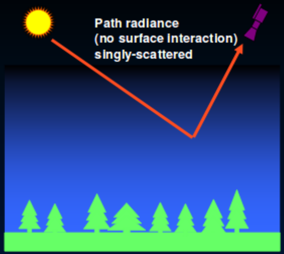
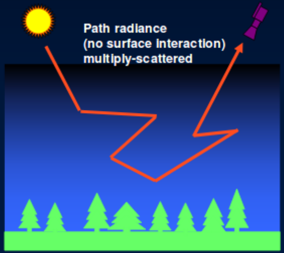
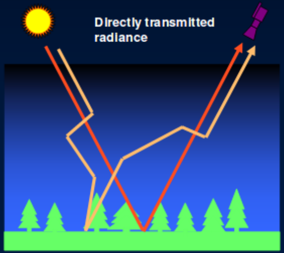
Sensori per aerosol a bordo di satelliti

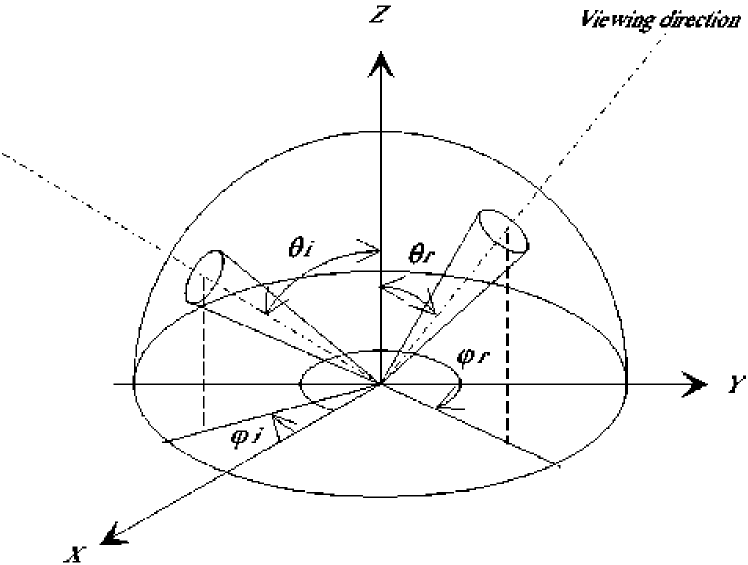
- Lo studio di aerosol da satellite ha avuto inizio dalla necessitá di correggerne l'effetto sulle misure di Ozono e della riflettivitá superficiale
- Nel caso dell'ozono l'assorbimento é largo, per cui l'estinzione da aerosol puó contaminare la misura
- Nel visibile-NIR la radianza dovuta a riflessioni dalla superficie é dello stesso ordine di grandezza (tranne casi particolari) della radianza dovuta all'atmosfera

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









Z
Viewing direction
θ_i
θ_r
φ_r
Y
φ_i
X

Formula per la radianza misurata

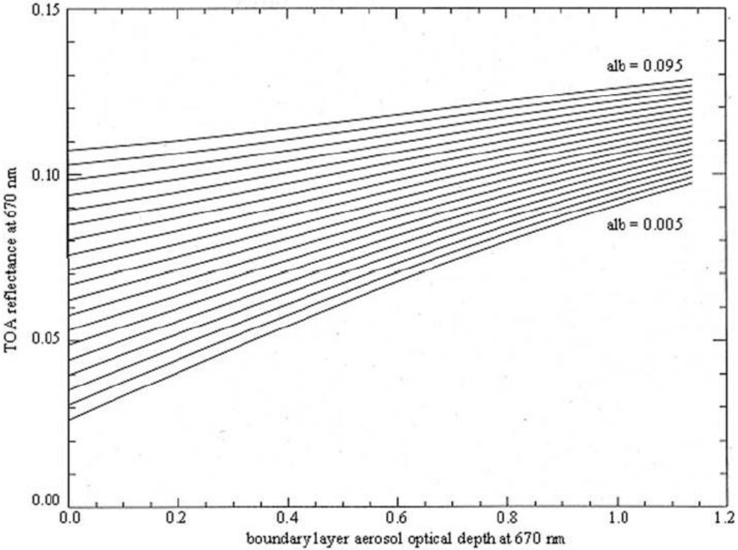
$$L_0(\mu, \phi) = L_0(0, \mu, \phi) + \frac{RF_0(\tau, \mu)}{1 - RS}$$

- L_0 path radiance
- $F_0(\tau), \mu)$ flusso solare alla superficie
- R riflettanza della superficie
- S flusso riflesso dall'atmosfera

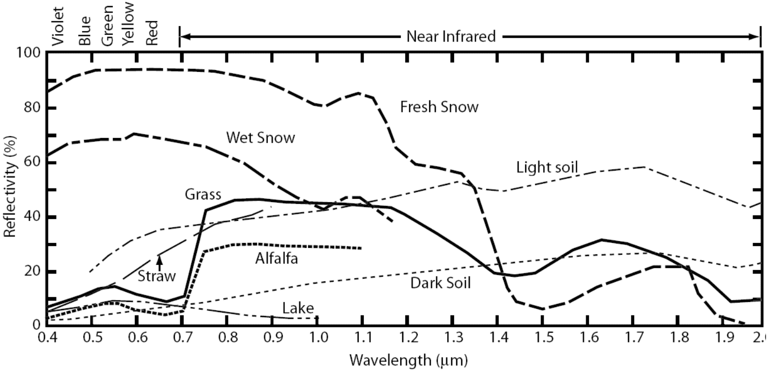
In prima approssimazione la path radiance é data dal singolo scattering, per spessori ottici piccoli:

$$L_0 = \frac{\omega_0}{4\pi} F_0 P(\Theta) \frac{\tau^\star}{\mu}$$

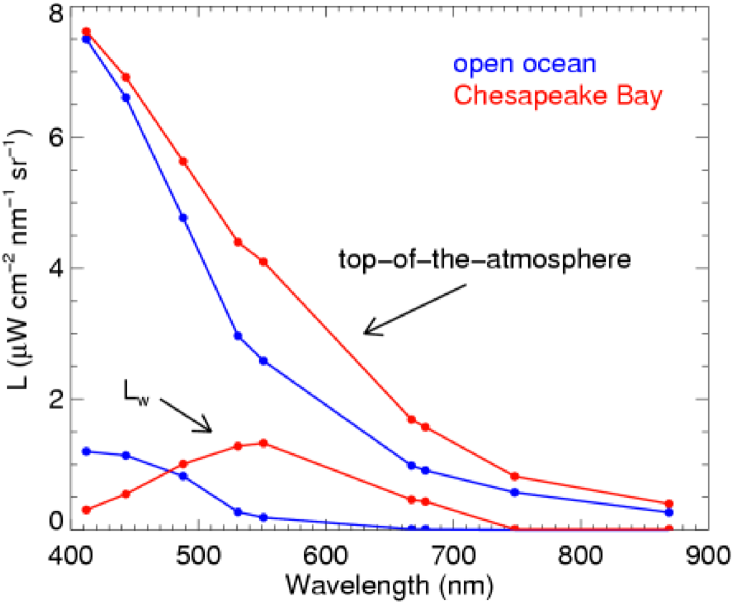
Quindi L_0 dipende sia dall'angolo di scattering che dallo spessore ottico


alb = 0.095
alb = 0.005
0.15
0.10
0.05
0.00
TOA reflectance at 670 nm
0.0
0.2
0.4
0.6
0.8
1.0
1.2
boundary layer aerosol optical depth at 670 nm

