MISR remote sensing of tropospheric aerosols

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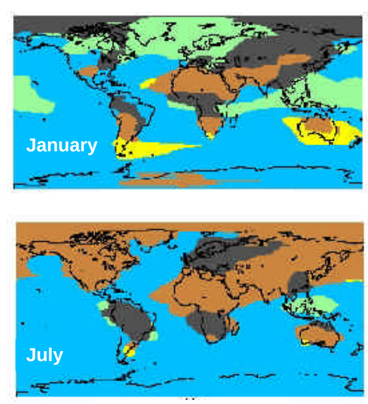
What are aerosols?

Aerosols are tiny particles suspended in the air

Natural sources:
- Volcanoes
- Dust storms
- Forest and grassland fires
- Living land and ocean vegetation
- Sea spray

Anthropogenic sources:
- Burning of fossil fuels through industrial activities, transportation systems, and urban heating
- Land cover and land use changes, e.g., biomass burning, deforestation, desertification



- Carbonaceous + Dusty Maritime
- Dusty Maritime + Coarse Dust
- Carbonaceous + Black Carbon Maritime
- Carbonaceous + Dusty Continental
- Carbonaceous + Black Carbon Continental

From Kahn et al. (2001),
Showing aggregate of five aerosol transport models

Why are aerosols important?

Aerosols scatter and absorb sunlight, and thus can cool or warm the surface and atmosphere

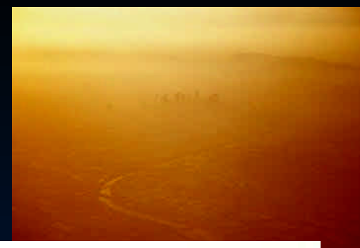
As nucleation centers, aerosols can change the drop size distribution within clouds, affecting cloud reflectance and lifetime

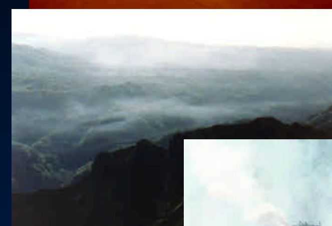
Fine particles penetrate lung tissue and affect respiratory function

High altitude aerosol plumes present hazards to aircraft

Aerosols affect the appearance of scenic vistas

Remote sensing studies of the surface must account for radiation transfer through the intervening atmosphere





Key aerosol microphysical parameters

Particle size and size distribution
Aerosol particles > 1 μm in size are produced by windblown dust and sea salt from sea spray and bursting bubbles. Aerosols smaller than 1 μm are mostly formed by condensation processes such as conversion of sulfur dioxide (SO_2) gas to sulfate particles and by formation of soot and smoke during burning processes

Effective radius
Moment of size distribution weighted by particle area and number density distribution

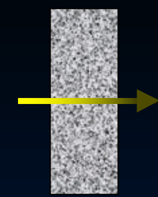
Complex refractive index
The real part mainly affects scattering and the imaginary part mainly affects absorption

Particle shape
Aerosol particles can be liquid or solid, and therefore spherical or nonspherical. The most common nonspherical particles are dust and cirrus

Key aerosol optical parameters

Optical depth

- negative logarithm of the direct-beam transmittance
- column integrated measure of the amount of extinction (absorption + scattering)

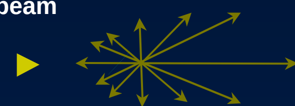


Single-scattering albedo ϖ_0

- given an interaction between a photon and a particle, the probability that the photon is scattered in some direction, rather than absorbed

Scattering phase function

- probability per unit solid angle that a photon is scattered into a particular direction relative to the direction of the incident beam



Angstrom exponent α

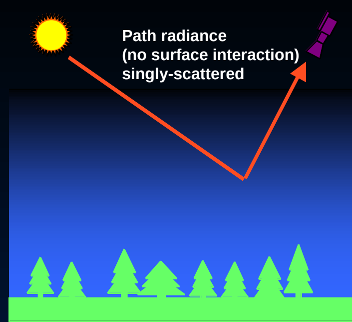
- exponent of power law representation of extinction vs. wavelength

microphysical properties

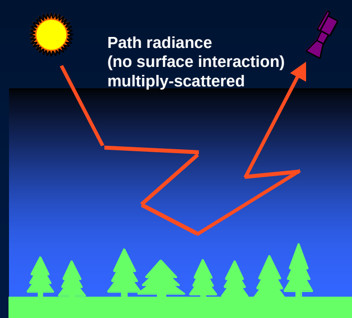
optical properties

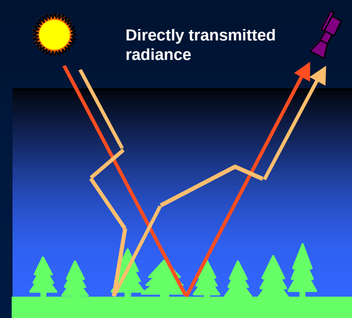
atmospheric radiative transfer

Observed multi-spectral, multi-angular radiances



Top-of-atmosphere radiation consists of singly- and multiply-scattered components that may or may not have interacted with the surface





How do multi-angle observations from MISR facilitate aerosol remote sensing?

1. CONDITIONING THE SIGNAL

a. Avoiding sunglint

Over water, sunglint invalidates the assumption of a nearly black surface, and multiple cameras enable using non-glint contaminated views

b. Identifying clouds

Multi-angle observations offer several powerful approaches

c. Enhancing sensitivity to thin aerosols

Off-nadir observations look through a longer atmospheric path, thus providing greater sensitivity to aerosols, particularly over land

How do multi-angle observations from MISR facilitate aerosol remote sensing?

2. INTERPRETING THE OBSERVATIONS

a. Accounting for the surface contribution to the top-of-atmosphere (TOA) radiances

Different methodologies are used depending on whether the underlying surface is land or water, and new methodologies over land are made possible

b. Constraining the non-uniqueness of the solutions

Multi-angle information complements multi-spectral constraints on particle properties

How do multi-angle observations from MISR facilitate aerosol remote sensing?

3. APPLYING THE RESULTS

a. Radiative effects

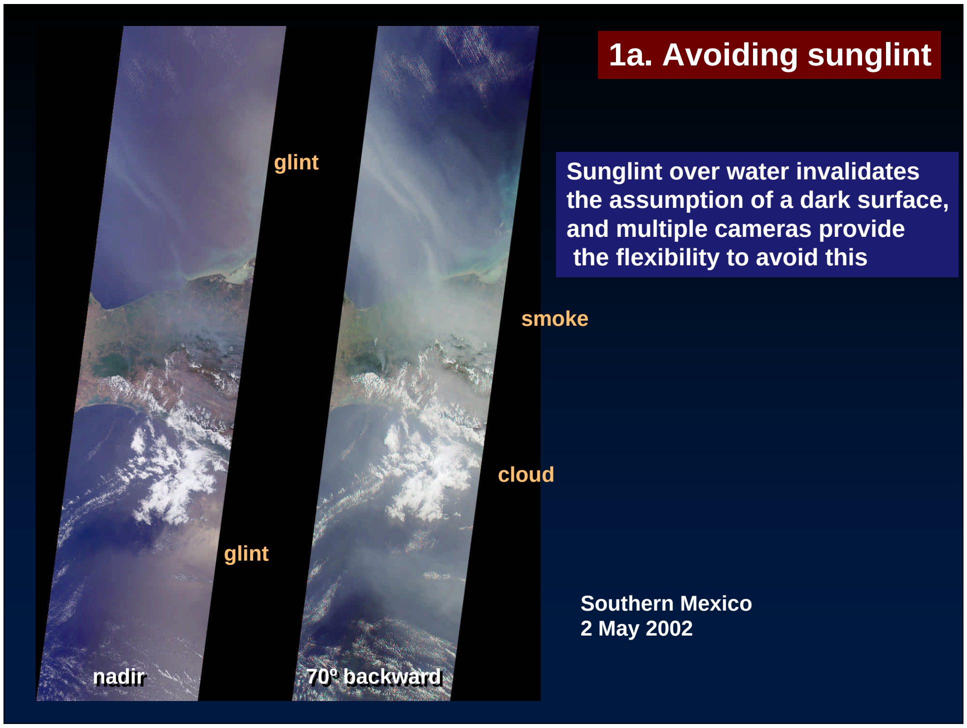
The multi-angle data provide simultaneous estimates of top-of-atmosphere albedo

