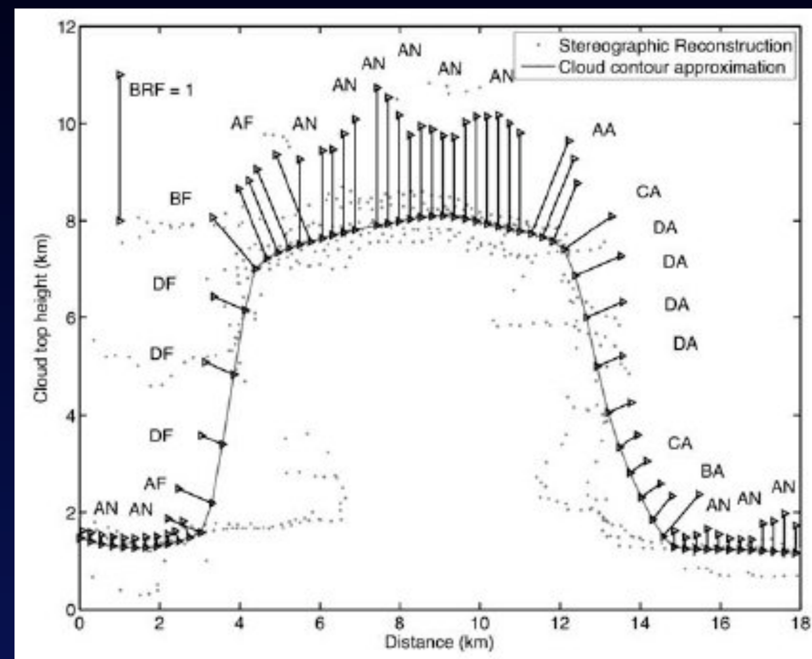
Optical tomography (OT)

- Recovers "the cross-sectional distribution of optical parameters inside a highly scattering medium from information contained in measurements…performed on the boundaries" [Klose and Hielscher (2003), *Inverse Problems* **19**]
- Pioneered in biomedical imaging — uses scattered near-IR light to study brain hemorrhages, breast cancer, and rheumatoid arthritis
- In atmospheric context, combines the "geometric" and "radiometric" multiangle measurement approaches



