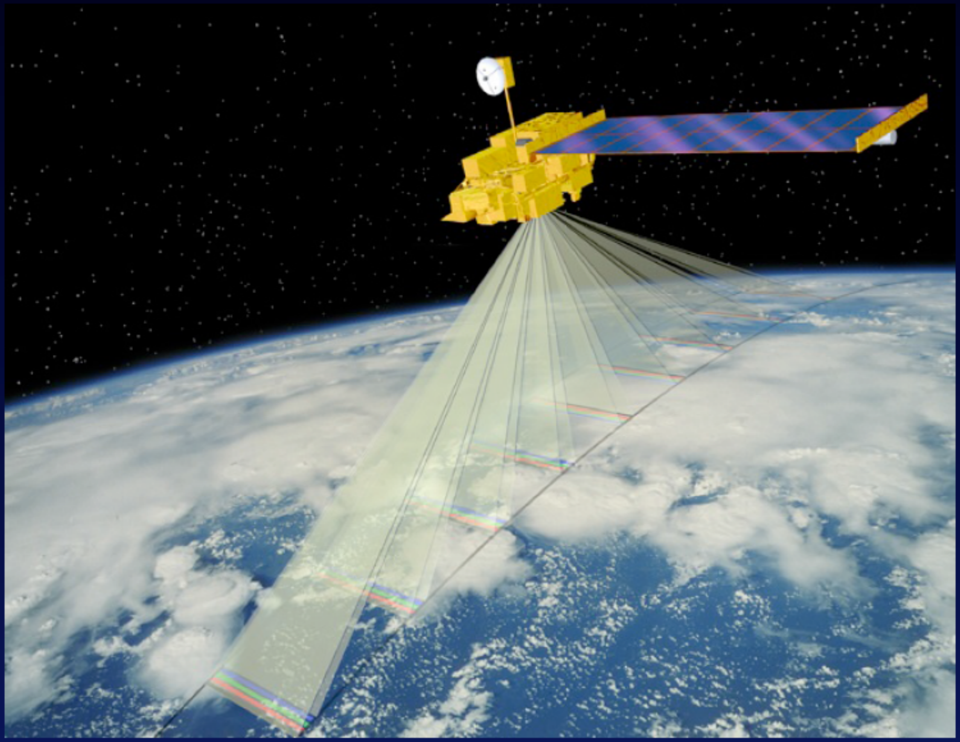
Reflections on current and future applications of multiangle imaging to aerosol and cloud remote sensing

David J. Diner
Jet Propulsion Laboratory, California Institute of Technology
and the MISR and MSPI teams

EGU
Vienna, Austria
May 4, 2010

Multi-angle Imaging SpectroRadiometer - MISR



Nine view angles at Earth surface: 70.5º forward to 70.5º backward

275 m - 1.1 km sampling

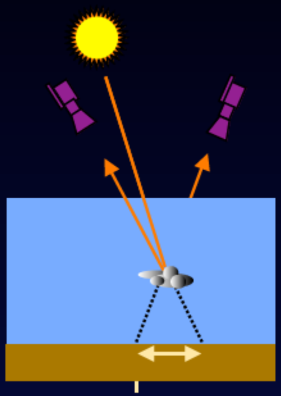
Four spectral bands at each angle: 446, 558, 672, 866 nm

400-km swath: 9-day coverage at equator, 2-day at poles

7 minutes to observe each scene at all nine angles

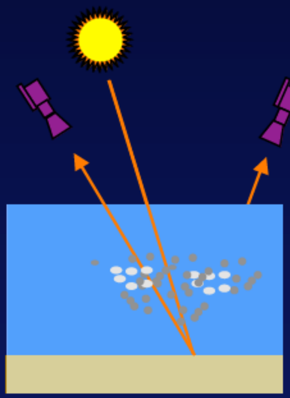
Multiangle observations of aerosols and clouds

