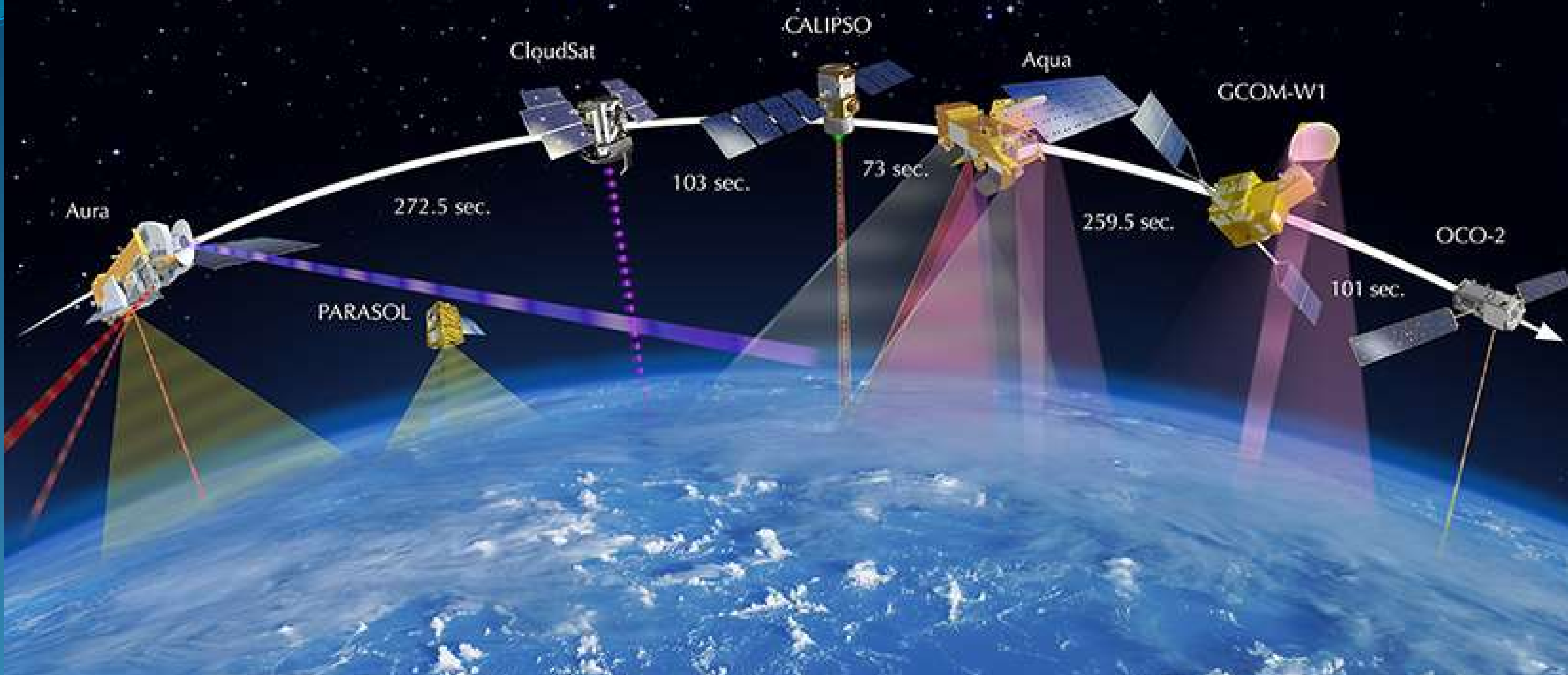
MET 611 – Satellite Data Applications



MODIS Aerosol Introduction