Riflettanze superficiali



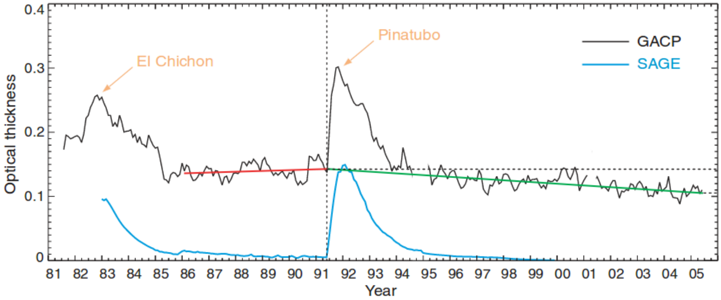
Riflettanze dal mare



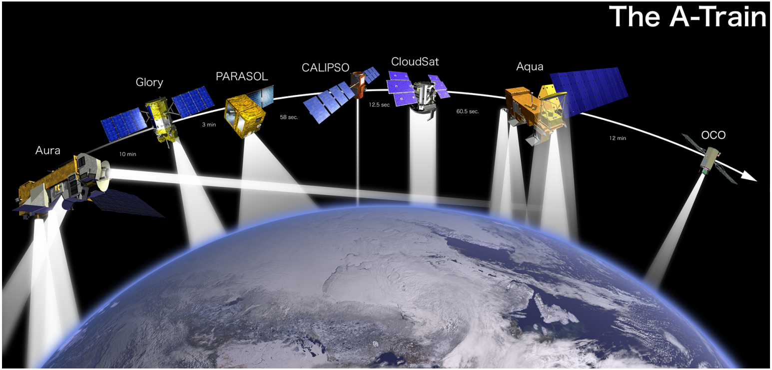
Misure di spessore ottico

- É necessario conoscere la riflettanza superficiale
- É necessario ipotizzare il tipo di aerosol
- Si puó ottenere una misura affidabile solo quando la riflettanza superficiale é piccola (*dark target*, in pratica sul mare nel vicino IR)

Serie a lungo termine di spessori ottici



Satelliti dedicati allo studio dell'atmosfera: A-train



Su ogni satellite sono imbarcati sensori multispettrali attivi e passivi per le diverse zone spettrali.

I dati sono usati per una caratterizzazione completa dell'atmosfera e della superficie.

Sensori dedicati anche agli aerosol

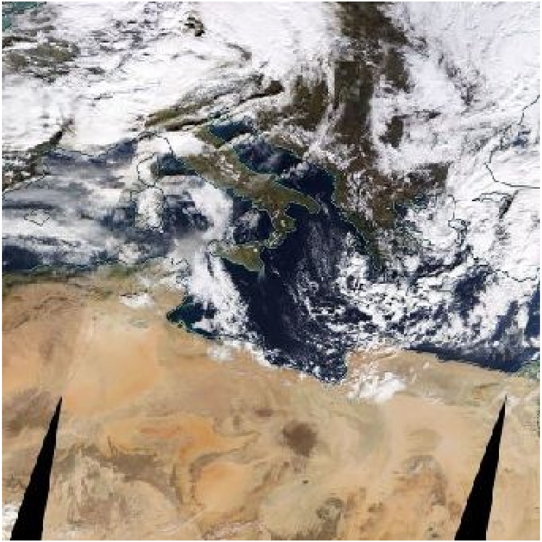
MODIS : MODerate resolution Imaging Spectroradiometer
Sul satellite Aqua e Terra
36 bande spettrali da visibile a IR

MISR : Multi-angle Imaging Spectro-Radiometer Spectrometer
(Su Terra)
4 lunghezze d'onda e 9 angoli di scattering.