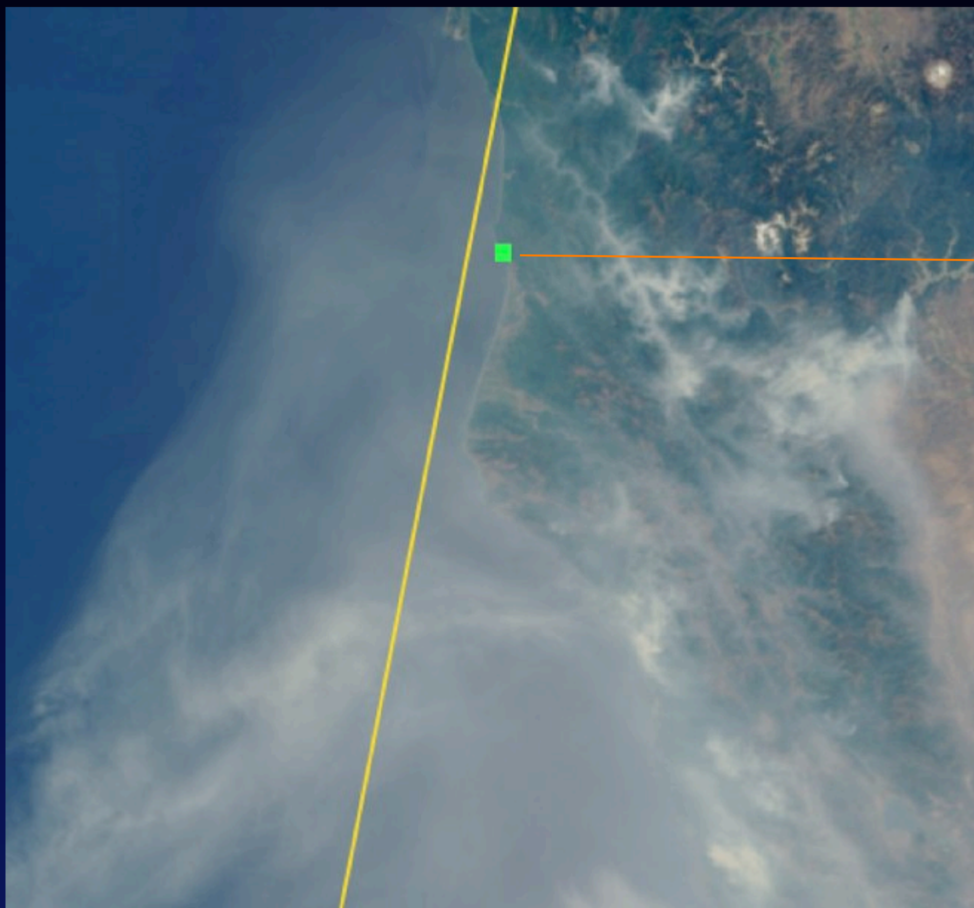
MISR multiangle cloud reconstruction



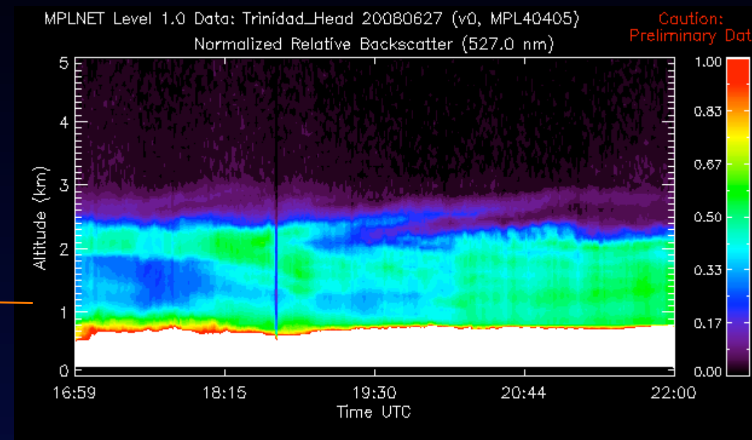


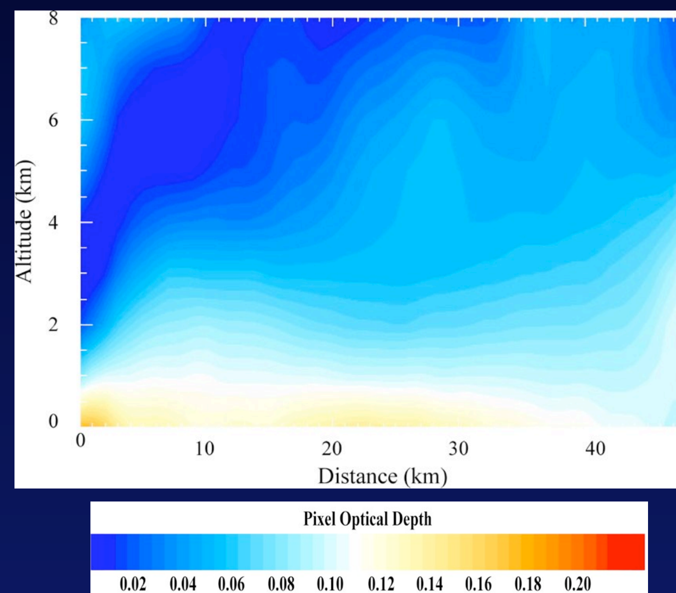
Cornet and Davies (2008), *JGR* **113;** Seiz and Davies (2006), *RSE* **100**

Aerosol tomographic reconstruction case study



MISR image of N. California smoke





Conclusions

- New technology innovations provide the building blocks for advanced boundary layer cloud and aerosol passive imagers

- Example instrument approaches include:
  - A stereo wide-angle camera with at least 5 view angles for height and wind measurements with high horizontal and vertical resolution – scalable in resolution. Extension to the IR is a technology challenge
  - A polarimetric wide angle camera with high angular density for cloud droplet size measurements using the cloudbow
  - Multispectral, high-accuracy polarimetry at multiple angles for detailed aerosol characterization

- Algorithm advances will be needed to take advantage of these instrument technologies
  - Practical, fast 3D radiative transfer-based retrievals
  - Adapting optical tomography to multiangular observations of clouds and aerosols