Cloud and aerosol plume heights and motion



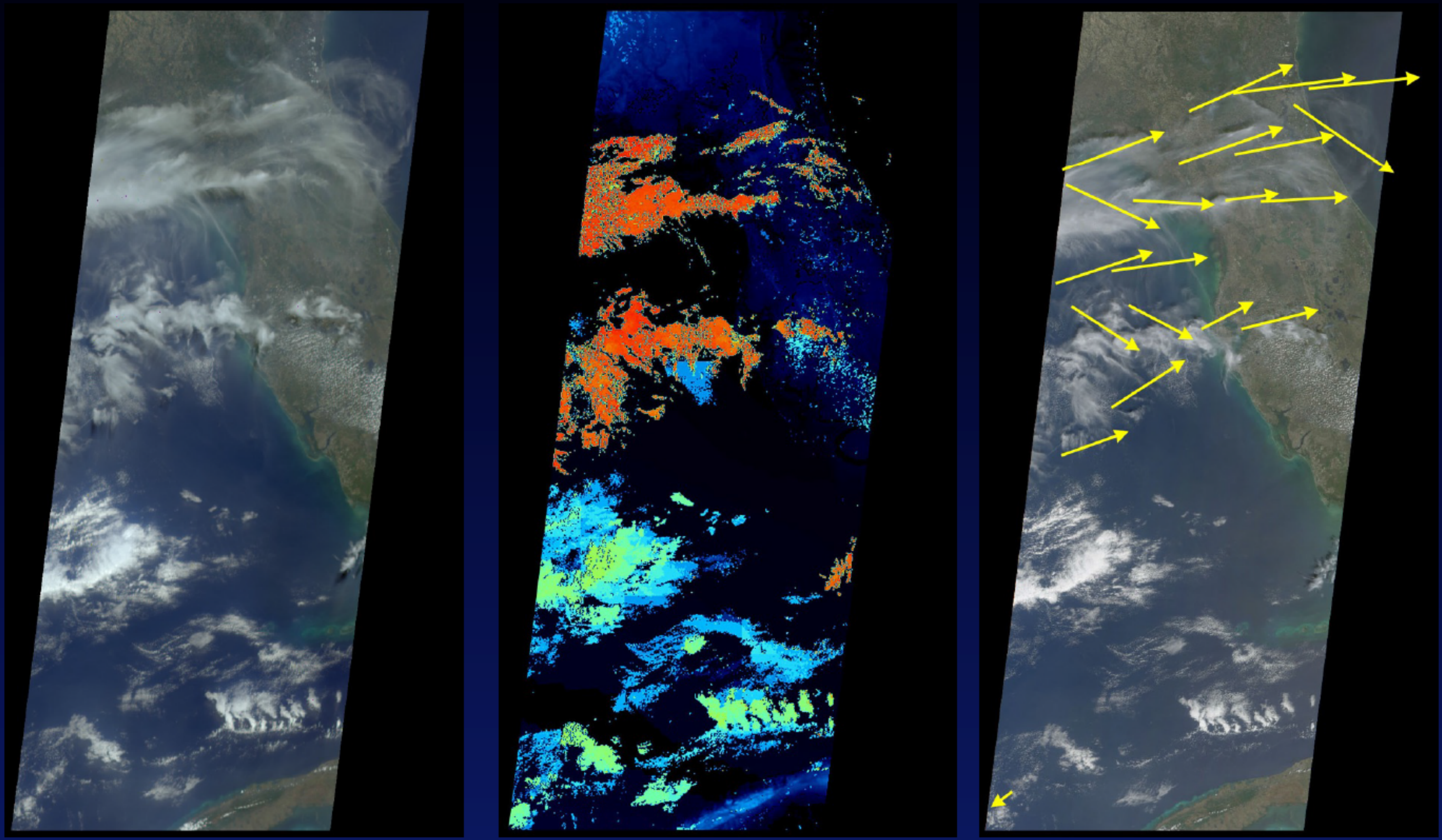
“Geometric” approach

Distributions, types, and trends of airborne particles



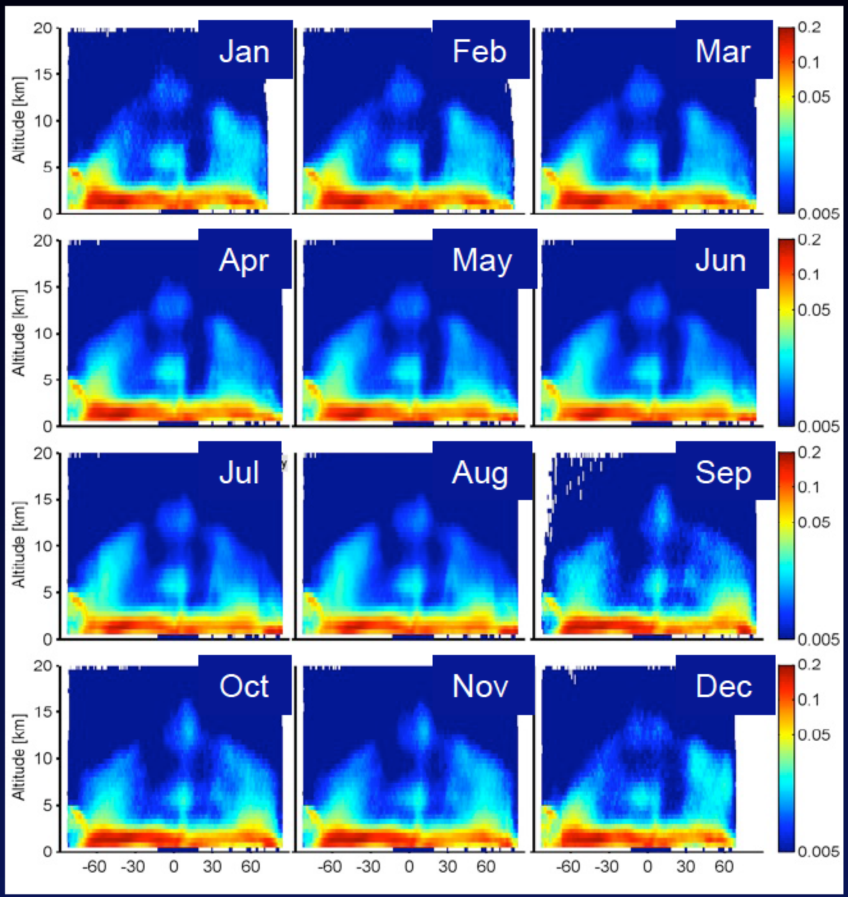
“Radiometric” approach

Geometric parallax and motion between views

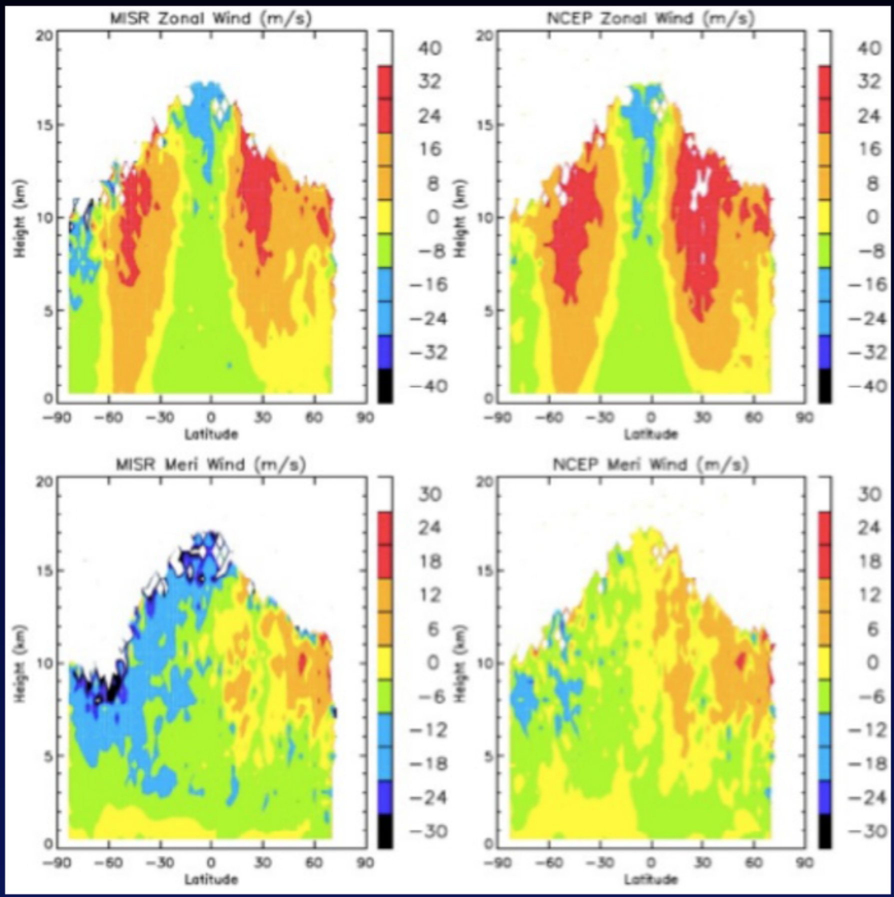


Multiangle flyover   Cloud-top heights   Cloud motion vector winds

Cloud height and wind climatologies from MISR



High sensitivity to low- and mid-level clouds

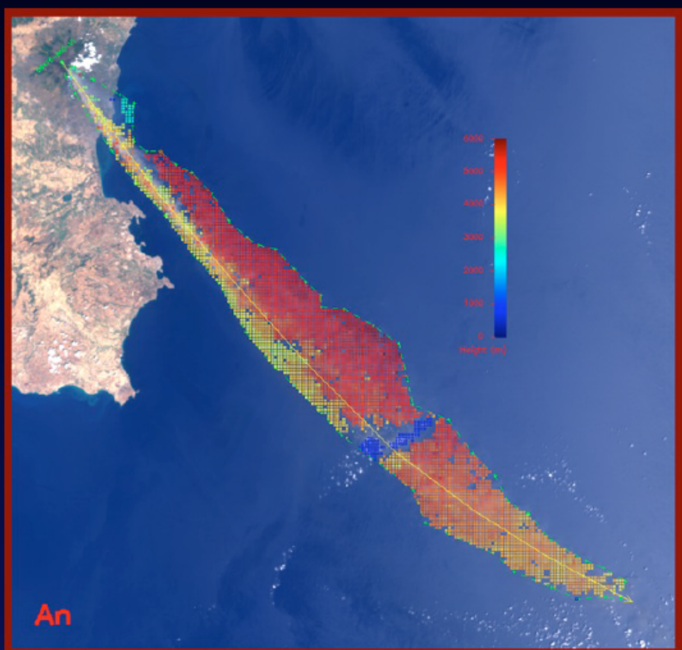


MISR-NCEP wind comparison, January 2005

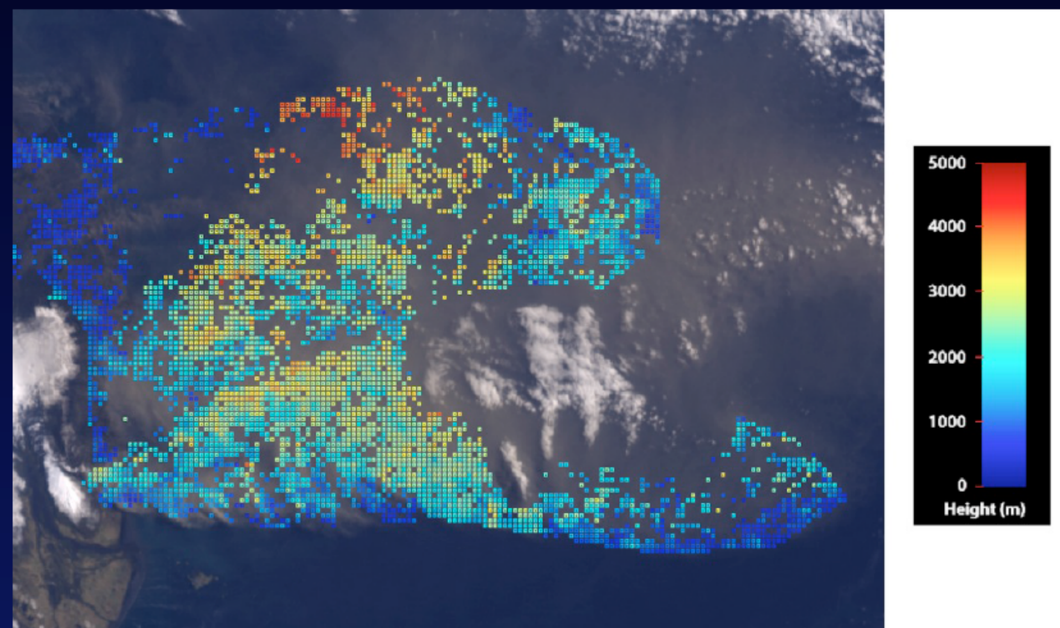
L. Di Girolamo, D. Wu, M. Garay

Volcano ash plume injection heights

Mt. Etna (2002)

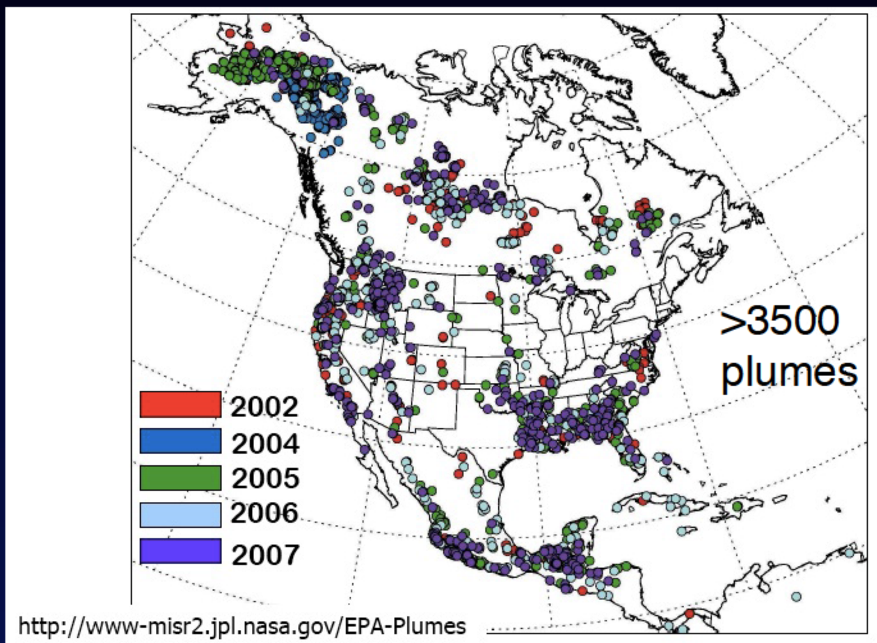


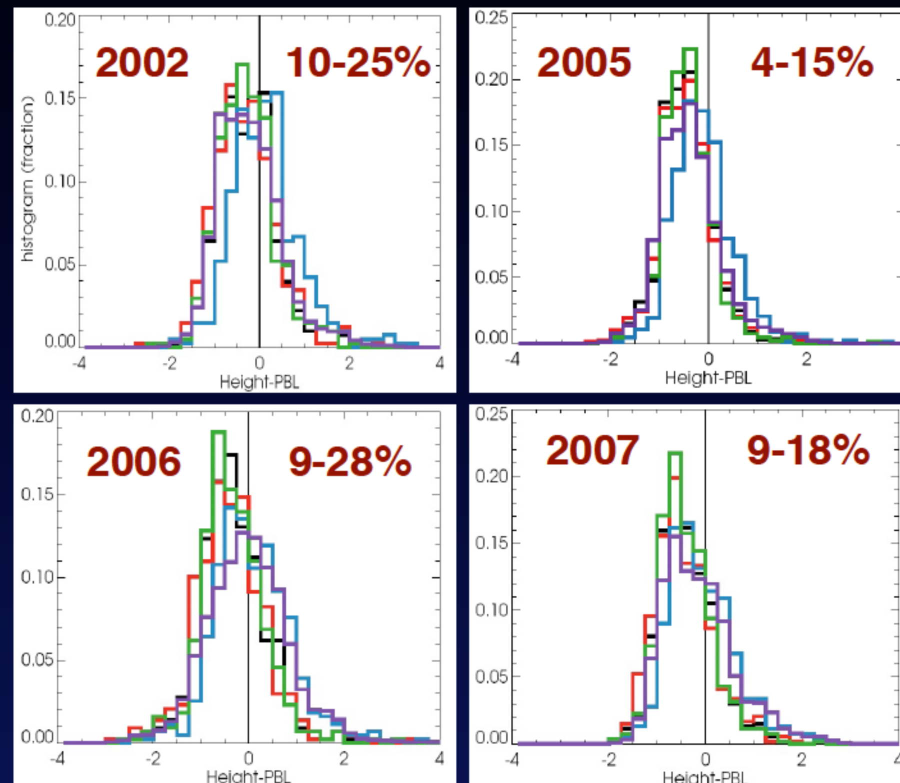
Eyjafjallajökull (2010)