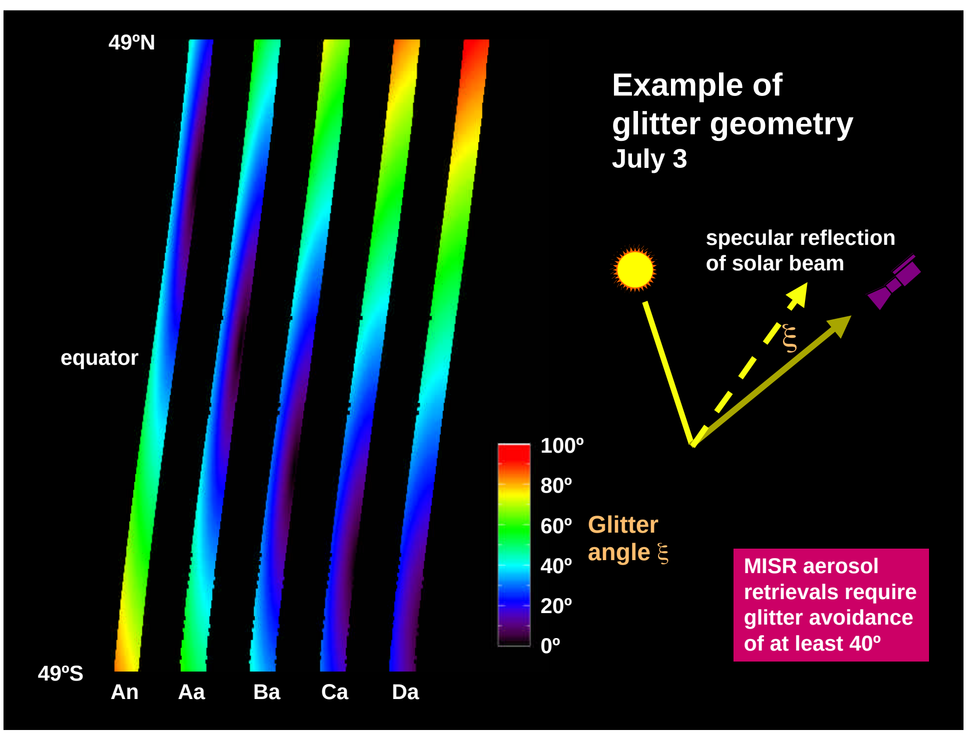
b. Volcano and smoke plume propagation

Stereoscopic retrievals provide simultaneous information about plume altitudes

c. Air quality

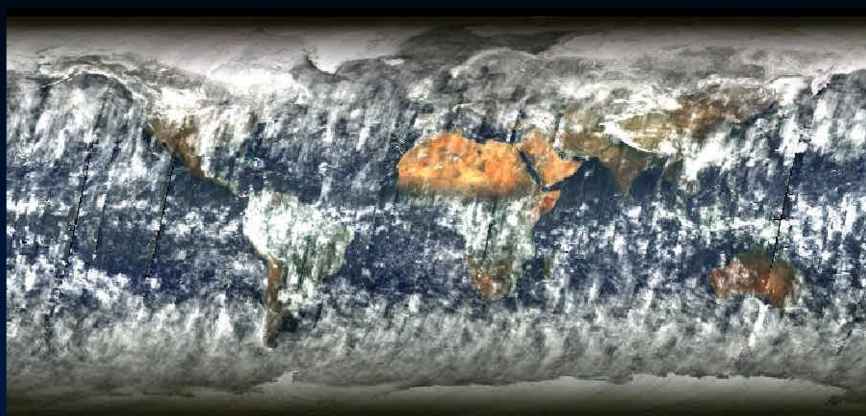
Multi-angle algorithms enable retrievals over non-vegetated areas, such as arid and urban regions


1a. Avoiding sunglint
Sunglint over water invalidates the assumption of a dark surface, and multiple cameras provide the flexibility to avoid this
glint
smoke
cloud
glint
nadir
70º backward
Southern Mexico
2 May 2002


Example of glitter geometry
July 3
49ºN
equator
49ºS
An
Aa
Ba
Ca
Da
specular reflection of solar beam
ξ
100º
80º
60º
40º
20º
0º
Glitter angle ξ
MISR aerosol retrievals require glitter avoidance of at least 40º

1b. Identifying clouds

Cloud clearing is essential for aerosol retrievals



Global radiance map, nadir camera
March 2002

MISR uses multiple scene classification methodologies to screen for clouds

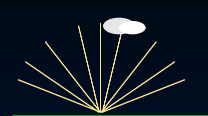
Smoothness of radiance variation with angle

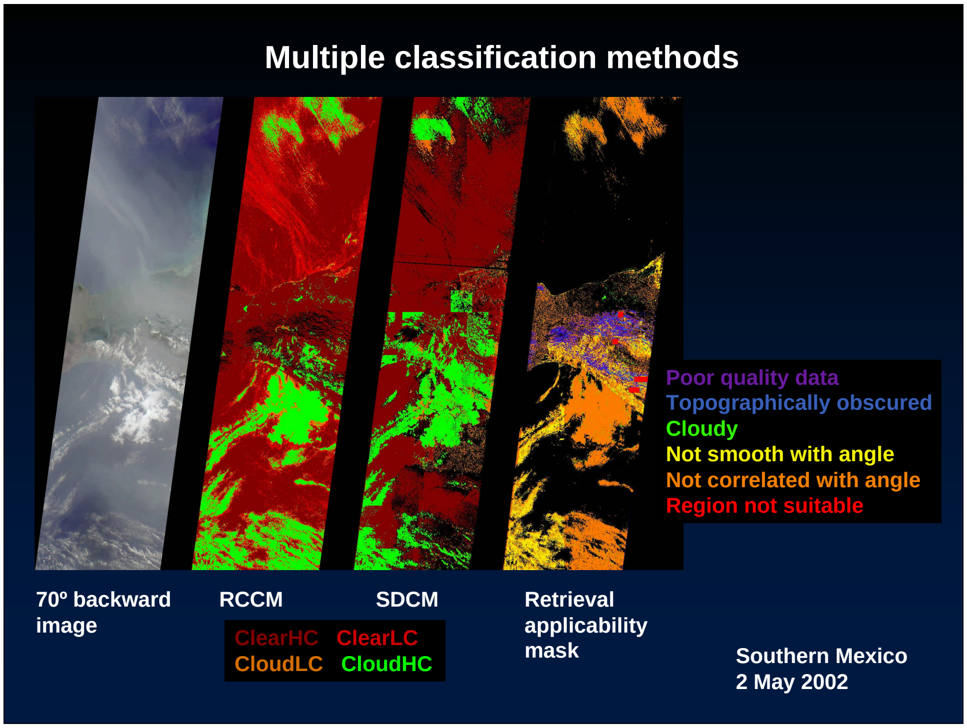
Correlation of spatial radiance pattern with angle