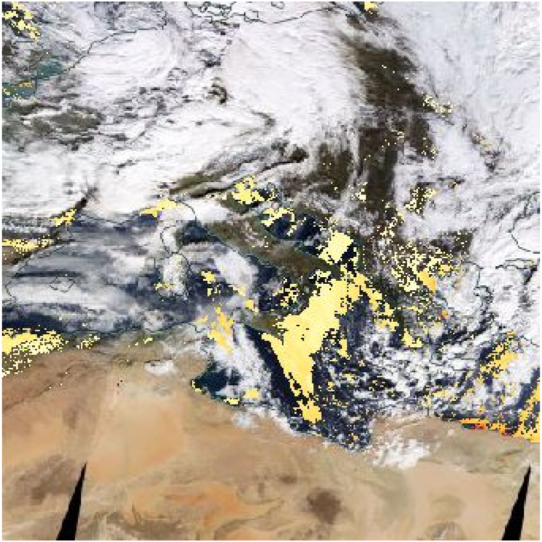
Immagini quasi in tempo reale

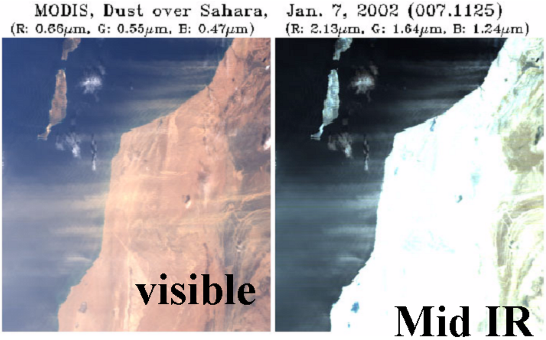
https://worldview.earthdata.nasa.gov

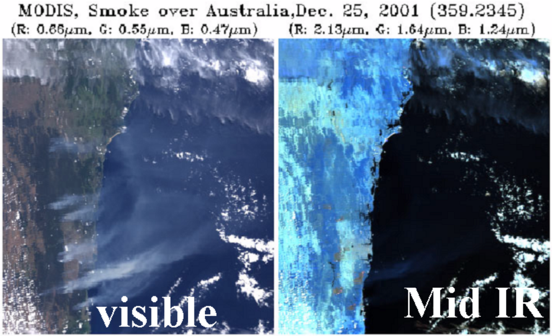
Immagini quasi in tempo reale

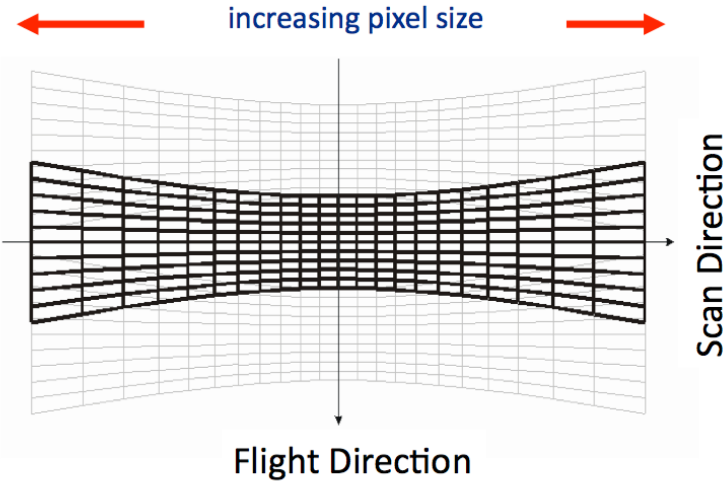


Immagini quasi in tempo reale

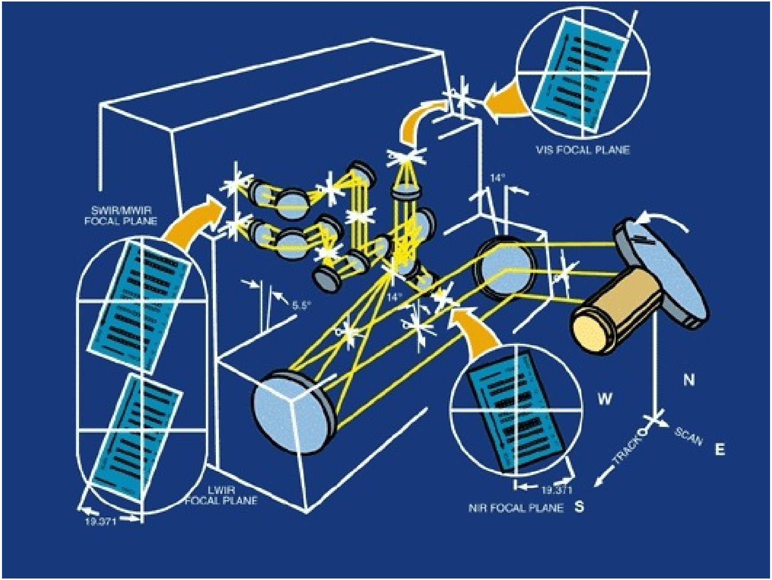



MODIS, Dust over Sahara, Jan. 7, 2002 (007.1125)
(R: 0.66μm, G: 0.55μm, B: 0.47μm)
(R: 2.13μm, G: 1.64μm, B: 1.24μm)
visible
Mid IR

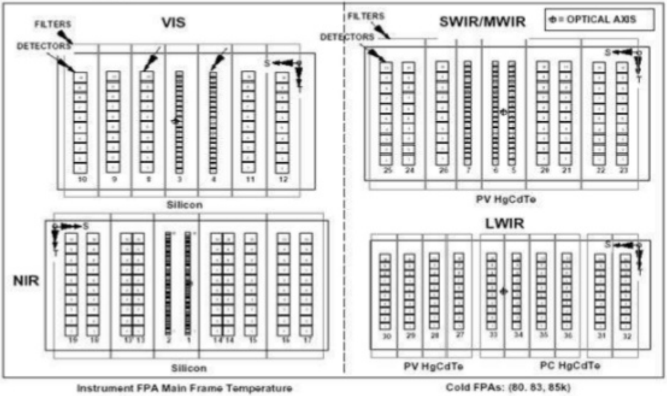

MODIS, Smoke over Australia,Dec. 25, 2001 (359.2345)
(R: 0.66μm, G: 0.55μm, B: 0.47μm)
(R: 2.13μm, G: 1.64μm, B: 1.24μm)
visible
Mid IR



pixel size: 250 m - 1 km (dipende dalla lunghezza d’onda)
larghezza scansione (swath): 2300 km


VIS FOCAL PLANE
SWIR/MWIR
FOCAL PLANE
14°
14°
5.5°
LWIR
FOCAL PLANE
19.371
19.371
NIR FOCAL PLANE
N
W
E
S
SCAN
TRACK

MODIS FOCAL PLANE



S: scan direction; T: track direction

B13 and B14 have 2 columns of detectors for TDI high and low gain output

Bande spettrali di MODIS - solari

Primary Use	Band No.	Bandwidth (nm)	Spectral Radiance	Required SNR
Land/Cloud Boundaries	1**	620-670	21.8	128
	2**	841-876	24.7	201
Land/Cloud Properties	3*	459-479	35.3	243
	4*	545-565	29.0	228
	5*	1230-1250	5.4	74
	6*	1628-1652	7.3	275
	7*	2105-2155	1.0	110
Ocean Color/ Phytoplankton/ Biogeochemistry	8	405-420	44.9	880
	9	438-448	41.9	838
	10	483-493	32.1	802
	11	526-536	27.9	754
	12	546-556	21.0	750
	13	662-672	9.5	910
	14	673-683	8.7	1087
	15	743-753	10.2	586
	16	862-877	6.2	516
Atmospheric Water Vapor	17	890-920	10.0	167
	18	931-941	3.6	57
	19	915-965	15.0	250

Bande spettrali di MODIS - IR termico

Primary Use	Band	Bandwidth (μm)	Spectral Radiance	Required NEDT (K)
Surface/Cloud Temperature	20	3.660-3.840	0.45(300K)	0.05
	21	3.929-3.989	2.38(335K)	2.00
	22	3.929-3.989	0.67(300K)	0.07
	23	4.020-4.080	0.79(300K)	0.07
Atmospheric Temperature	24	4.433-4.498	0.17(250K)	0.25
	25	4.482-4.549	0.59(275K)	0.25
Cirrus Clouds	26	1.360-1.390	6.00	150 (SNR)
Water Vapor	27	6.535-6.895	1.16(240K)	0.25
	28	7.175-7.475	2.18(250K)	0.25
	29	8.400-8.700	9.58(300K)	0.05
Ozone	30	9.580-9.880	3.69(250K)	0.25
Surface/Cloud Temperature	31	10.780-11.280	9.55(300K)	0.05
	32	11.770-12.270	8.94(300K)	0.05
Cloud Top Altitude	33	13.185-13.485	4.52(260K)	0.25
	34	13.485-13.785	3.76(250K)	0.25
	35	13.785-14.085	3.11(240K)	0.25
	36	14.085-14.385	2.08(220K)	0.35

Spectral Radiance values are in W/m^2-um-sr
NEDT = Noise-equivalent temperature difference

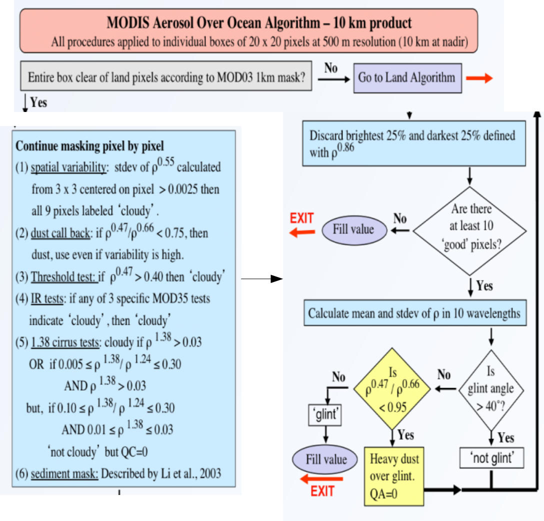
Come si ottengono le proprietá degli aerosol?

- Occorre fare un'ipotesi sulla riflettivitá del terreno (si distinguono i casi di riflettivitá dal mare e dal terreno. Si escludono i casi con nuvole e superfici brillanti)
- Si riduce la complessitá degli aerosol a un certo numero di tipi (size distribution e indice di rifrazione)
- Si variano le combinazioni tra i vari tipi di aerosol in modo da riprodurre al meglio le radianze osservate.
- risultato: spessore ottico a 0.55 nm e frazione del modo fine.
- Sul terreno si ottiene anche la riflettivitá a 2.5 μ