D. Nelson, S. Scollo

Smoke plume injection height climatology





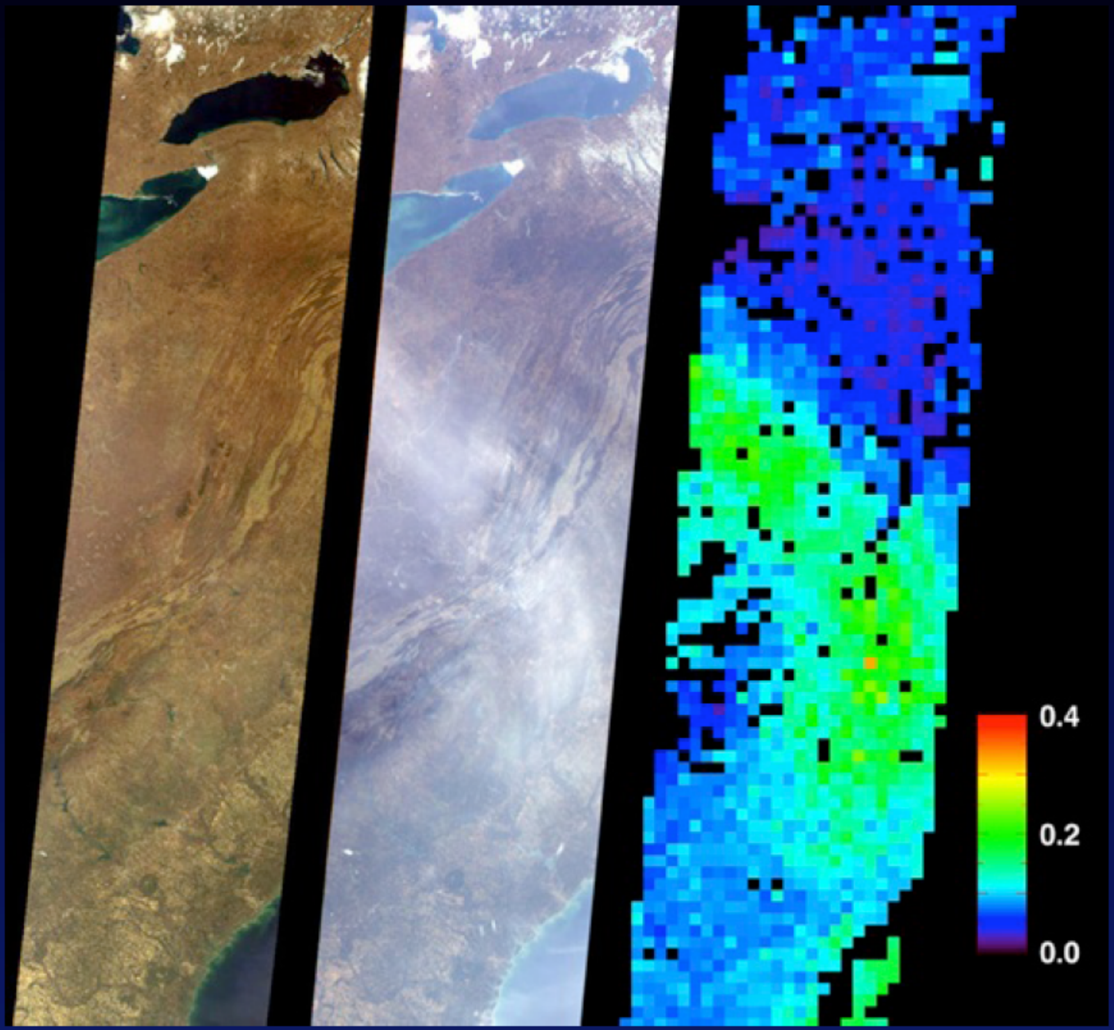
Percentage of plumes exceeding the boundary layer height by >0.5 km.

M. Val Martin et al. (2010), ACP; R. Kahn et al. (2007), JGR

Radiometric variation with changing view angle

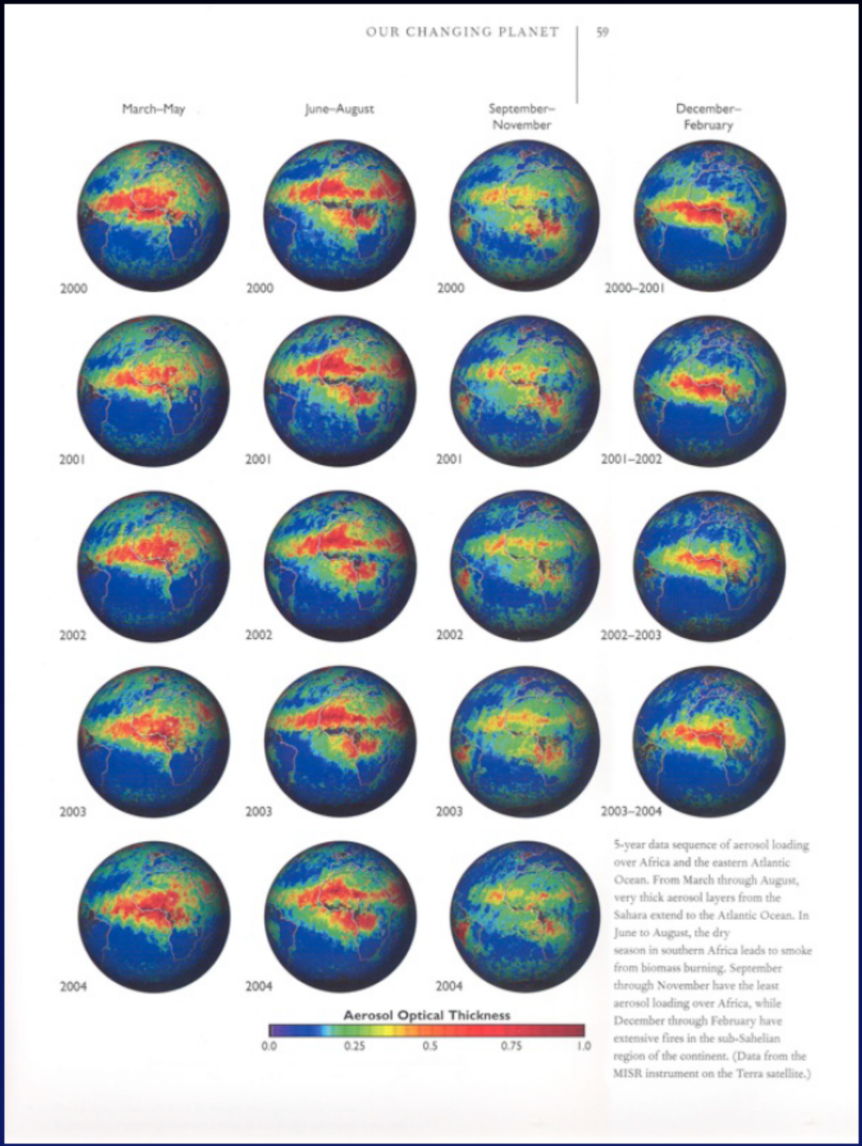
View from airplane

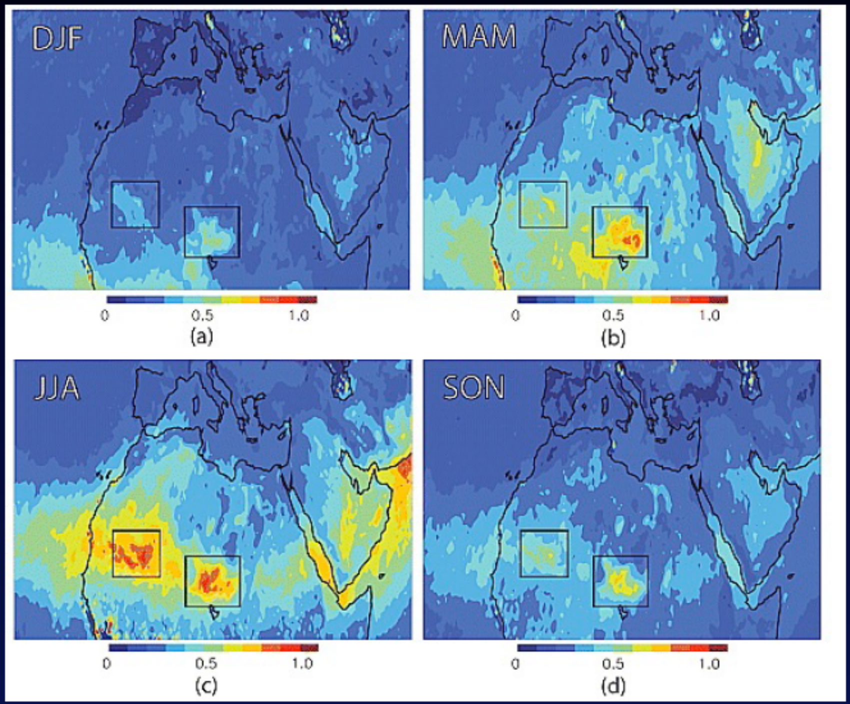
View from MISR



nadir 70° aerosol optical depth (AOD)