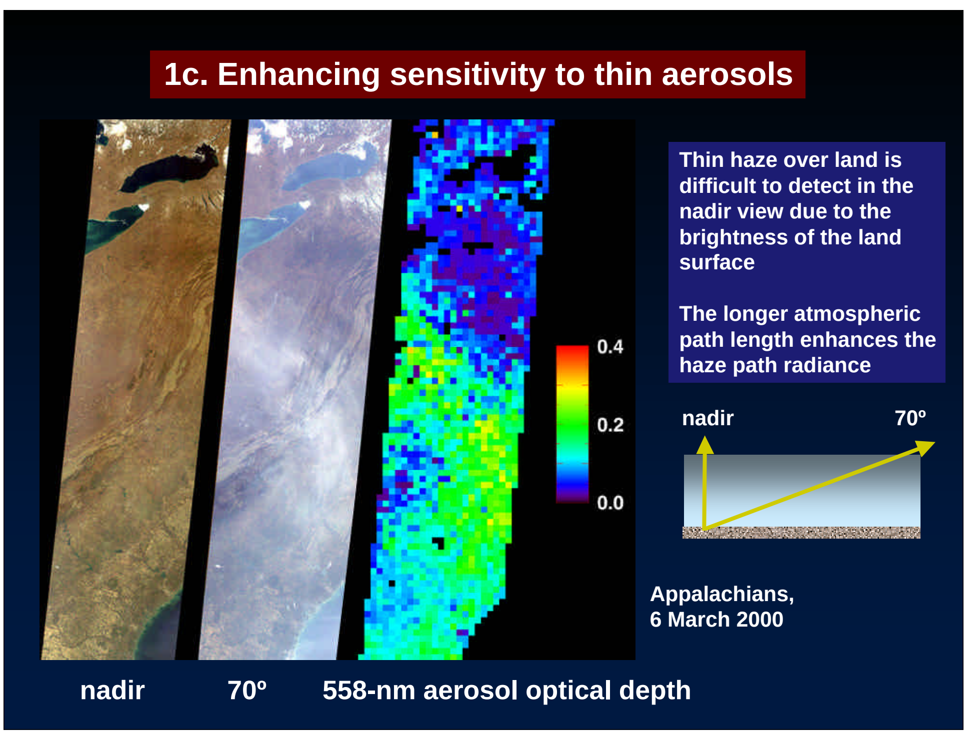
Use of darkest 1.1-km subregion within 17.6-km aerosol retrieval region (over water)

Radiance thresholding cloud mask (RCCM)

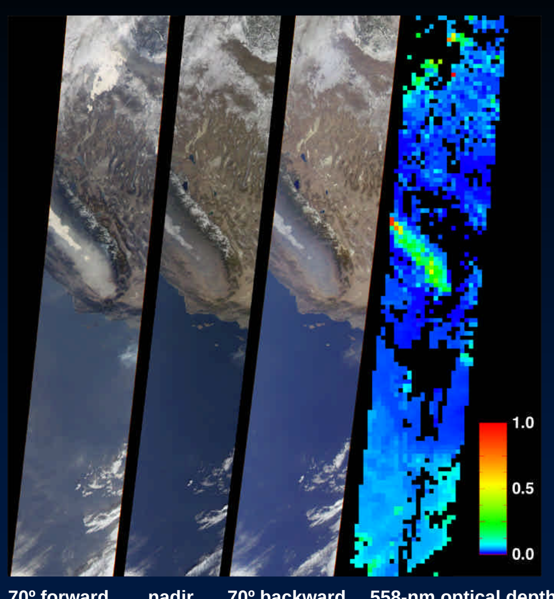
Stereoscopic cloud mask (SDCM)




Multiple classification methods
Poor quality data
Topographically obscured
Cloudy
Not smooth with angle
Not correlated with angle
Region not suitable
70º backward image
RCCM
SDCM
ClearHC ClearLC
CloudLC CloudHC
Retrieval applicability mask
Southern Mexico
2 May 2002


1c. Enhancing sensitivity to thin aerosols
Thin haze over land is difficult to detect in the nadir view due to the brightness of the land surface
The longer atmospheric path length enhances the haze path radiance
0.4
0.2
0.0
nadir
70º
Appalachians,
6 March 2000
nadir
70º
558-nm aerosol optical depth

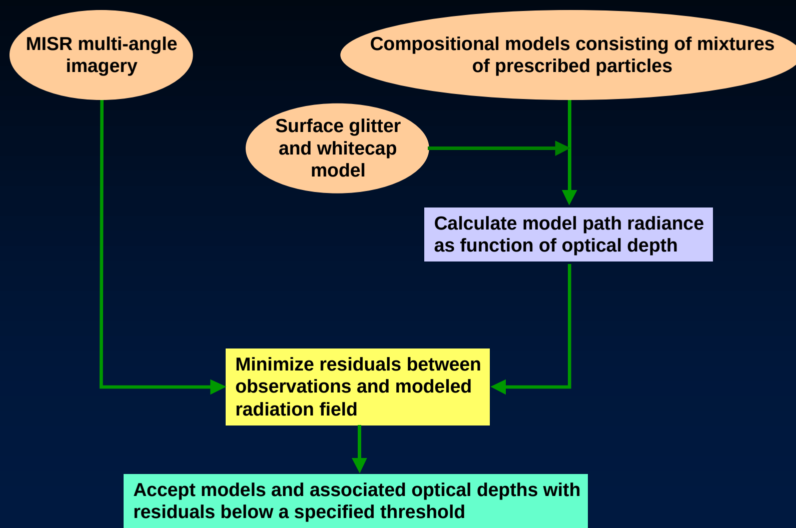
2a. Accounting for the surface contribution to TOA radiances



Despite the different ways of treating the surface, and the vast difference in water and land reflectance, good continuity is obtained across the land-water boundary

Southern California
and western Nevada
3 January 2001

Aerosol retrieval methodology over water



Multiple goodness of fit metrics

$$\chi^2_{abs} = N^{-1}_{channels} \sum_{angle} \sum_{band} [L_{MISR} - L_{path} - L_{surface}]^2 / [0.05 L_{MISR}]^2$$

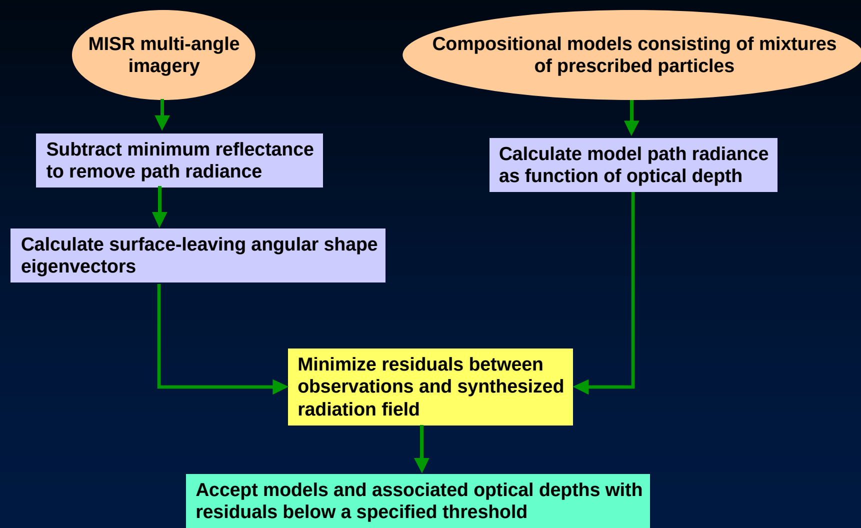
where $L_{surface}$ is modeled as a prescribed contribution from sunglint and whitecaps