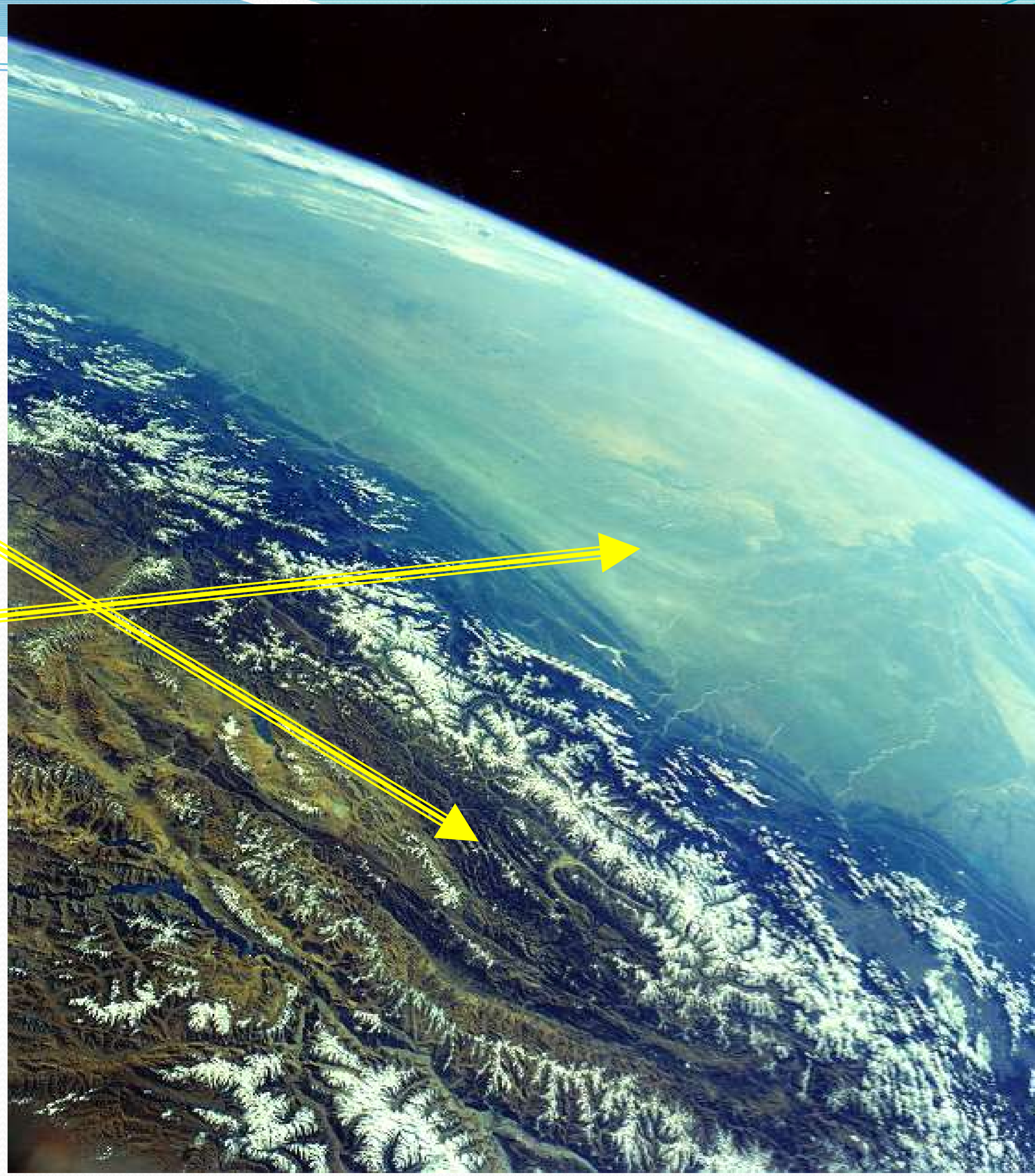
Jennifer D. S. Griswold

What are aerosols and where are they from ?