Saharan dust seasonality

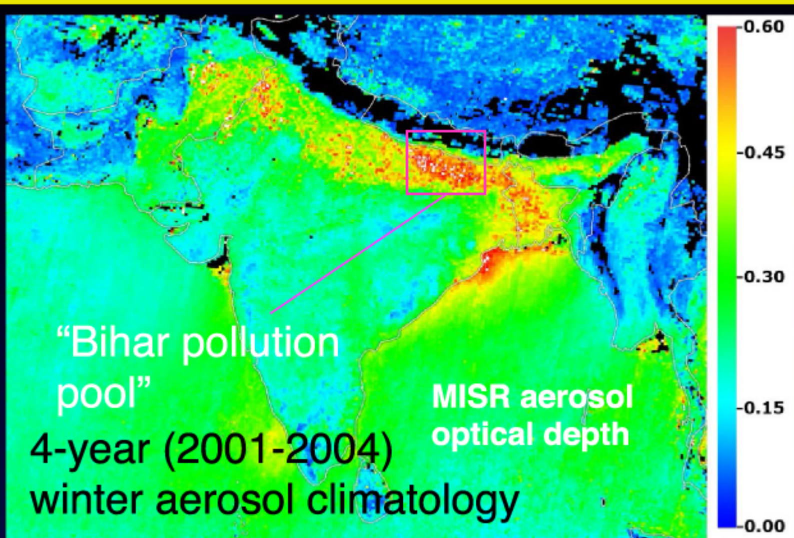


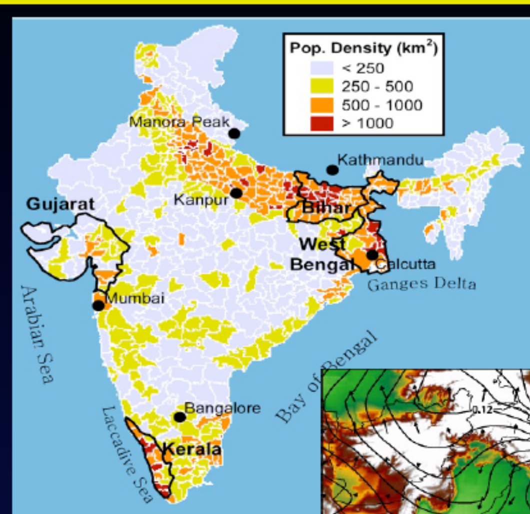


MISR data show major dust sources in the Bodélé Basin and Mali/Mauritania

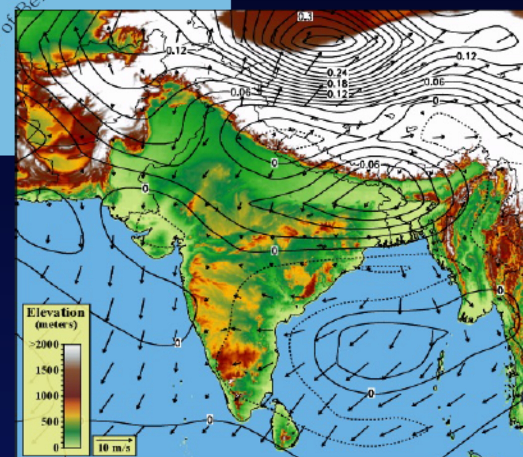
M. King et al. (2007), Cambridge Univ. Press;
C. Koven and I. Fung (2008), JGR

Pollution over India

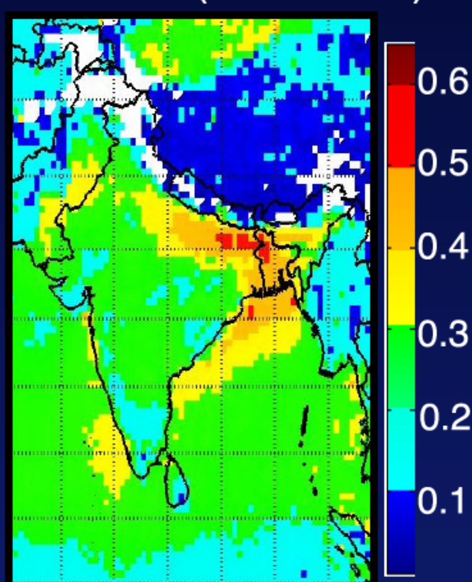




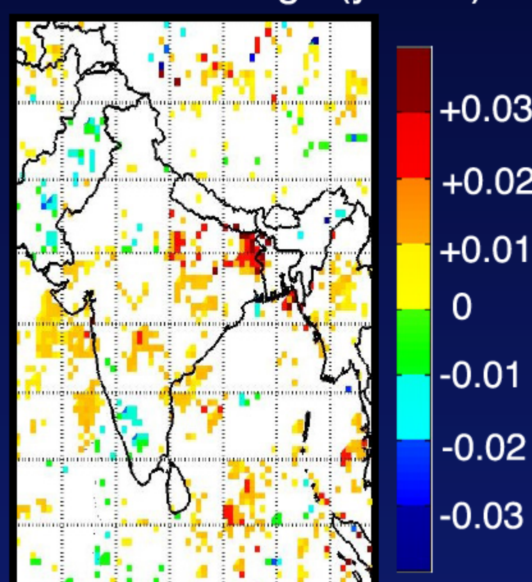
Topography and winds



Mean AOD (2000-2008)



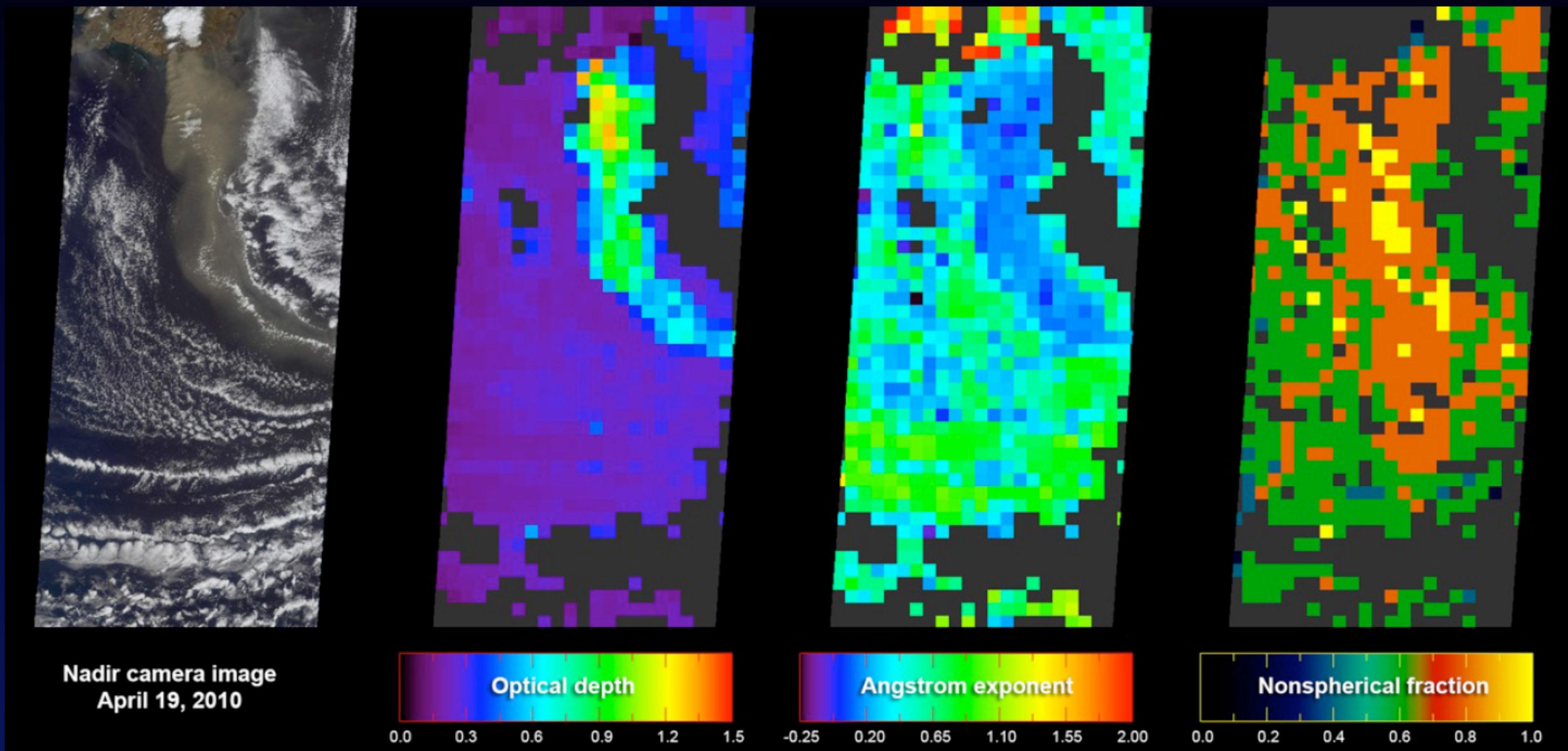
AOD rate of change (year $^{-1}$)



9-year (2000-2008) winter aerosol climatology

L. Di Girolamo et al. (2004), GRL; S. Dey and L. Di Girolamo, JGR, in press

Volcanic plume particle properties



Eyjafjallajökull - 19 April 2010

Aerosol-Cloud-Ecosystem (ACE) mission

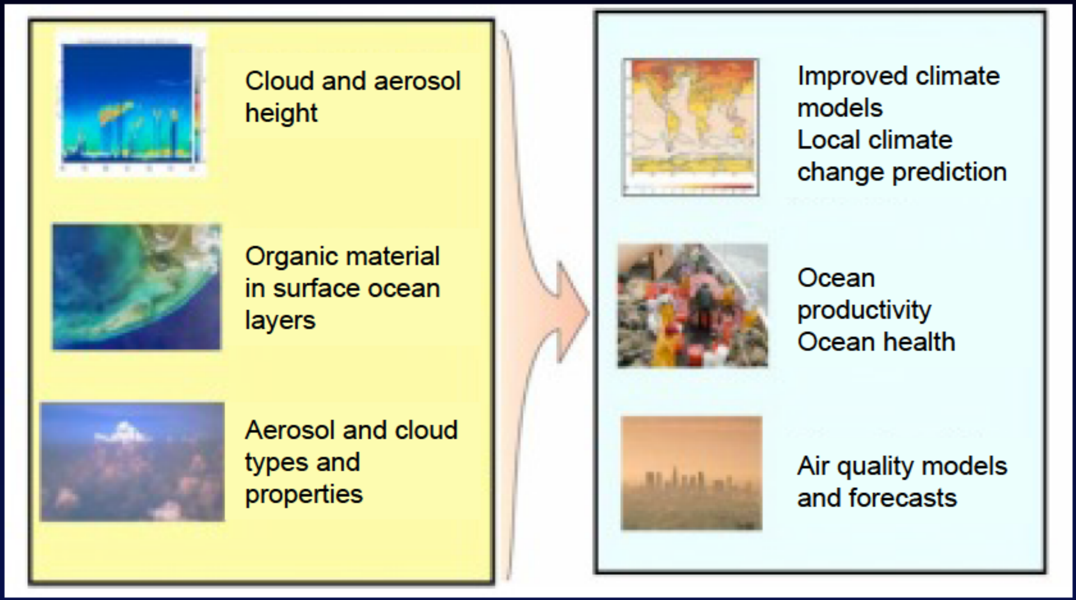
- NAS Decadal Survey, January 2007

Sensors

Advanced lidar

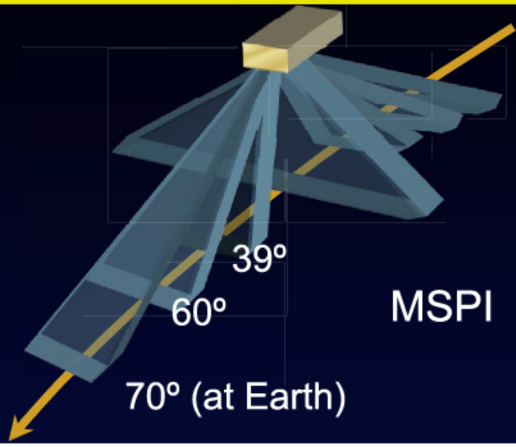
Advanced cloud radar

Ocean color spectrometer



Imaging spectropolarimeter → "A highly accurate multiangle multiwavelength polarimeter… with ~1 km pixel size"