χ^2_{geom} : Similarly defined except measured and modeled radiances are normalized to the camera-average values

χ^2_{spec} : Similarly defined except measured and modeled radiances are normalized to the red-band values

χ^2_{maxdev} : Largest term in the χ^2_{abs} summation

Aerosol retrieval methodology over land



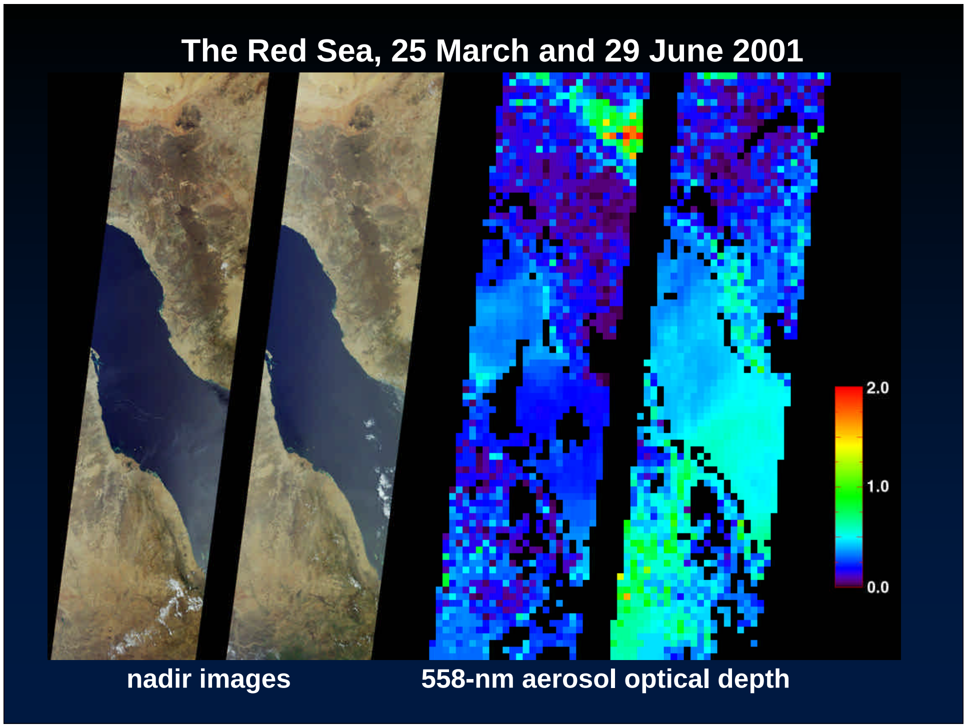
Goodness of fit metric

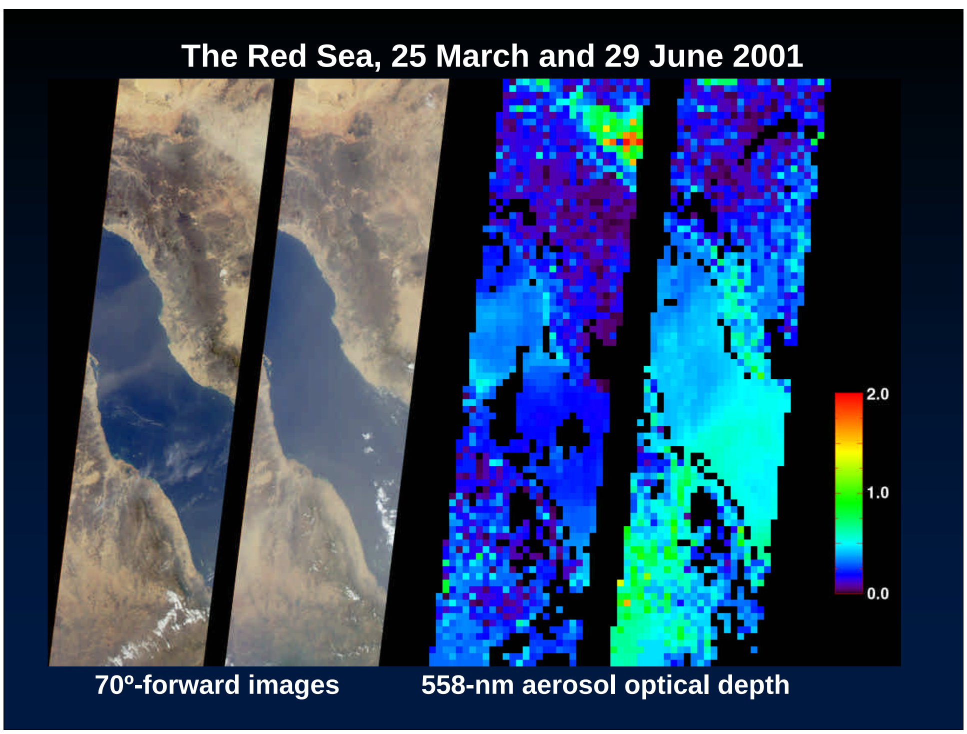
$$\chi^2_{het} = N^{-1}_{channels} \sum_{angle} \sum_{band} [L_{MISR} - L_{path} - L_{surface}]^2 / [0.05 L_{MISR}]^2$$

where $L_{surface}$ is modeled as a dynamically derived sum of empirical orthogonal functions that are least-square fitted to $L_{MISR} - L_{path}$

Simplified concept:

- The technique requires surface contrast to be visible through the atmosphere
- Imagine two pixels with different albedos but the same variation in reflectance as a function of angle
- $L_{MISR,TOA(1)} = L_{path} + L_{surface(1)}$; $L_{MISR,TOA(2)} = L_{path} + L_{surface(2)}$
- $\Delta L_{MISR,TOA} = \Delta L_{surface}$ (path radiance subtracts out)
- The angular variation of $L_{surface}$ is then given by $\Delta L_{MISR,TOA}$. To within a constant of proportionality, this is used to constrain $L_{MISR} - L_{path}$ by summing over all angles
- The EOF approach is invoked to account for multiple surface angular reflectance shapes within the scene


The Red Sea, 25 March and 29 June 2001
2.0
1.0
0.0
nadir images
558-nm aerosol optical depth


The Red Sea, 25 March and 29 June 2001
2.0
1.0
0.0
70º-forward images
558-nm aerosol optical depth