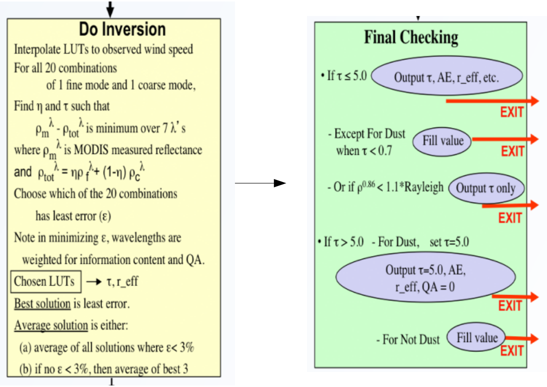
Proprietá degli aerosol usate per MODIS

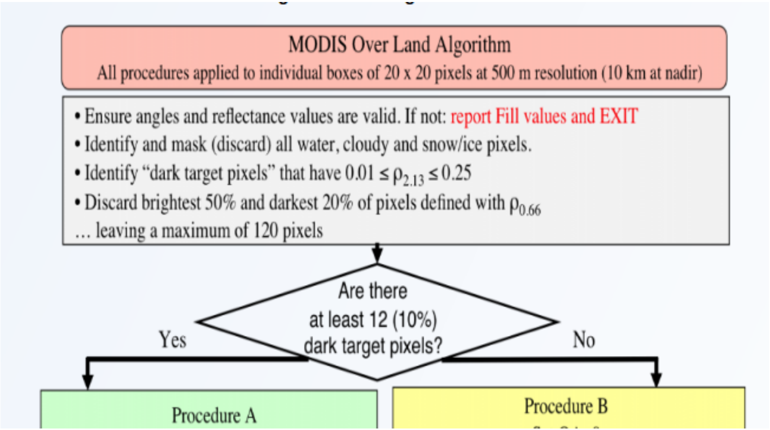
F	λ=0.47-->0.86μm	λ =1.24μm	λ =1.64μm	λ =2.12μm	r_g	σ	r_{eff}	Comments
1	1.45-0.0035i	1.45-0.0035i	1.43-0.01i	1.40-0.005i	0.07	0.40	0.10	Water Soluble
2	1.45-0.0035i	1.45-0.0035i	1.43-0.01i	1.40-0.005i	0.06	0.60	0.15	Water Soluble
3	1.40-0.0020i	1.40-0.0020i	1.39-0.005i	1.36-0.003i	0.08	0.60	0.20	Water Soluble with humidity
4	1.40-0.0020i	1.40-0.0020i	1.39-0.005i	1.36-0.003i	0.10	0.60	0.25	Water Soluble with humidity

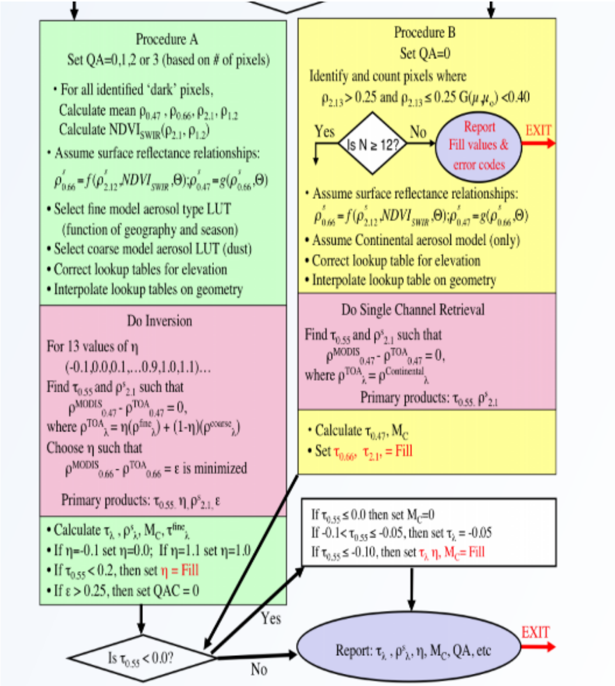
C	λ =0.47-->0.86μm	λ =1.24μm	λ =1.64μm	λ =2.12μm	r_g	σ	r_{eff}	Comments
5	1.35-0.001i	1.35-0.001i	1.35-0.001i	1.35-0.001i	0.40	0.60	0.98	Wet sea salt type
6	1.35-0.001i	1.35-0.001i	1.35-0.001i	1.35-0.001i	0.60	0.60	1.48	Wet sea salt type
7	1.35-0.001i	1.35-0.001i	1.35-0.001i	1.35-0.001i	0.80	0.60	1.98	Wet sea salt type
8	1.53-0.003i (0.47) 1.53-0.001i (0.55) 1.53-0.000i (0.66) 1.53-0.000i (0.86)	1.46-0.000i	1.46-0.001i	1.46-0.000i	0.60	0.60	1.48	Dust-like type
9	1.53-0.003i (0.47) 1.53-0.001i (0.55) 1.53-0.000i (0.66) 1.53-0.000i (0.86)	1.46-0.000i	1.46-0.001i	1.46-0.000i	0.50	0.80	2.50	Dust-like type

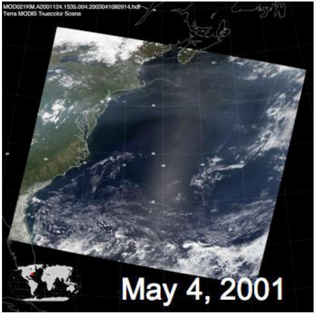


MODIS Aerosol Over Ocean Algorithm – 10 km product
All procedures applied to individual boxes of 20 x 20 pixels at 500 m resolution (10 km at nadir)
Entire box clear of land pixels according to MOD03 1km mask?
No
Go to Land Algorithm
Yes
Continue masking pixel by pixel
(1) spatial variability: stdev of ρ0.55 calculated from 3 x 3 centered on pixel > 0.0025 then all 9 pixels labeled 'cloudy'.
(2) dust call back: if ρ0.47/ρ0.66 < 0.75, then dust, use even if variability is high.
(3) Threshold test: if ρ0.47 > 0.40 then 'cloudy'
(4) IR tests: if any of 3 specific MOD35 tests indicate 'cloudy', then 'cloudy'
(5) 1.38 cirrus tests: cloudy if ρ 1.38 > 0.03
OR if 0.005 ≤ ρ 1.38/ ρ 1.24 ≤ 0.30
AND ρ 1.38 > 0.03
but, if 0.10 ≤ ρ 1.38/ ρ 1.24 ≤ 0.30
AND 0.01 ≤ ρ 1.38 ≤ 0.03
'not cloudy' but QC=0
(6) sediment mask: Described by Li et al., 2003
Discard brightest 25% and darkest 25% defined with ρ0.86
Are there at least 10 'good' pixels?
No
Fill value
EXIT
Yes
Calculate mean and stdev of ρ in 10 wavelengths
Is glint angle > 40°?
No
Is ρ0.47 / ρ0.66 < 0.95
No
'glint'
Fill value
EXIT
Yes
Heavy dust over glint. QA=0
Yes
'not glint'

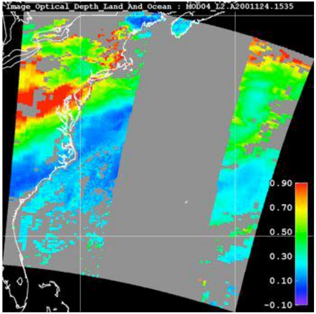

Do Inversion
Interpolate LUTs to observed wind speed
For all 20 combinations
of 1 fine mode and 1 coarse mode,
Find η and τ such that
$\rho_m^\lambda - \rho_{tot}^\lambda$ is minimum over 7 λ's
where ρ_m^λ is MODIS measured reflectance
and $\rho_{tot}^\lambda = \eta\rho_f^\lambda + (1-\eta)\rho_c^\lambda$
Choose which of the 20 combinations
has least error (ε)
Note in minimizing ε, wavelengths are
weighted for information content and QA.
Chosen LUTs → τ, r_eff
Best solution is least error.
Average solution is either:
(a) average of all solutions where ε< 3%
(b) if no ε < 3%, then average of best 3
Final Checking
• If τ ≤ 5.0
Output τ, AE, r_eff, etc.
EXIT
- Except For Dust
when τ < 0.7
Fill value
EXIT
- Or if $\rho^{0.86}$ < 1.1*Rayleigh
Output τ only
EXIT
• If τ > 5.0 - For Dust, set τ=5.0
Output τ=5.0, AE,
r_eff, QA = 0
EXIT
- For Not Dust
Fill value
EXIT