Multiangle SpectroPolarimetric Imager - MSPI



Broader spectral range

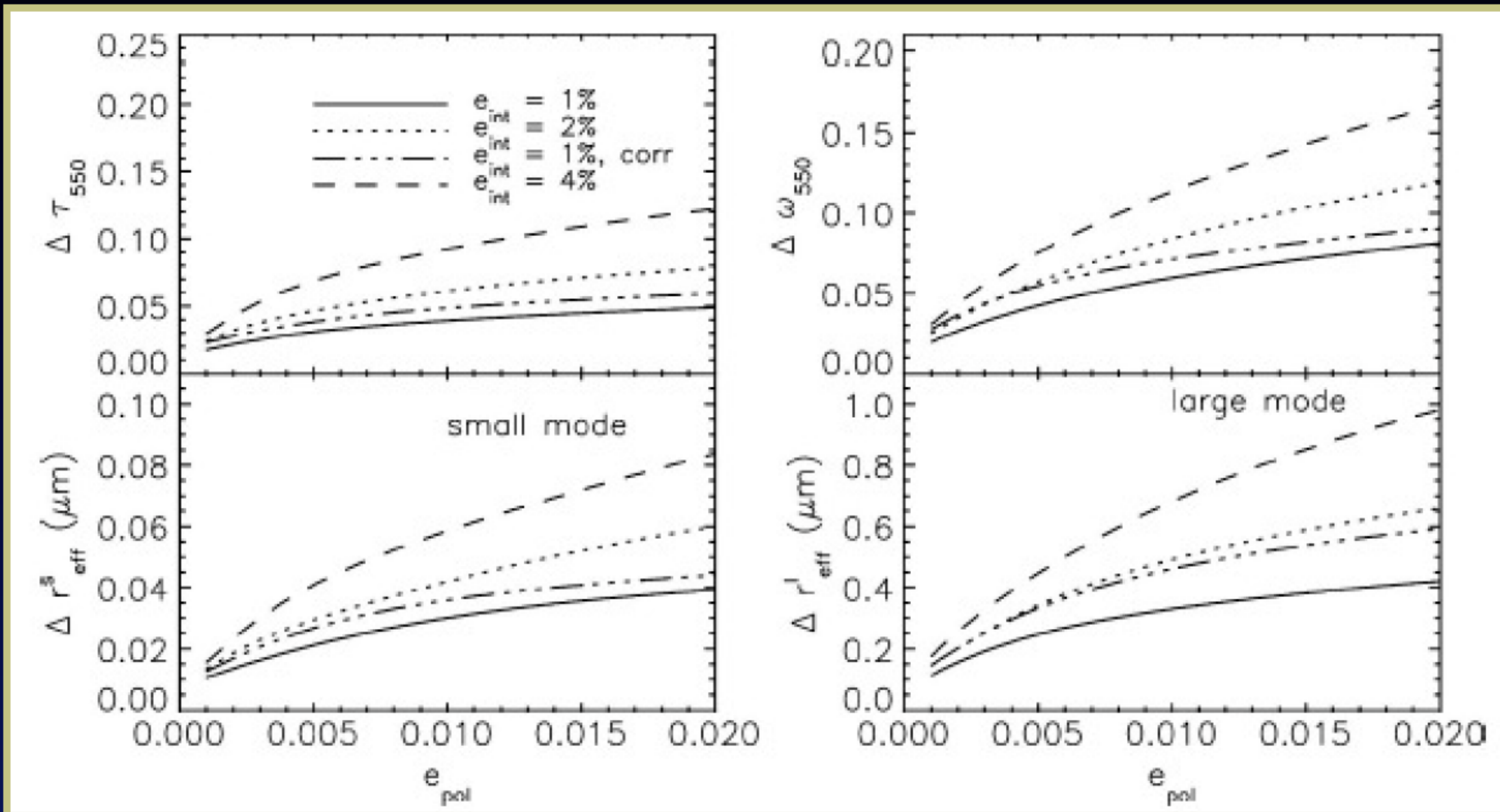
Wider swath

Higher resolution (nadir)

Greater functionality (polarimetry)

Capability	Purpose	MISR	MSPI
UV bands	Aerosol absorption and height	Not included	355, 380 nm
VNIR bands	Fine mode aerosols, land and ocean surface	446, 558, 672, 866 nm	445, 470*, 555, 660*, 865 nm
SWIR bands	Coarse mode aerosol, clouds, atmospheric correction	Not included	1595*, 1875, 2130 nm *polarimetric bands
Multiangle views	Aerosols, albedo, texture	0º-70º views, 9 angles	0º-70º views, 7 angles
Polarimetry	Aerosol refractive index, surface texture and orientation	Not included	0.5% DOLP tolerance
Spatial resolution	Scene classification, stereo	275 m – 1.1 km	125 m – 2.2 km
Global coverage	Capture events, climate statistics	9 days	4 days (off nadir); 2 days (nadir)

Aerosol sensitivity and polarimetry

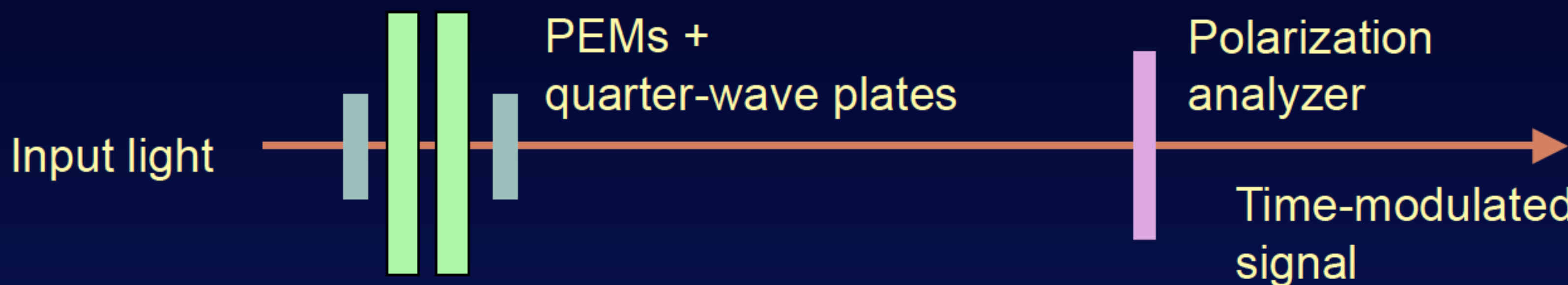


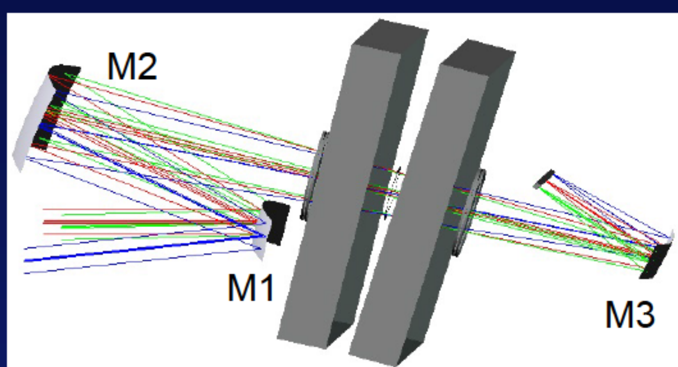
To add high-accuracy information content to multiangle intensity data, uncertainty of 0.5% or better in degree of linear polarization is required.

O. Hasekamp and J. Landgraf (2007), Appl. Opt.

MSPI polarization measurement approach

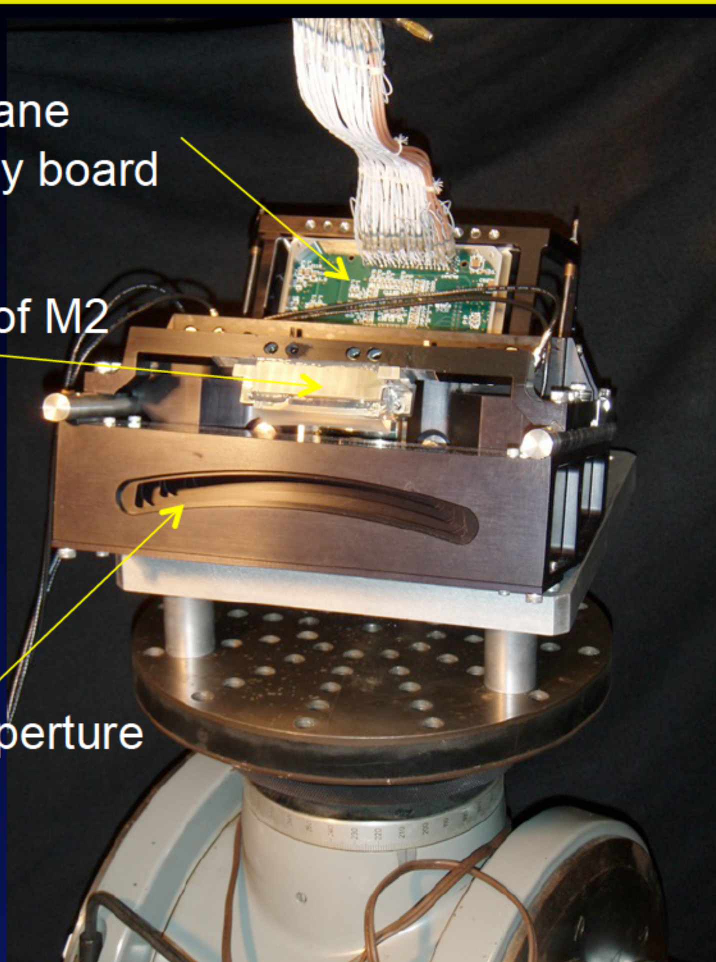
- To measure DOLP accurately, we time-modulate the linear Stokes components Q and U – leaving intensity I unmodulated – using photo-elastic modulators (PEMs):
  - This temporal modulation enables retrieval of $q = Q/I$ (and $u = U/I$) as *relative* measurements





Reflective optics and a dual-PEM assembly provide intensity and polarization imaging over broad spectral range and wide FOV.