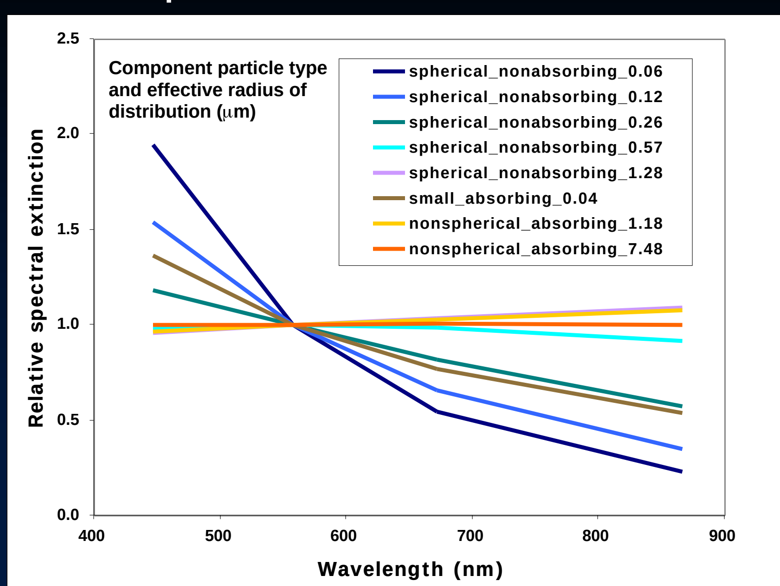
2b. Constraining the non-uniqueness of the solutions

A set of "component particles" of prescribed microphysical/optical properties is established

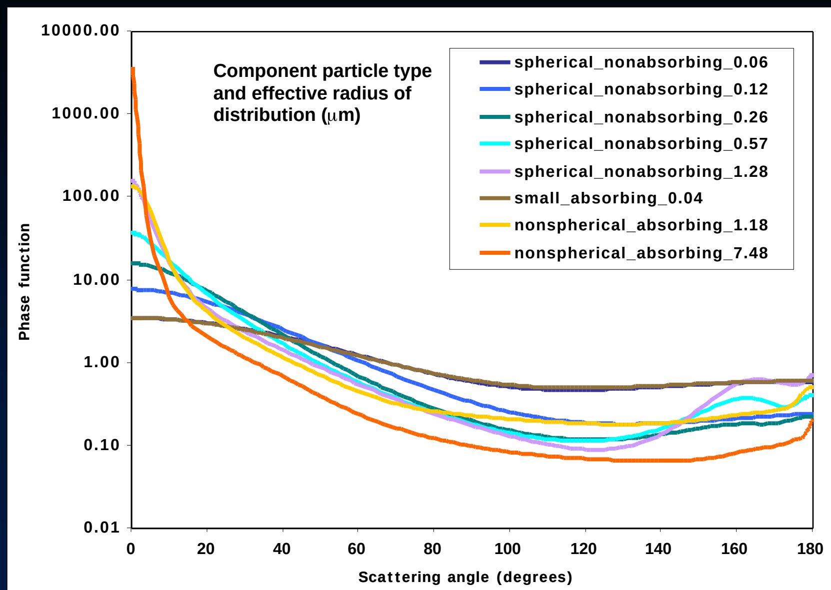
- spherical nonabsorbing (e.g., sulfates, sea spray)
- small absorbing (admixtures with black carbon)
- nonspherical nonabsorbing (cirrus)
- nonspherical absorbing (dust)

Mixtures of these component particles in predetermined ratios are also established and various radiative transfer quantities (e.g., path radiance) are precalculated and stored in a look-up table

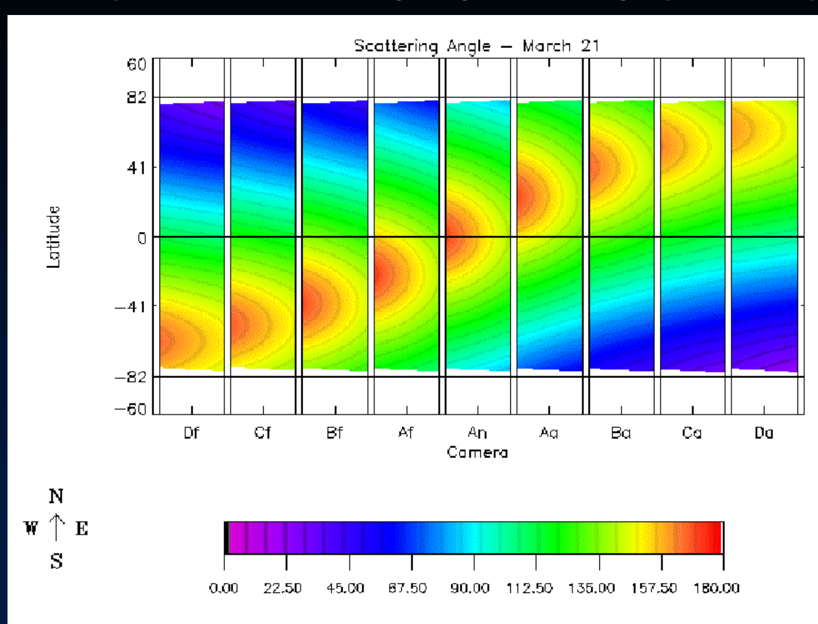
Spectral extinction of component aerosols relative to 558 nm



Scattering phase functions of component aerosols



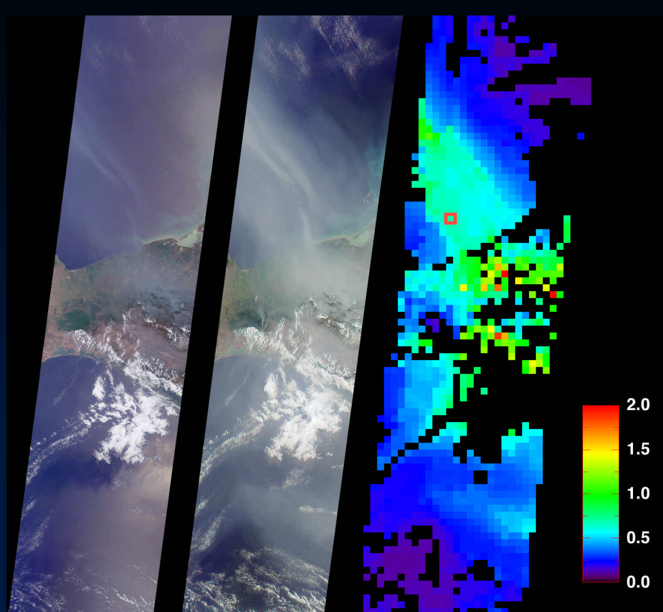
Example MISR scattering angle coverage (March 21)



24 mixtures used in retrievals

		r_{eff} (components)	α	ϖ_0
1	Spherical Small Clean	0.06	3.22	1.00
2	Spherical Small Clean	0.06, 0.12	2.71	1.00
3	Spherical Small Clean	0.12	2.24	1.00
4	Spherical Small Clean	0.12, 0.26	1.63	1.00
5	Spherical Medium Clean	0.26	1.09	1.00
6	Spherical Medium Clean	0.26, 0.57	0.56	1.00
7	Spherical Medium Clean	0.57	0.10	1.00
8	Spherical Medium Clean	0.57, 1.28	-0.05	1.00
9	Spherical Bimodal Clean	0.12, 1.28	0.82	1.00
10	Spherical Bimodal Clean	0.06, 1.28	1.19	1.00
11	Spherical Small Absorbing	0.06. 0.04	2.87	0.88
12	Spherical Small Absorbing	0.06, 0.12, 0.04	2.50	0.88
13	Spherical Small Absorbing	0.12, 0.04	2.09	0.88
14	Spherical Small Absorbing	0.12, 0.26, 0.04	1.62	0.88
15	Spherical Medium Absorbing	0.26, 0.04	1.13	0.88
16	Spherical Medium Absorbing	0.26, 0.57, 0.04	0.71	0.88
17	Spherical Medium Absorbing	0.57, 0.04	0.29	0.88
18	Dusty Low	0.26, 1.18	1.46	0.97
19	Dusty Low	0.26, 1.18	0.85	0.94
20	Dusty Low	0.26, 1.18	0.33	0.91
21	Dusty Low	1.18	-0.11	0.88
22	Dusty Low	1.18, 7.48	-0.08	0.83
23	Dusty Low	1.18, 7.48	-0.06	0.79
24	Dusty High	1.18	-0.11	0.88