MODIS Over Land Algorithm
All procedures applied to individual boxes of 20 x 20 pixels at 500 m resolution (10 km at nadir)
• Ensure angles and reflectance values are valid. If not: report Fill values and EXIT
• Identify and mask (discard) all water, cloudy and snow/ice pixels.
• Identify "dark target pixels" that have 0.01 ≤ ρ2.13 ≤ 0.25
• Discard brightest 50% and darkest 20% of pixels defined with ρ0.66
… leaving a maximum of 120 pixels
Are there at least 12 (10%) dark target pixels?
Yes
No
Procedure A
Procedure B

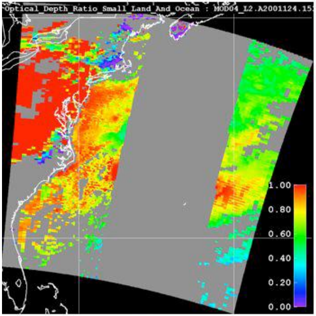

Procedure A
Set QA=0,1,2 or 3 (based on # of pixels)
• For all identified 'dark' pixels,
Calculate mean $\rho_{0.47}$, $\rho_{0.66}$, $\rho_{2.1}$, $\rho_{1.2}$
Calculate $NDVI_{SWIR}(\rho_{2.1}, \rho_{1.2})$
• Assume surface reflectance relationships:
$\rho^{s}_{0.66} = f(\rho^{s}_{2.12}, NDVI_{SWIR}, \Theta); \rho^{s}_{0.47} = g(\rho^{s}_{0.66}, \Theta)$
• Select fine model aerosol type LUT
(function of geography and season)
• Select coarse model aerosol LUT (dust)
• Correct lookup tables for elevation
• Interpolate lookup tables on geometry
Do Inversion
For 13 values of η
(-0.1,0.0,0.1,...0.9,1.0,1.1)...
Find $\tau_{0.55}$ and $\rho^{s}_{2.1}$ such that
$\rho^{MODIS}_{0.47} - \rho^{TOA}_{0.47} = 0$,
where $\rho^{TOA}_{\lambda} = \eta(\rho^{fine}_{\lambda}) + (1-\eta)(\rho^{coarse}_{\lambda})$
Choose η such that
$\rho^{MODIS}_{0.66} - \rho^{TOA}_{0.66} = \varepsilon$ is minimized
Primary products: $\tau_{0.55}$, η, $\rho^{s}_{2.1}$, ε
• Calculate τ_{λ}, ρ^{s}_{λ}, M_C, τ^{fine}_{λ}
• If η=-0.1 set η=0.0; If η=1.1 set η=1.0
• If $\tau_{0.55} < 0.2$, then set η = Fill
• If ε > 0.25, then set QAC = 0
Is $\tau_{0.55} < 0.0$?
Yes
No
Procedure B
Set QA=0
Identify and count pixels where
$\rho_{2.13} > 0.25$ and $\rho_{2.13} \leq 0.25\ G(\mu, \mu_0) < 0.40$
Yes
Is N ≥ 12?
No
Report
Fill values &
error codes
EXIT
• Assume surface reflectance relationships:
$\rho^{s}_{0.66} = f(\rho^{s}_{2.12}, NDVI_{SWIR}, \Theta); \rho^{s}_{0.47} = g(\rho^{s}_{0.66}, \Theta)$
• Assume Continental aerosol model (only)
• Correct lookup table for elevation
• Interpolate lookup table on geometry
Do Single Channel Retrieval
Find $\tau_{0.55}$ and $\rho^{s}_{2.1}$ such that
$\rho^{MODIS}_{0.47} - \rho^{TOA}_{0.47} = 0$,
where $\rho^{TOA}_{\lambda} = \rho^{Continental}_{\lambda}$
Primary products: $\tau_{0.55}$, $\rho^{s}_{2.1}$
• Calculate $\tau_{0.47}$, M_C
• Set $\tau_{0.66}$, $\tau_{2.1}$, = Fill
If $\tau_{0.55} \leq 0.0$ then set M_C=0
If $-0.1 < \tau_{0.55} \leq -0.05$, then set $\tau_{\lambda} = -0.05$
If $\tau_{0.55} \leq -0.10$, then set τ_{λ}, η, M_C= Fill
Report: τ_{λ}, ρ^{s}_{λ}, η, M_C, QA, etc
EXIT



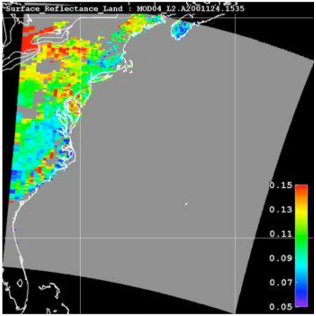
A) RGB: $\rho^M(0.66, 0.55, 0.47\ \mu m)$