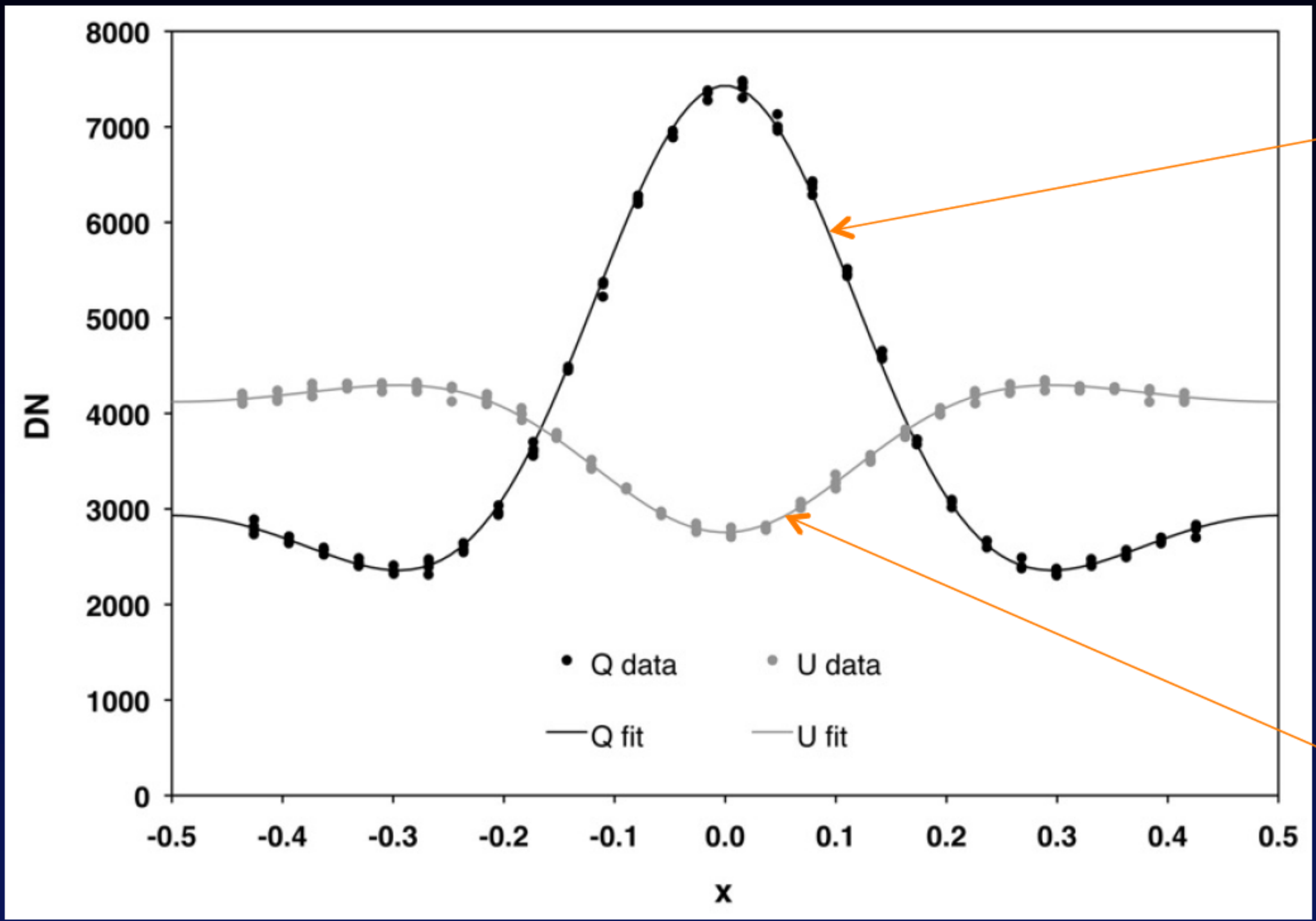
Prototype camera and gimbal (GroundMSPI)



Spectral bands

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

Polarimetry using temporal modulation

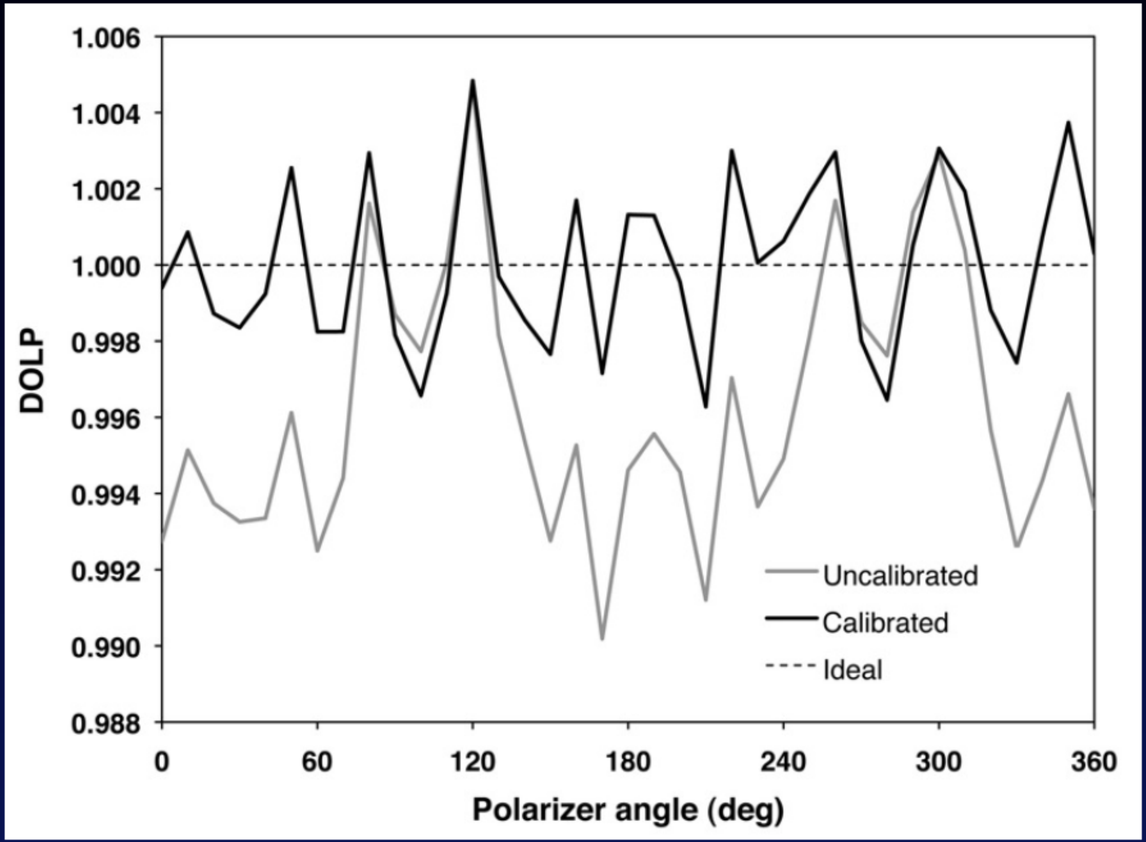


Measures both Q and I

Measures both U and I

1 frame ~ 40 msec

Polarimetric calibration at 660 nm



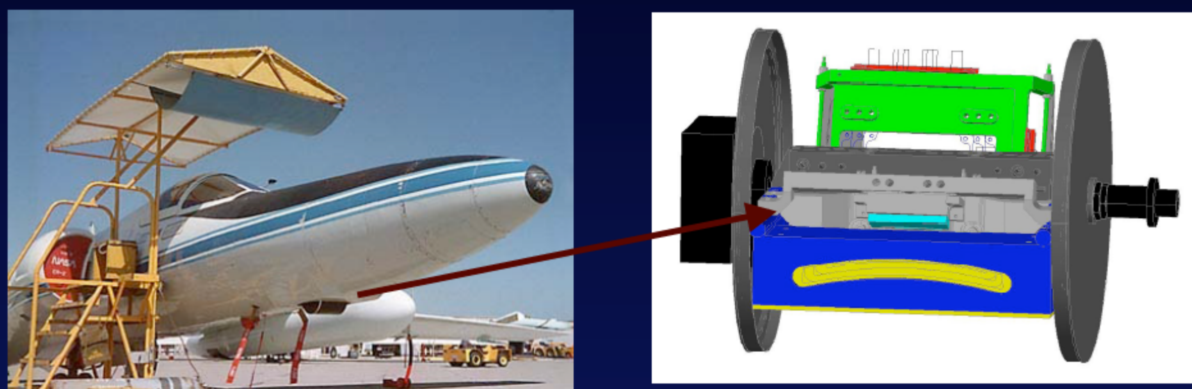
	Uncalibrated	Calibrated
DOLP	0.9962 ± 0.0034	1.0000 ± 0.0022

GroundMSPI imagery: intensity

GroundMSPI generates high-quality polarimetry

Camera upgrades currently in process

- AirMSPI (to fly on the NASA ER-2, upgrade of AirMISR)
  - Similar to GroundMSPI but with:
    - Improved mirror coatings and athermalized quarter wave plates
    - Optical probe for controlling the PEMs in flight
  - Flight test scheduled for late May 2010



- Currently developing technologies for extension of MSPI into the SWIR

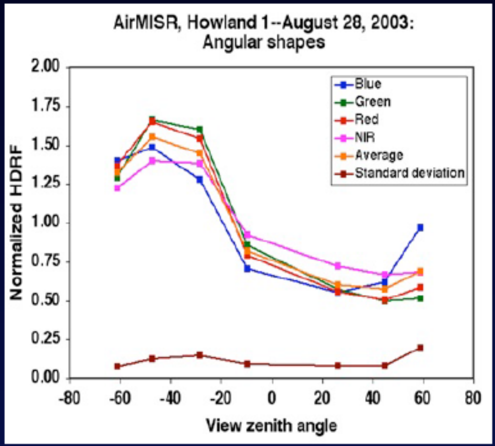
Algorithm advances are needed too!