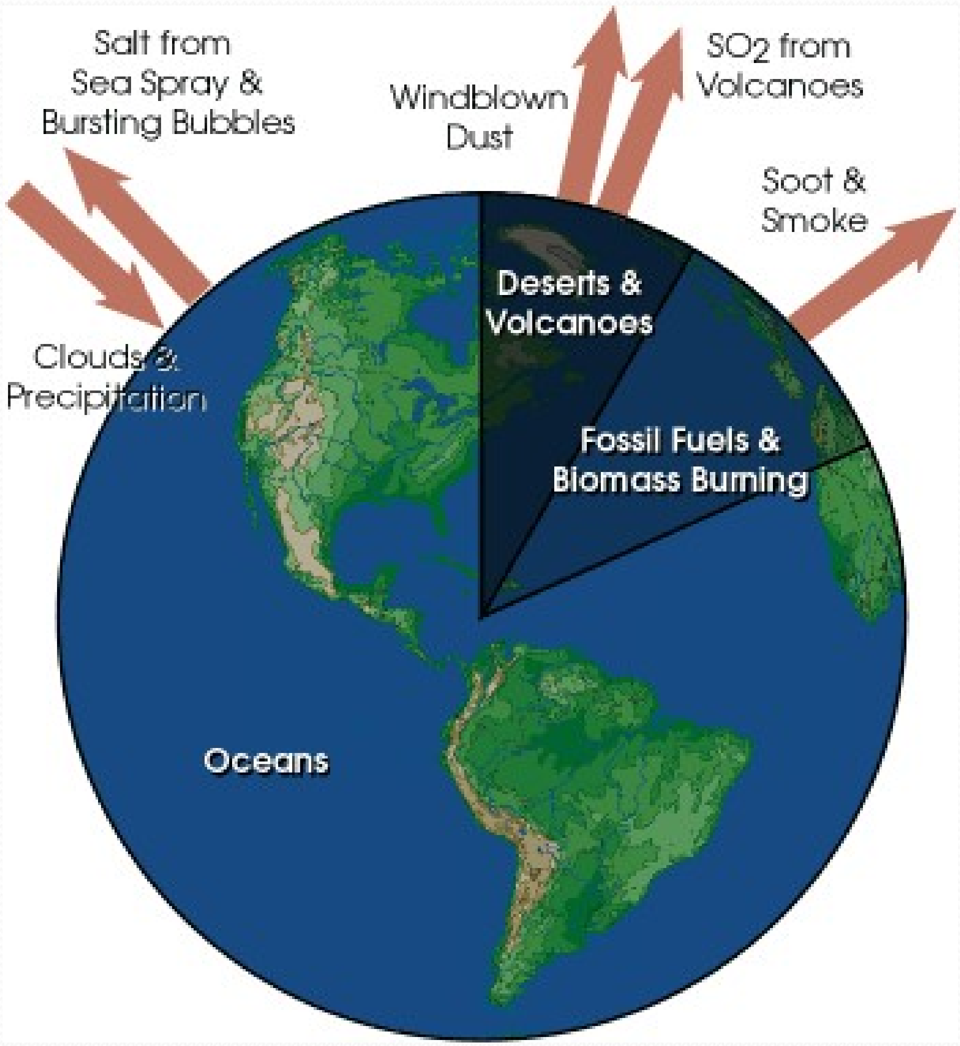
Pollution

- The view from Tibet
- Sea of pollution Over India

Image from the Shuttle



Aerosol Types and Origins



- Aerosol particles larger than about 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 (released from volcanic eruptions) to sulfate particles and by formation of soot and smoke during burning processes.
- After formation, the aerosols are mixed and transported by atmospheric motions and are primarily removed by cloud and precipitation processes.