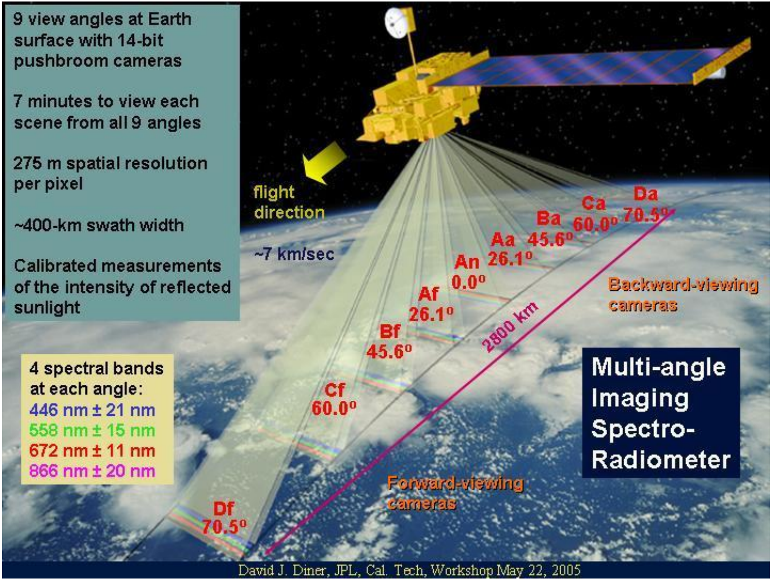
B) $\tau(0.55\ \mu m)$

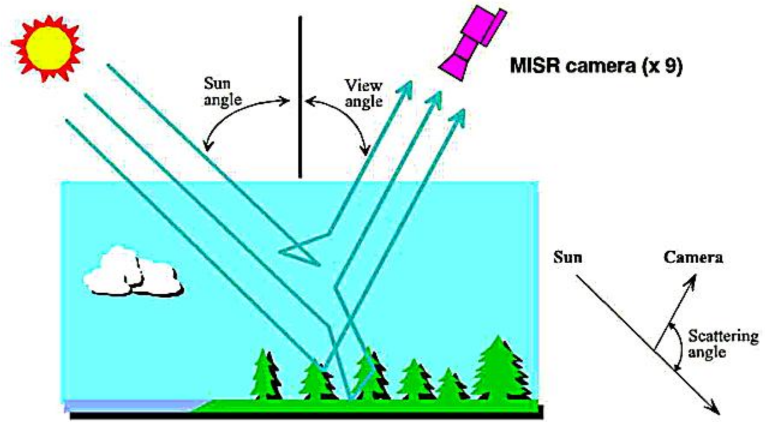


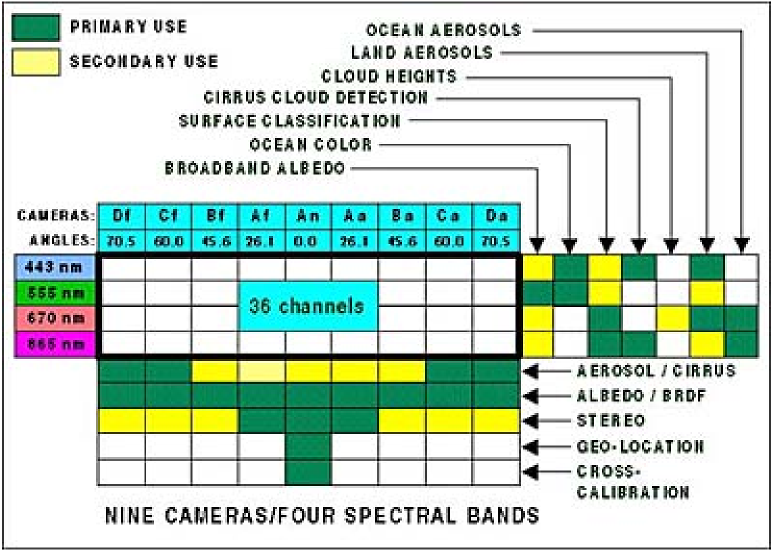
C) $\eta(0.55\ \mu m)$

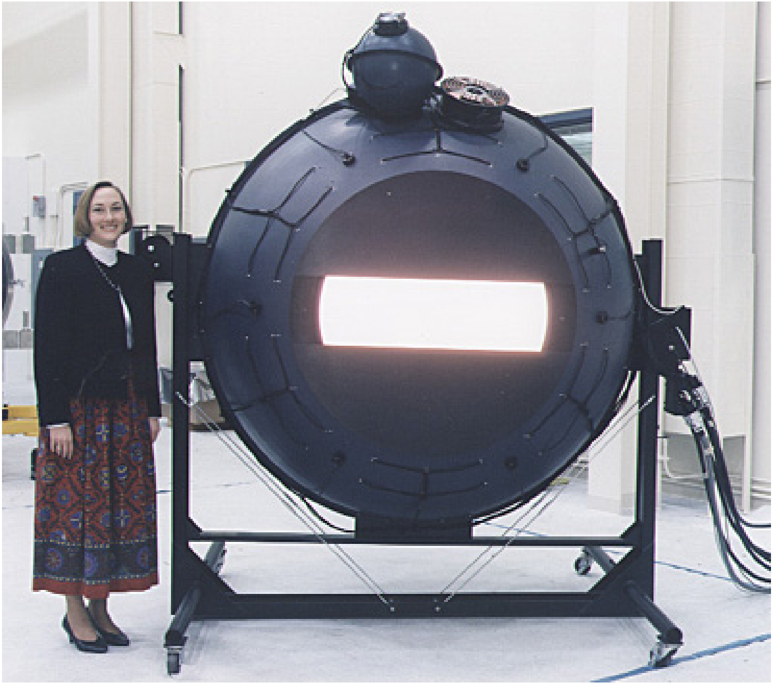


D) $\rho^s\ (2.1\ \mu m)$

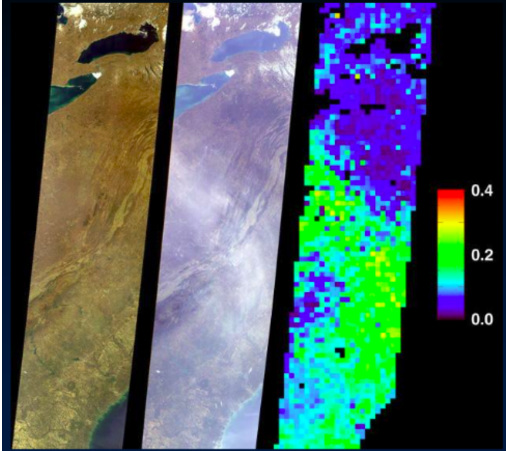

9 view angles at Earth surface with 14-bit pushbroom cameras
7 minutes to view each scene from all 9 angles
275 m spatial resolution per pixel
~400-km swath width
Calibrated measurements of the intensity of reflected sunlight
4 spectral bands at each angle:
446 nm ± 21 nm
558 nm ± 15 nm
672 nm ± 11 nm
866 nm ± 20 nm
flight direction
~7 km/sec
Da 70.5°
Ca 60.0°
Ba 45.6°
Aa 26.1°
An 0.0°
Af 26.1°
Bf 45.6°
Cf 60.0°
Df 70.5°
2800 km
Backward-viewing cameras
Forward-viewing cameras
Multi-angle Imaging Spectro-Radiometer
David J. Diner, JPL, Cal. Tech, Workshop May 22, 2005


MISR camera (x 9)
Sun angle
View angle
Sun
Camera
Scattering angle


PRIMARY USE
SECONDARY USE
OCEAN AEROSOLS
LAND AEROSOLS
CLOUD HEIGHTS
CIRRUS CLOUD DETECTION
SURFACE CLASSIFICATION
OCEAN COLOR
BROADBAND ALBEDO
CAMERAS: Df Cf Bf Af An Aa Ba Ca Da
ANGLES: 70.5 60.0 45.6 26.1 0.0 26.1 45.6 60.0 70.5
443 nm
555 nm
670 nm
865 nm
36 channels
AEROSOL / CIRRUS
ALBEDO / BRDF
STEREO
GEO-LOCATION
CROSS-CALIBRATION
NINE CAMERAS/FOUR SPECTRAL BANDS



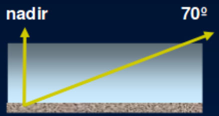
1c. Enhancing sensitivity to thin aerosols



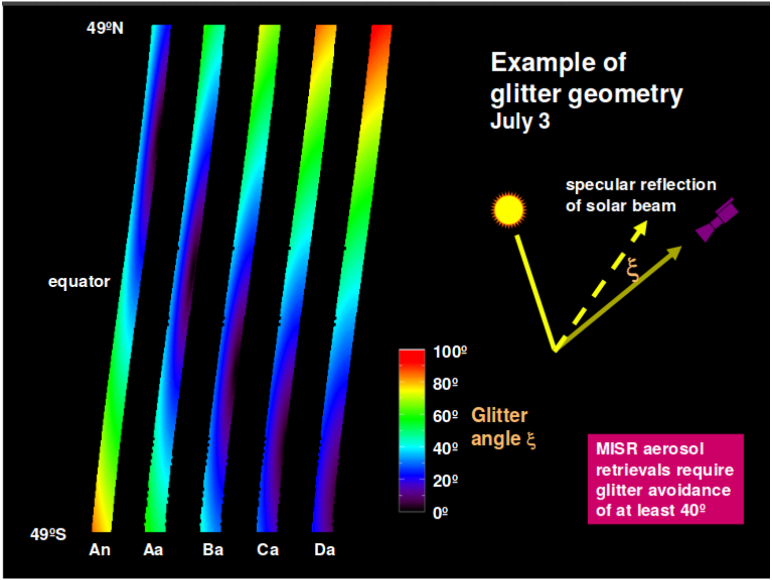
nadir 70º 558-nm aerosol optical depth

Thin haze over land is difficult to detect in the nadir view due to the brightness of the land surface