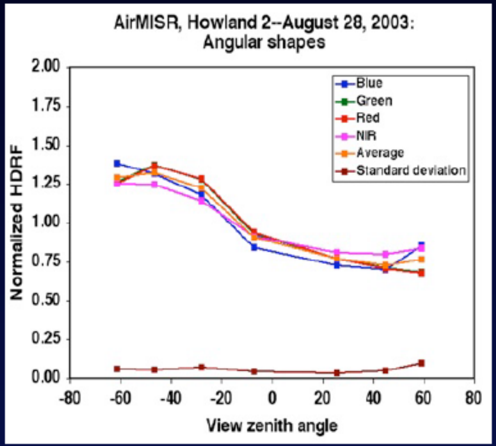
Current paradigm	New paradigm
Lookup tables (LUTs) to relate particle properties to radiances	Fast, accurate run-time radiative transfer calculations with parameter optimization

- Limitations of LUTs (Katsev et al., 2009)
  - Lookup tables can rapidly grow to very large size, requiring large computer memory and intensive I/O
  - Coarsely discretize continuously varying parameters
- Retrieval can be cast as an optimization of aerosol and surface parametric models (Govaerts et al., 2009; Waquet et al., 2009)
  - Aerosols: At least bimodal ognormal distribution of spherical particles → r_c, σ, n_r, n_i for each mode; total AOD; nonsphericity; height
  - Surface: Parameterized BRDF constraining angular and spectral functionality

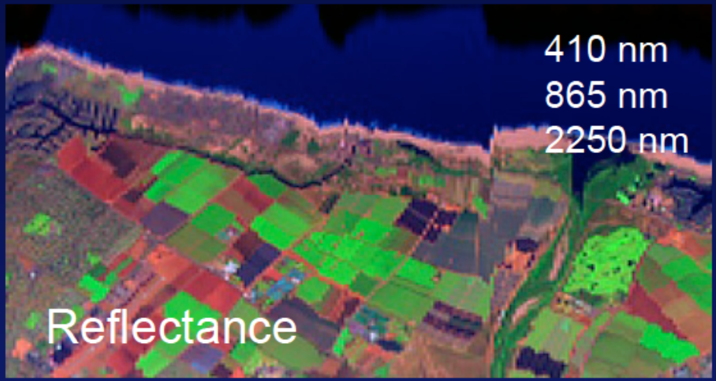
Combining multiangle intensity and polarimetry

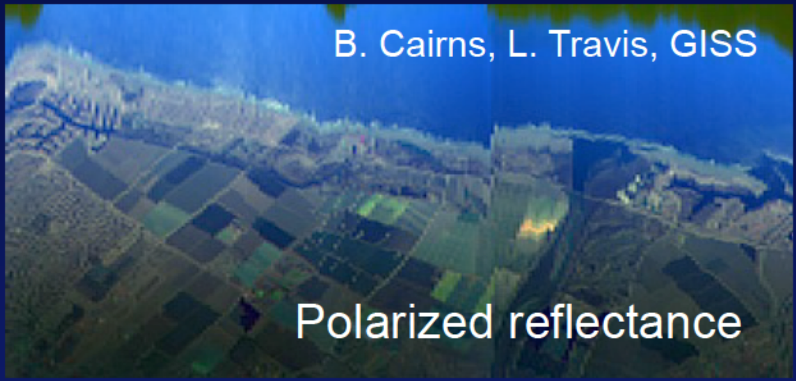
- Multiangle intensity and polarization data provide constraints on the surface boundary condition required for aerosol retrieval.
  - Spectral invariance of angular shapes of surface bidirectional reflectance factors (AATSR, MISR, AirMISR, RSP)





  - Spectral neutrality of surface polarized reflectance (POLDER, RSP)





Surface BRDF model

- Volumetric depolarizing scattering term plus a polarizing term modeled as an angular distribution of specularly reflecting facets.

$$\mathbf{f}_\lambda(-\mu,\mu_0,\phi-\phi_0) = \frac{a_\lambda}{\pi}[(\mu+\mu_0)\mu_0\mu]^{k-1}\exp[b\cdot\cos\Omega]\cdot\begin{bmatrix}1&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&0\end{bmatrix}$$

all terms spectrally neutral except a_λ

$$+\zeta\frac{p'(\beta)}{4\cos\beta\cos\theta\cos\theta_0}\mathbf{M}(-\alpha)\mathbf{F}(\gamma,n_r,n_i)\mathbf{M}(\alpha_0)$$

Modified Rahman-Pinty-Verstraete

Fresnel facets with angular probability distribution in tilt angle β

$$p'(\beta)=\frac{1}{2\pi} \qquad p'(\beta)=\frac{\cos\beta}{\pi} \qquad p'(\beta)=\frac{1}{2\pi\sigma^2\cos^3\beta}\exp\left(-\frac{\tan^2\beta}{2\sigma^2}\right)$$

Uniform — Bréon — Gaussian

Evaluation of surface BRDF using GroundMSPI

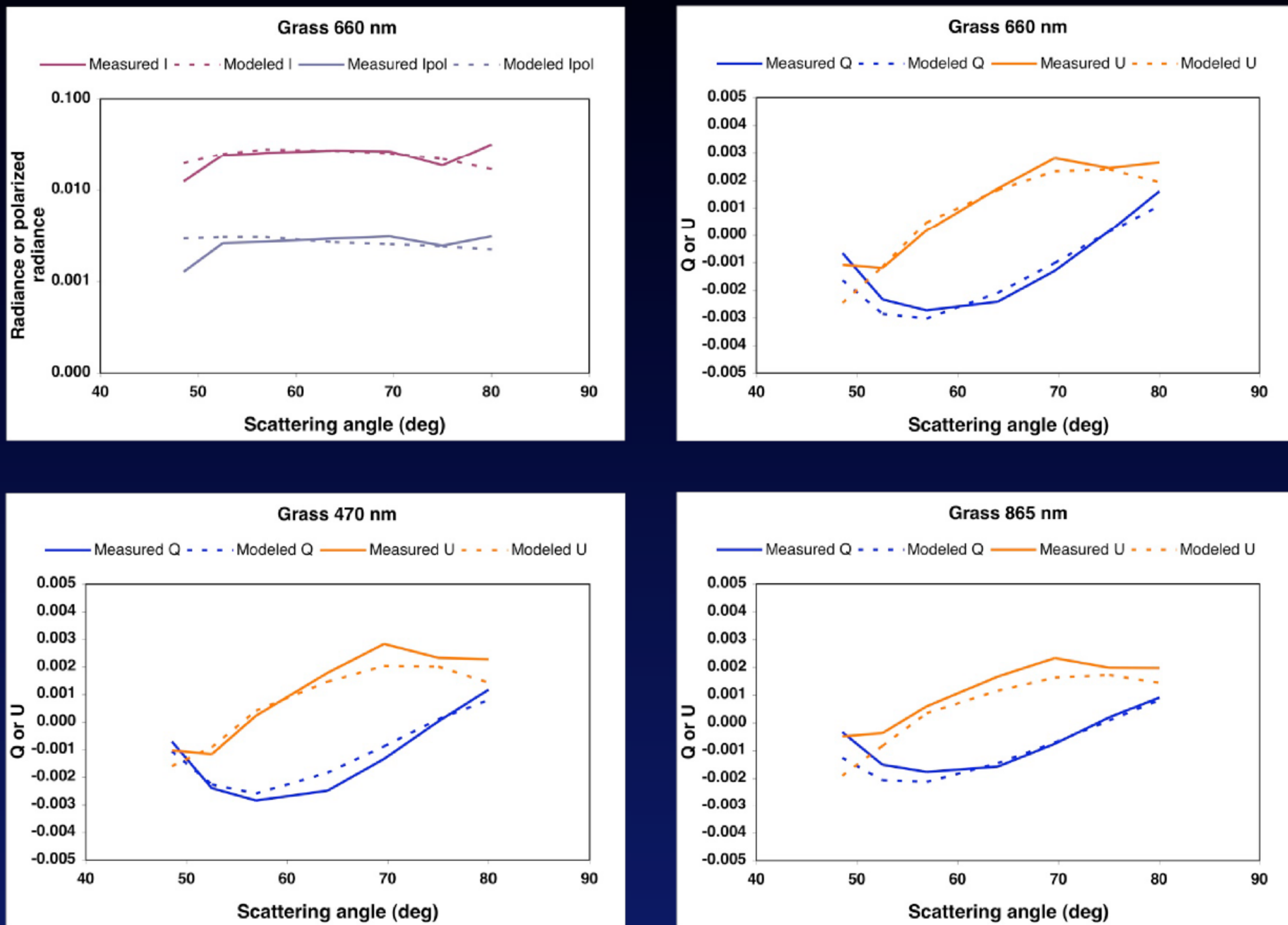
470, 660, 865 nm

Truck roof

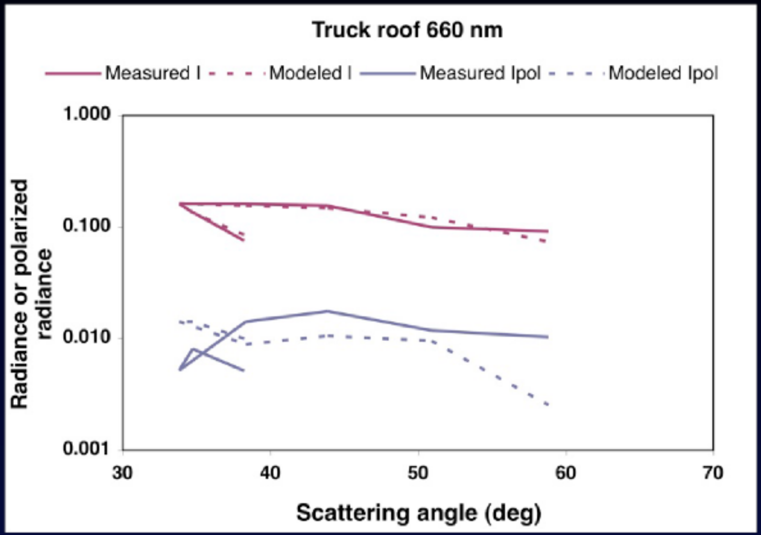
Analyzed time series of data
8:44 am, 9:44 am, 10:43 am, 11:44 am, 12:45 pm, 1:44 pm, 2:44 pm, 3:44 pm PST
January 6, 2010