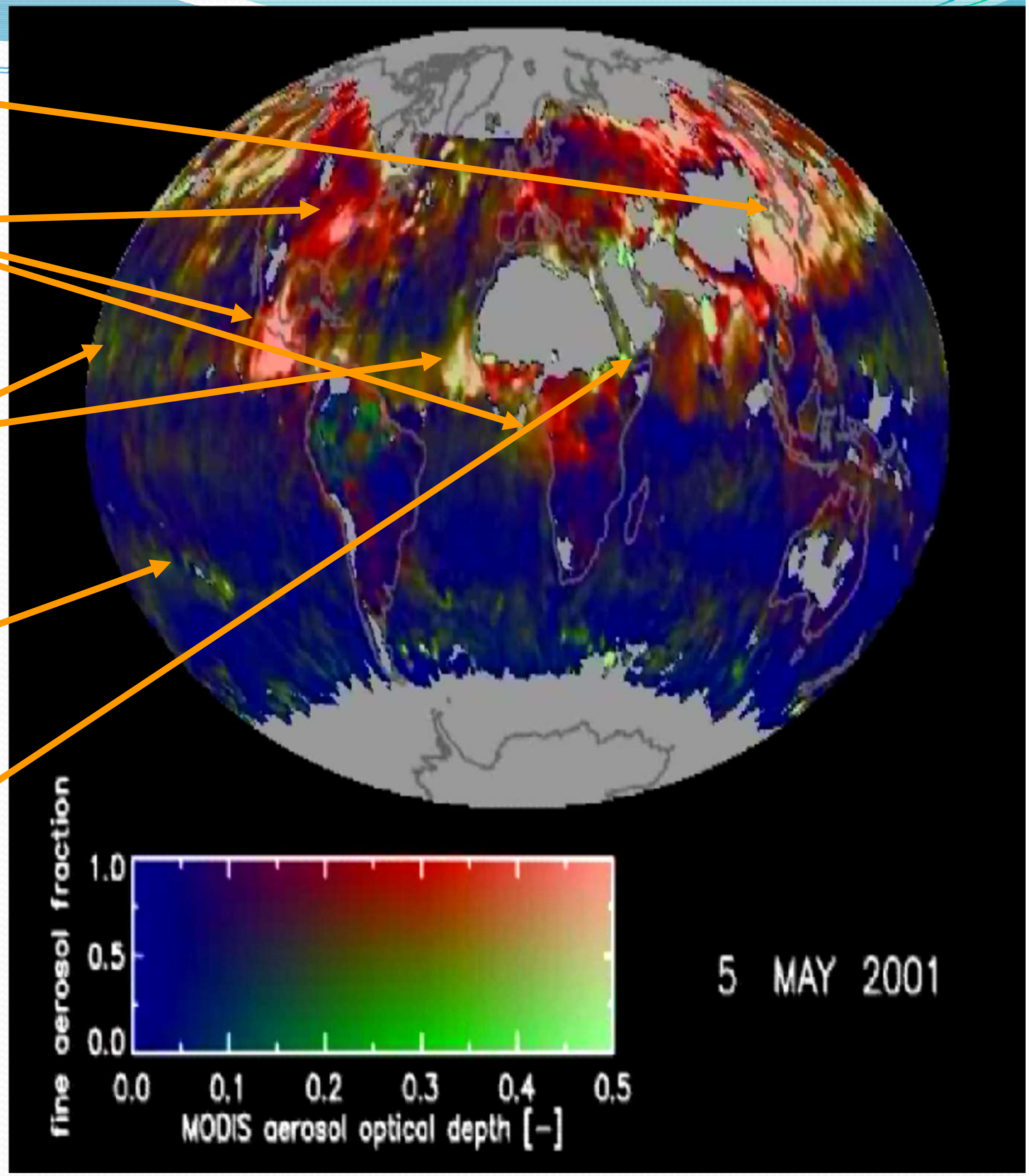
Pollution/dust in China

Smoke
Pollution

Saharan dust

Sea Salt

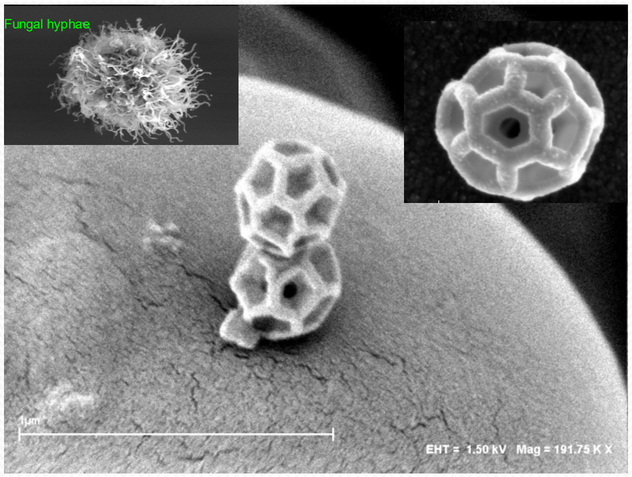
Pollution/dust in India

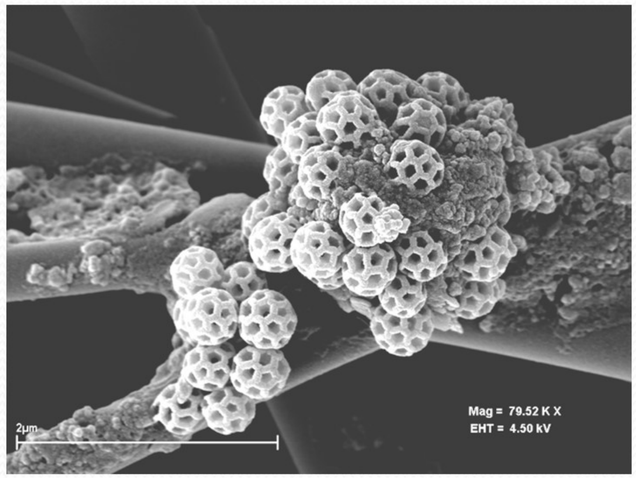