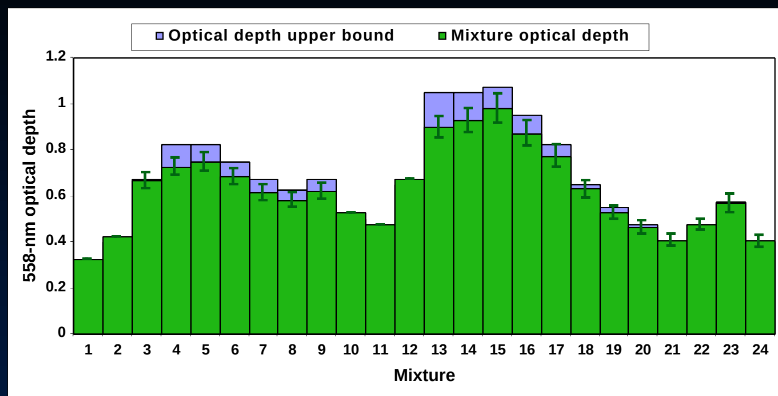
Retrieval case study



Southern Mexico
2 May 2002

558-nm optical depth

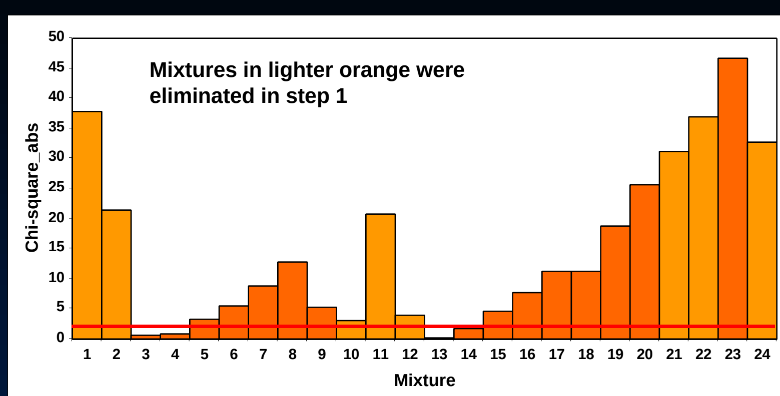
Retrieval case study
Orbit 12616, smoke



Optical depth is a function of aerosol type, so multi-angle and multi-spectral information is used to narrow the range of candidate solutions

Step 1: All 36 channels of MISR are used to establish an optical depth upper bound, and mixtures for which the best-fitting optical exceeds this limit are eliminated

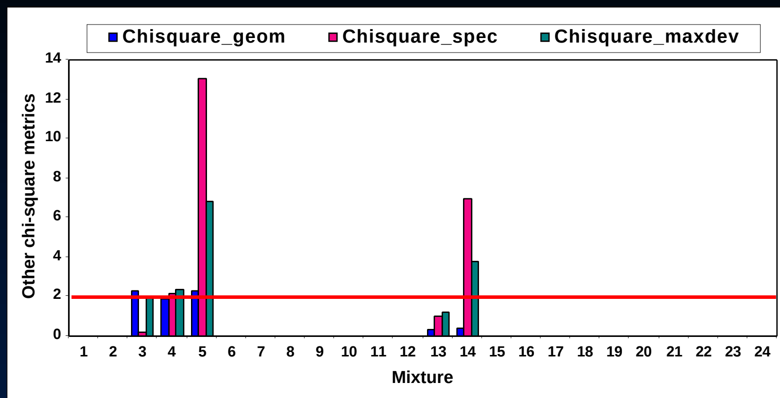
Retrieval case study
Orbit 12616, smoke



Step 2: Mixtures for which the χ^2_{abs} residual exceeds a specified threshold are eliminated

Ideally the threshold is ~1, but with quantized proportions of component particles in the mixtures, this is relaxed so as not to sacrifice coverage

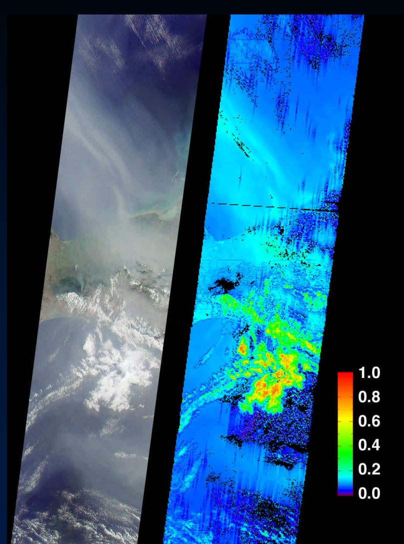
Retrieval case study
Orbit 12616, smoke



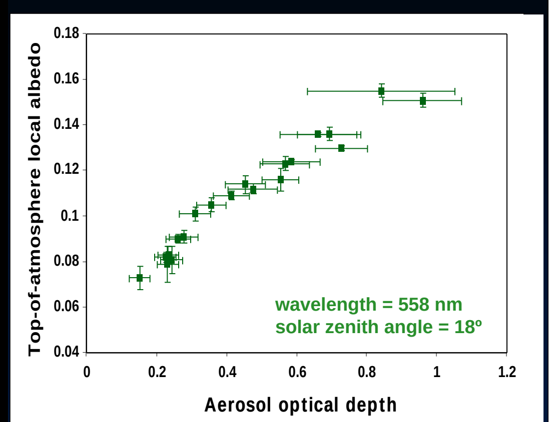
Step 3: Mixtures for which the other χ^2 residuals exceed specified thresholds are eliminated