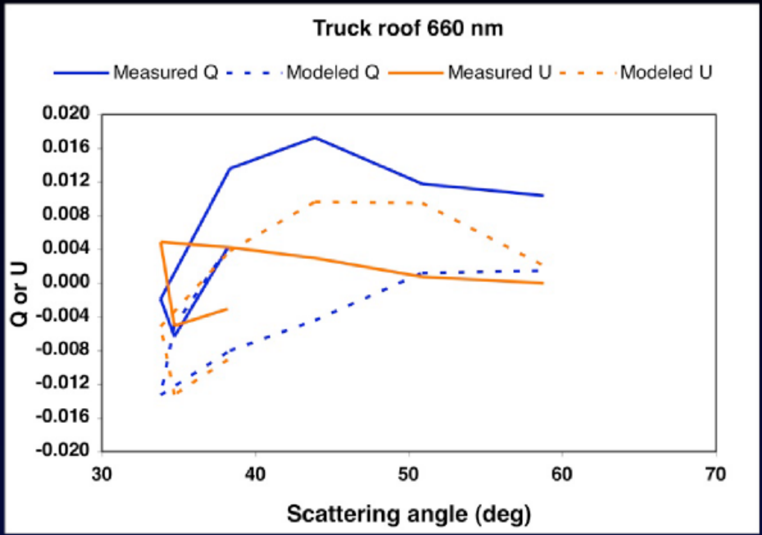
Grass

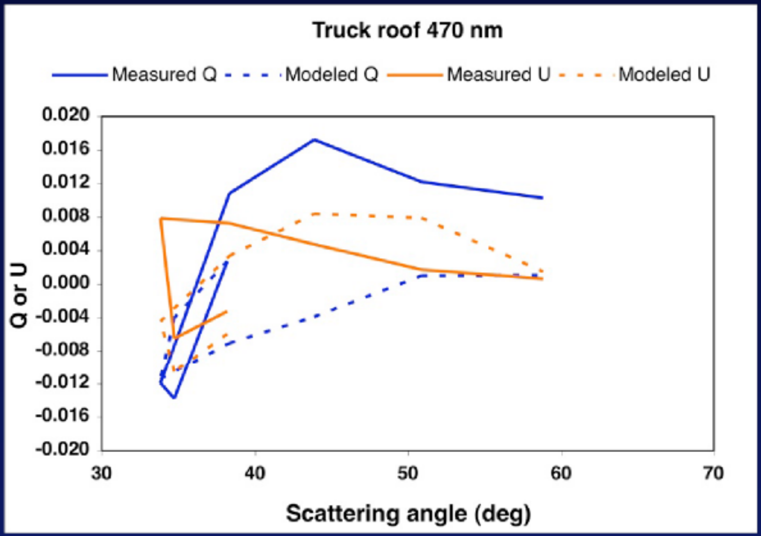
Multispectral fits to grass target

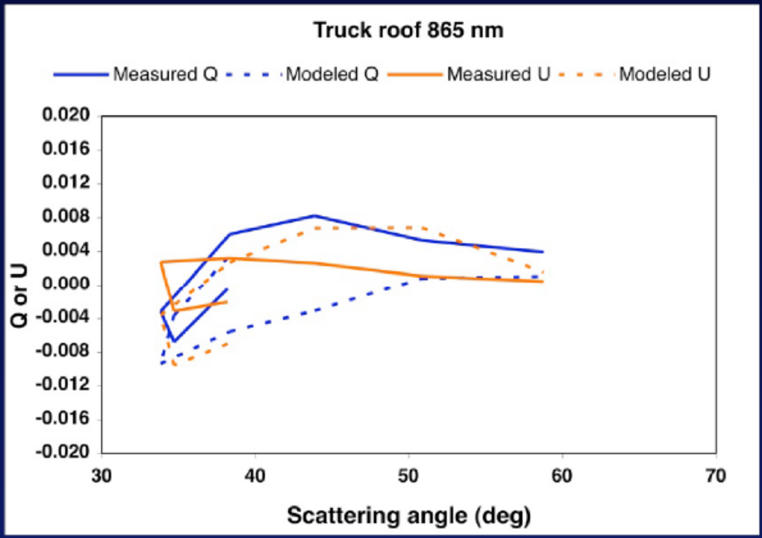


Multispectral fits to truck roof target



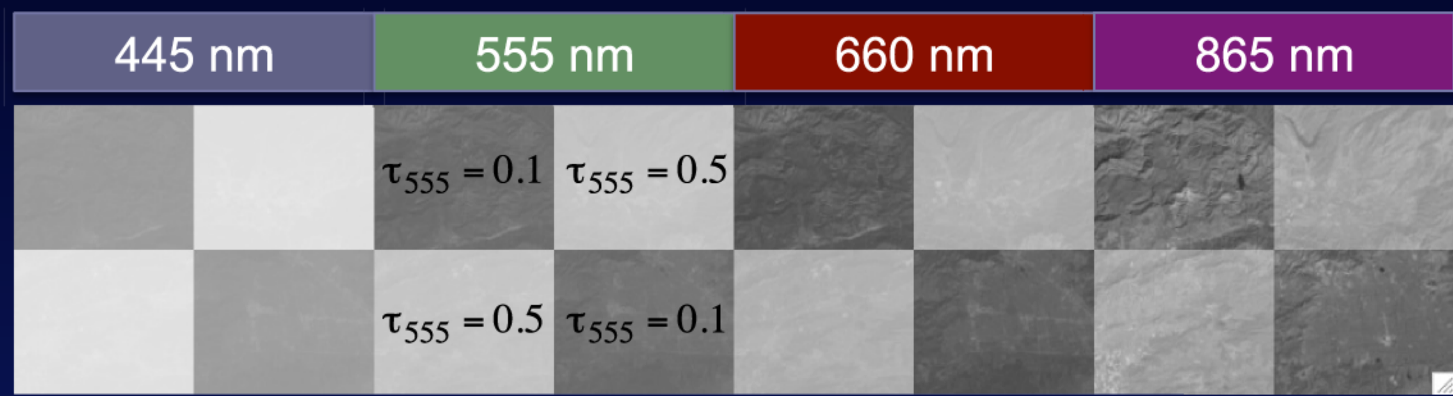






Simulated TOA data

- Synthetic top-of-atmosphere Stokes vectors were generated by running a vector Successive Orders of Scattering RT code
  - Calculations were performed for 4 spectral bands and 9 angles.



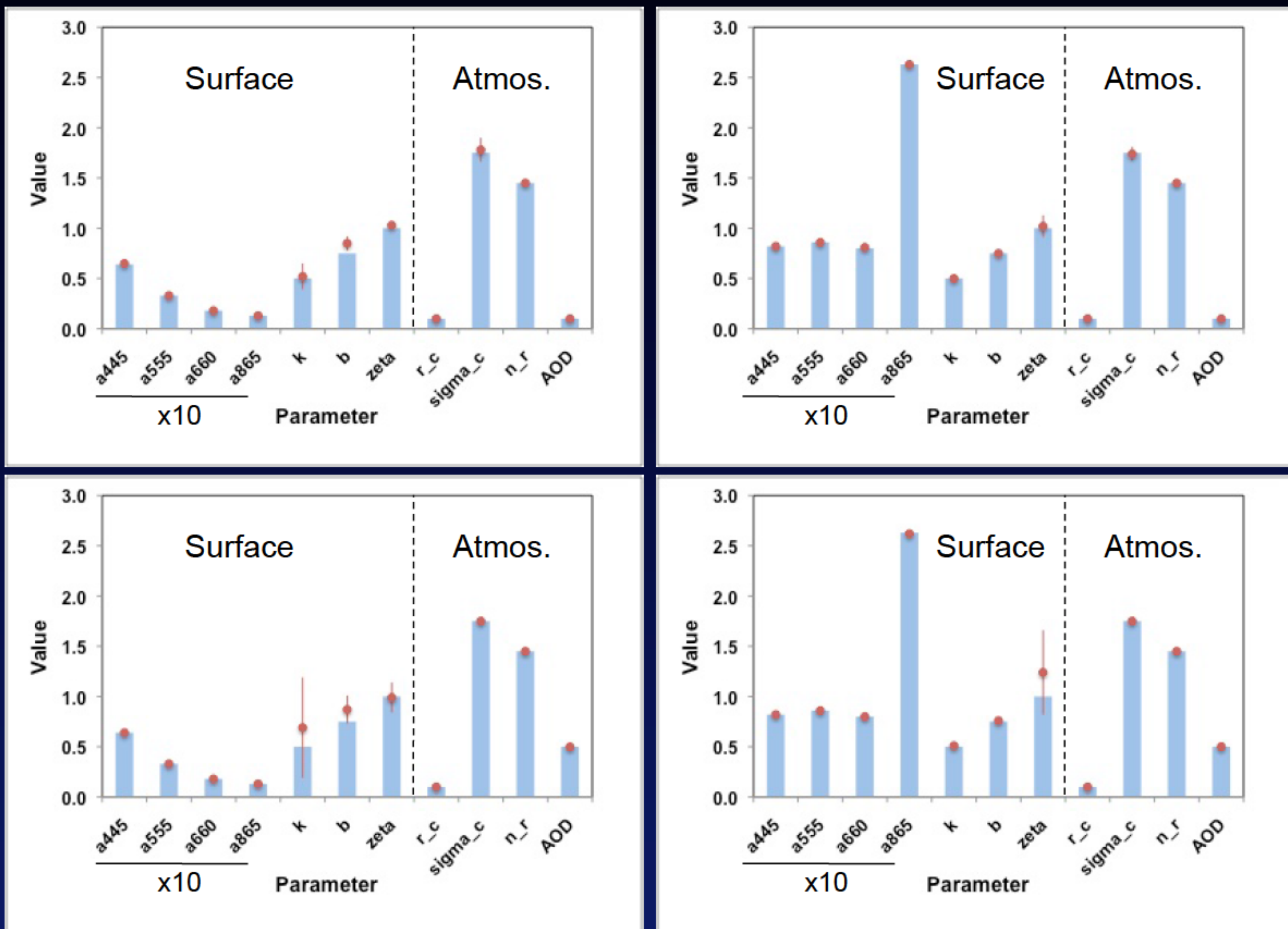
View zenith: 70°
View azimuth: 14°
Sun zenith: 54°
Sun azimuth: 336°

Rayleigh scattering and a nonabsorbing fine mode aerosol (n_r = 1.45) with log-normal size distribution (r_c = 0.1 μm and σ_c = 1.75) were placed above the surface

SOS code courtesy Y. Hu, P. Zhai

Initial retrieval tests

■ "Truth" ● Parameters retrieved using Levenberg-Marquardt optimization



AOD=0.1

AOD=0.5

LUT vs. runtime optimization test

- Last year Alex Kokhanovsky conducted a "blind" retrieval experiment with various instrument teams
  - Simulated radiances were provided but aerosol properties were unknown to each team
  - Teams used their algorithms to retrieve aerosol characteristics
- AOD results for MISR algorithm

	AOD_{558}	Comment
"Truth"	0.991	r_{char} = 0.1 µm, σ = 2.718, n_r = 1.38
MISR LUT – standard mixture set use in operational retrievals	0.892	LUT does not contain good size distribution analog
Optimization – *interim* result	0.981	Particle properties close to correct but optimization not yet converged

Conclusions

- Building on MISR heritage, new technology innovations make it feasible to integrate multiangular, multispectral, and high-accuracy polarimetric imaging capabilities into a single instrument.

- To take advantage of the multidimensional information content, retrievals will require:
  - Development of physically representative surface bidirectional reflectance models including polarization
  - Rapid optimization of aerosol and surface parameters in a coupled retrieval, replacing LUTs with runtime RT processing

- GroundMSPI and AirMSPI provide unique testbeds for exploring these issues.