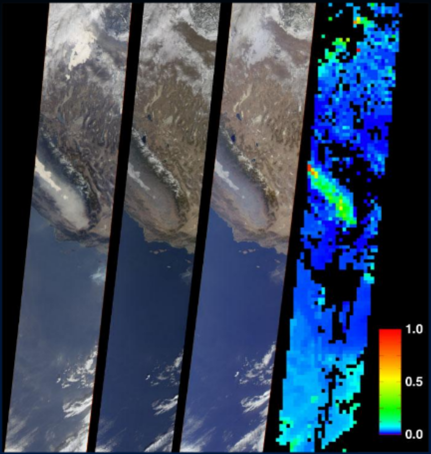
The longer atmospheric path length enhances the haze path radiance



Appalachians,
6 March 2000


49ºN
equator
49ºS
An
Aa
Ba
Ca
Da
Example of
glitter geometry
July 3
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

2a. Accounting for the surface contribution to TOA radiances

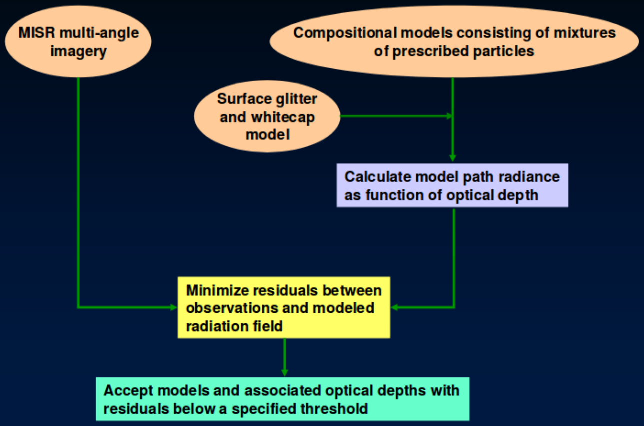


70º forward   nadir   70º backward   558-nm optical depth

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

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

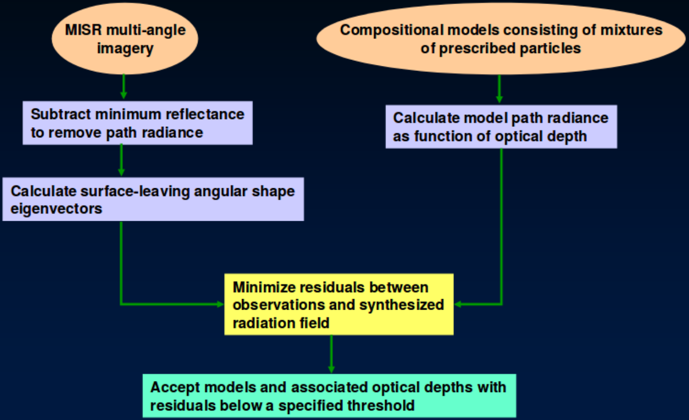
where $L_{surface}$ is modeled as a prescribed contribution from sunglint and whitecaps

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



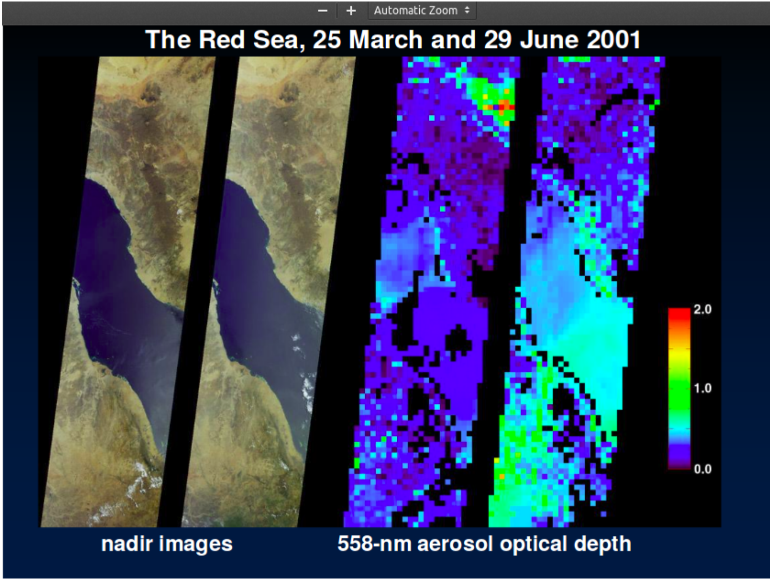
Goodness of fit metric

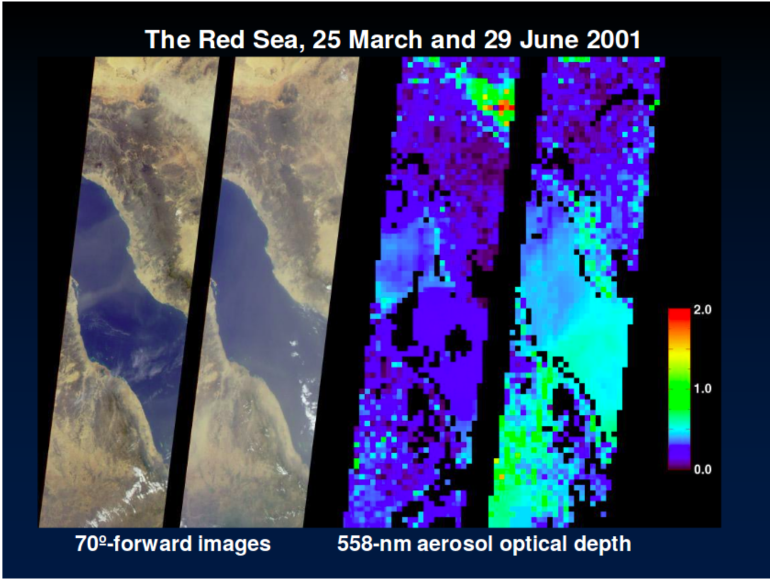
$$\chi^2_{het} = N^{-1}_{channels} \sum_{angle} \sum_{band} [L_{MISR} - L_{path} - L_{surface}]^2 / [0.05 L_{MISR}]^2$$

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

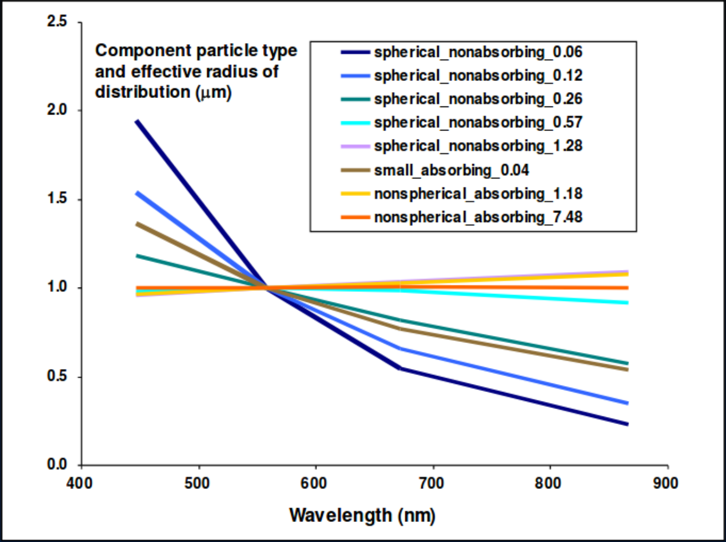

Automatic Zoom
The Red Sea, 25 March and 29 June 2001
2.0
1.0
0.0
nadir images
558-nm aerosol optical depth