For this case the best mixture is:
(13) Spherical Small Absorbing

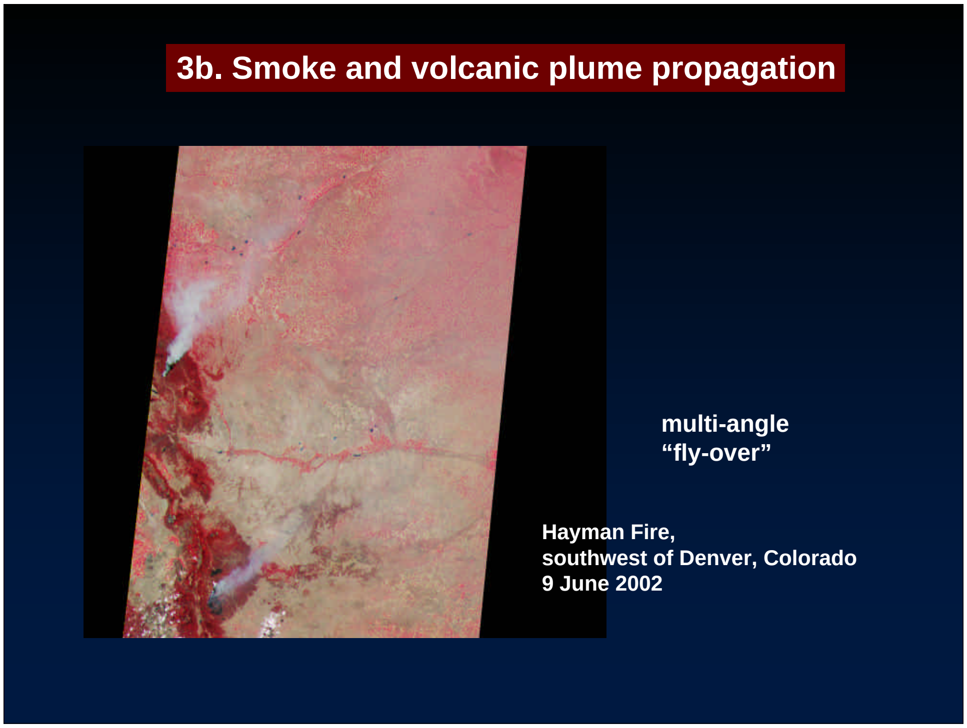
3a. Radiative effects

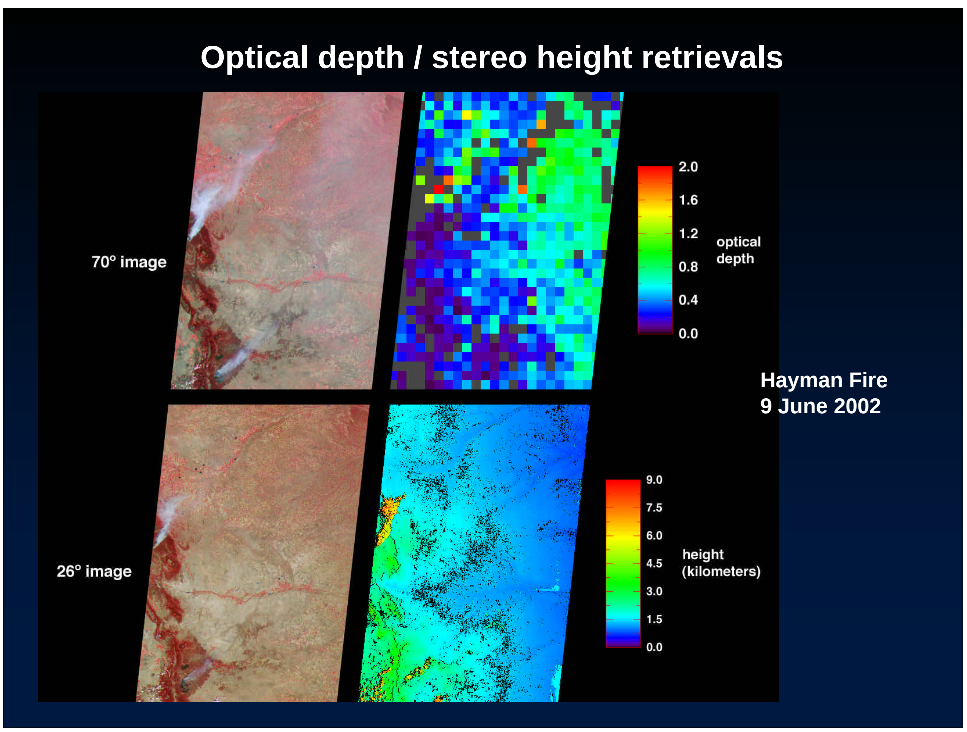


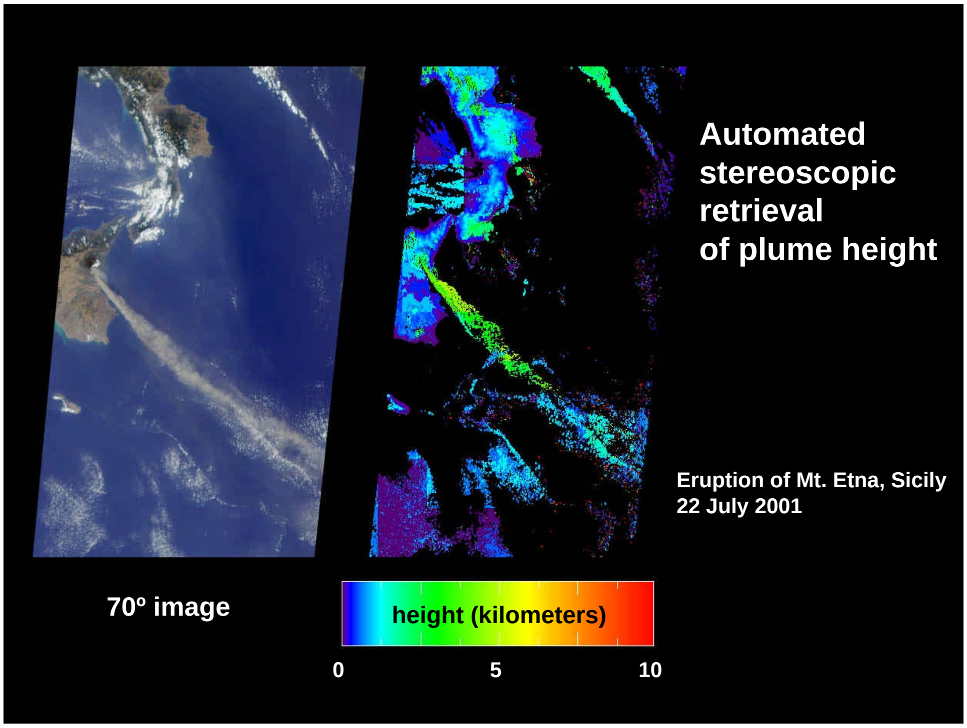
70º backward TOA local albedo

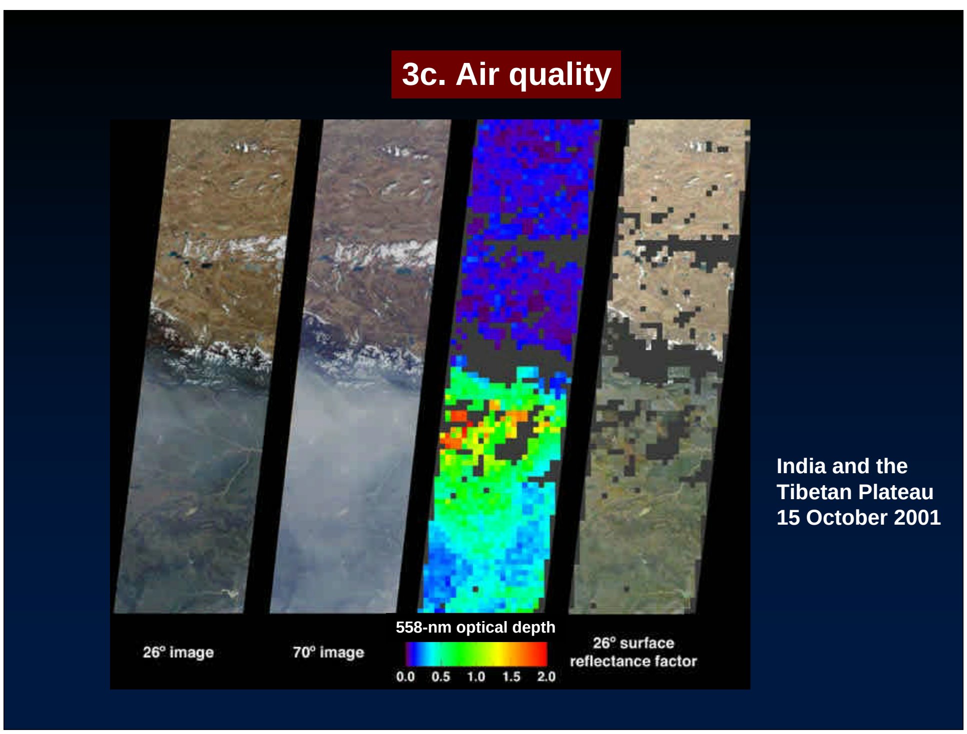


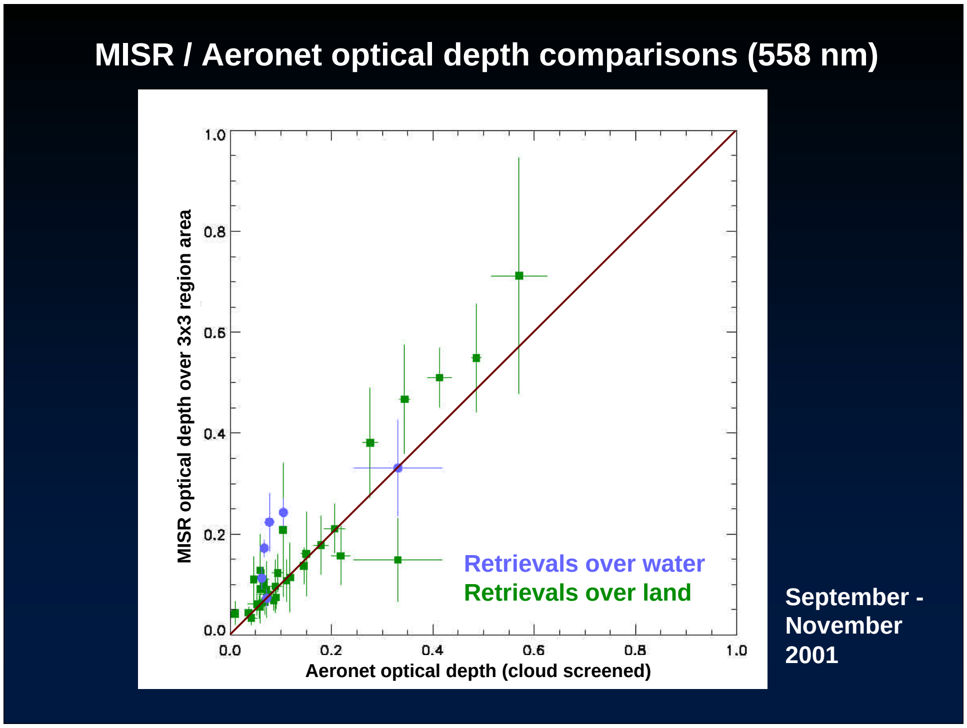
Southern Mexico
2 May 2002

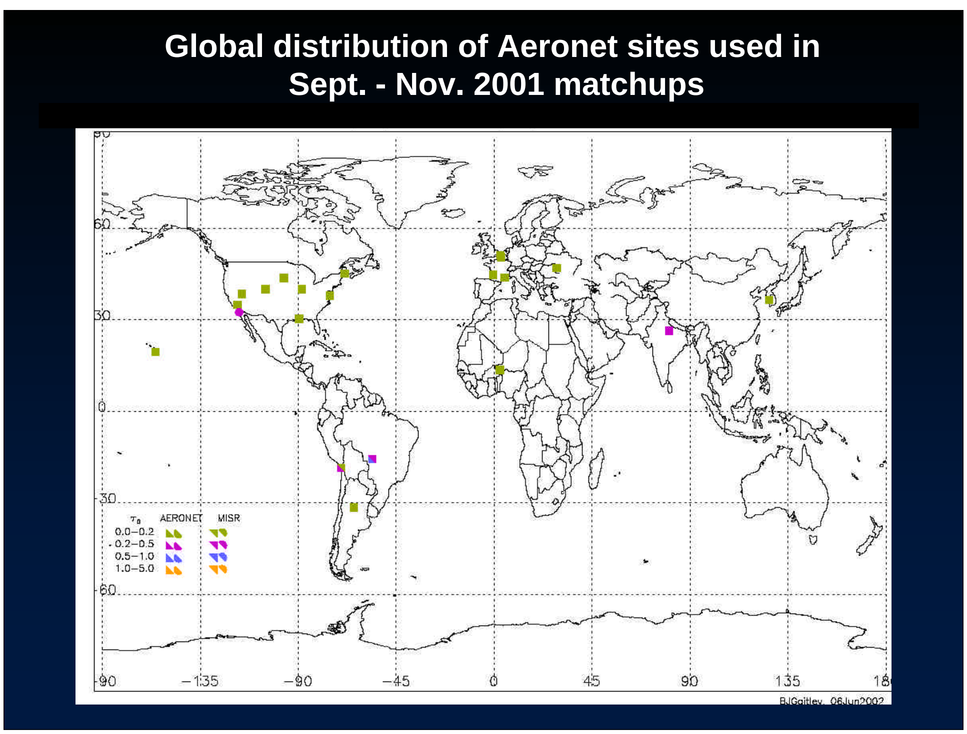

3b. Smoke and volcanic plume propagation
multi-angle
“fly-over”
Hayman Fire,
southwest of Denver, Colorado
9 June 2002


Optical depth / stereo height retrievals
70° image
2.0
1.6
1.2
0.8
0.4
0.0
optical
depth
Hayman Fire
9 June 2002
26° image
9.0
7.5
6.0
4.5
3.0
1.5
0.0
height
(kilometers)


Automated
stereoscopic
retrieval
of plume height
Eruption of Mt. Etna, Sicily
22 July 2001
70º image
height (kilometers)
0
5
10


3c. Air quality
India and the
Tibetan Plateau
15 October 2001
26º image
70º image
558-nm optical depth
0.0 0.5 1.0 1.5 2.0
26º surface
reflectance factor


MISR / Aeronet optical depth comparisons (558 nm)
MISR optical depth over 3x3 region area
Aeronet optical depth (cloud screened)
Retrievals over water
Retrievals over land
September - November 2001


Global distribution of Aeronet sites used in Sept. - Nov. 2001 matchups
AERONET
MISR
0.0–0.2
0.2–0.5
0.5–1.0
1.0–5.0

Summary

MISR aerosol products are based upon new algorithms

- -- novel cloud screening approaches
- -- unprecedented aerosol retrieval approach over land, enabling monitoring of vegetated *and* non-vegetated areas

Products are improving with time as we gain more experience

- -- quality assessment and validation are underway

Much work is in progress or planned

- -- refinement of instrument radiometric and geometric calibration
- -- improved cloud screening, including implementation of multiangular cirrus mask
- -- improvement in retrievals over bright, homogeneous areas
- -- formal validation of retrieval uncertainties and particle property characterizations
- -- improved dust models
- -- comparisons with other satellite instruments

MISR aerosol data products are available
through the Langley Atmospheric Sciences Data Center DAAC
http://eosweb.larc.nasa.gov

More information about MISR
http://www-misr.jpl.nasa.gov