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

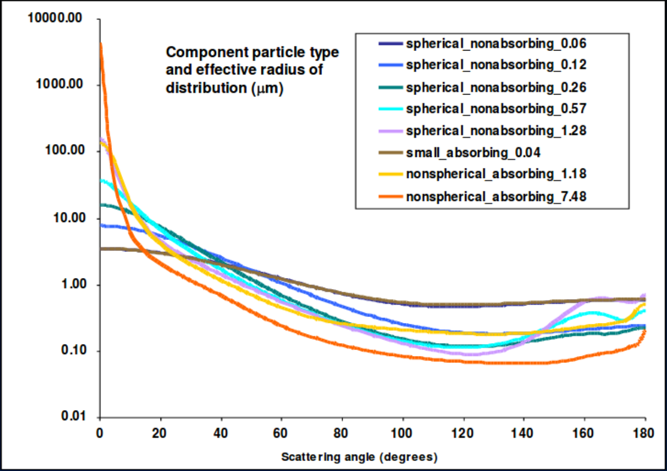
24 mixtures used in retrievals

		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

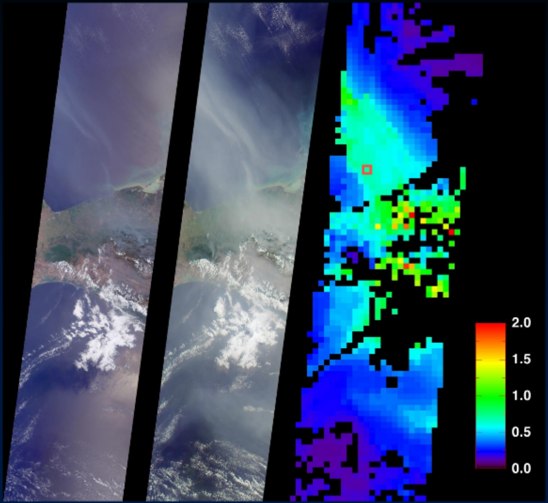
Spectral extinction of component aerosols relative to 558 nm



Scattering phase functions of component aerosols



Retrieval case study

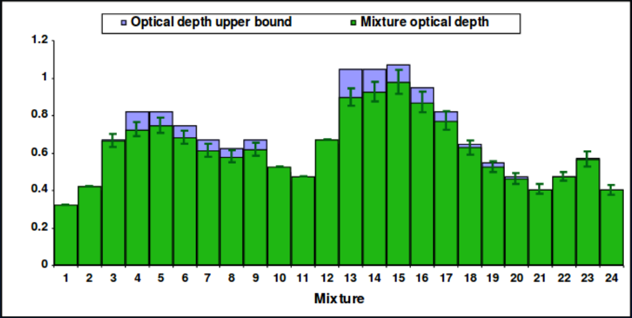


Southern Mexico
2 May 2002

558-nm optical depth

Retrieval case study

Orbit 12616, smoke

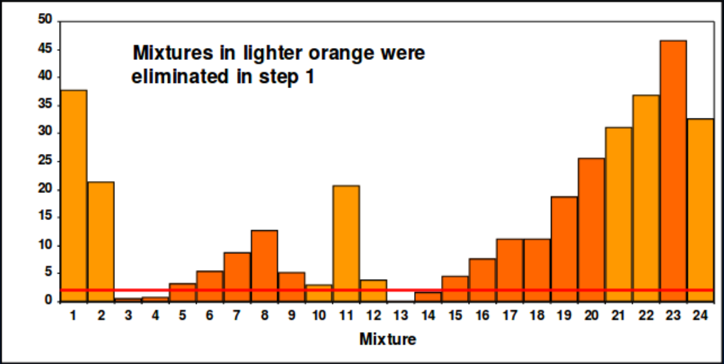


Optical depth is a function of aerosol type, so multi-angle and multi-spectral information is used to narrow the range of candidate solutions

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

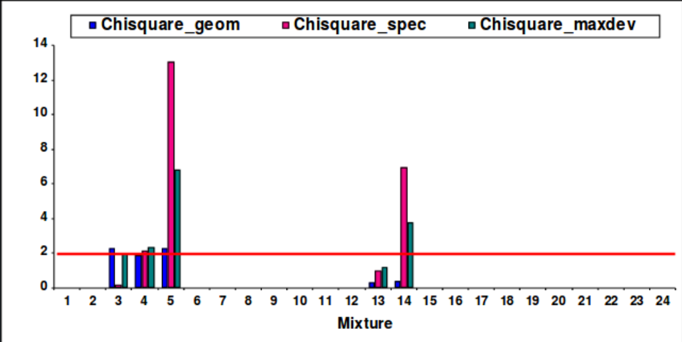


Step 2: Mixtures for which the χ^2_{abs} residual exceeds a specified threshold are eliminated

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

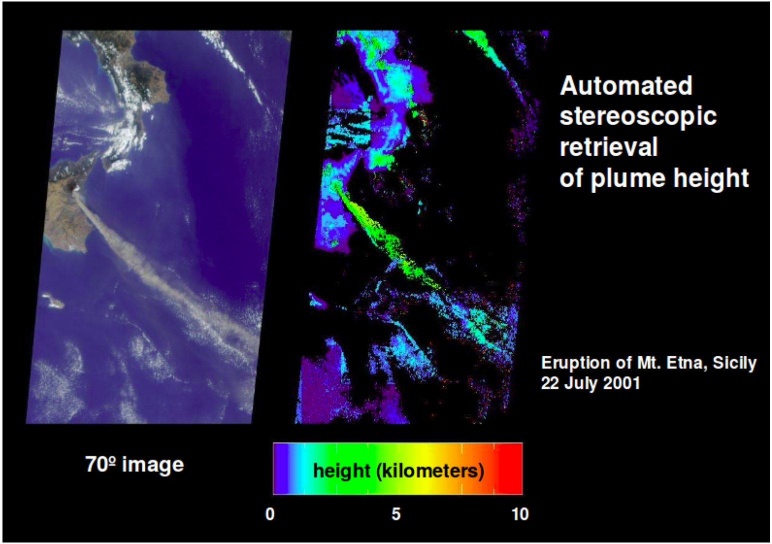
Retrieval case study

Orbit 12616, smoke

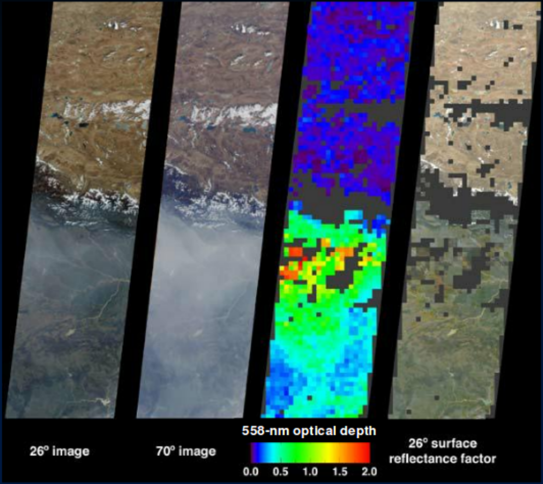


Step 3: Mixtures for which the other χ^2 residuals exceed specified thresholds are eliminated

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


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