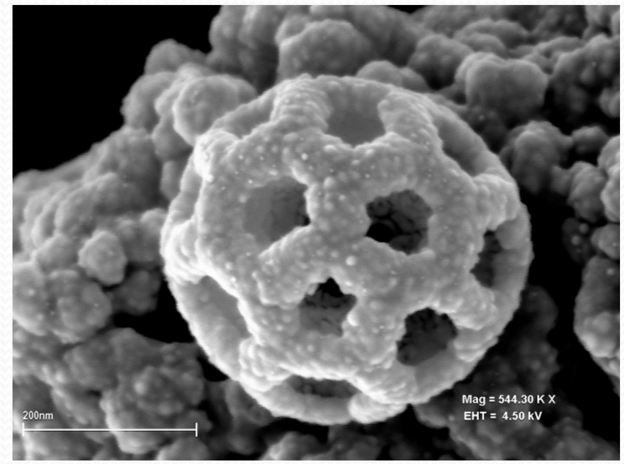
Dust and smoke are Transported to the North-East Atlantic. From MODIS

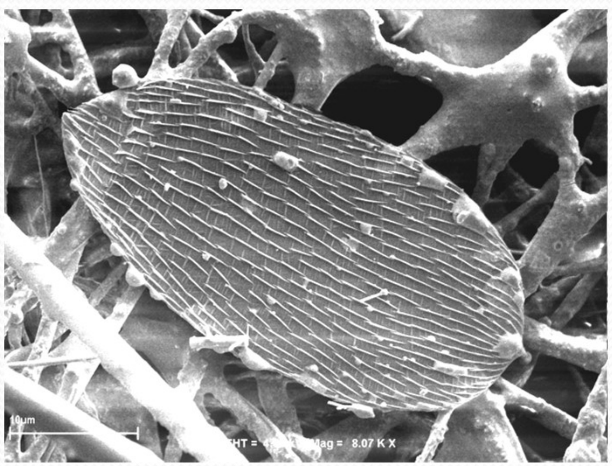
Natural Biogenic Aerosol

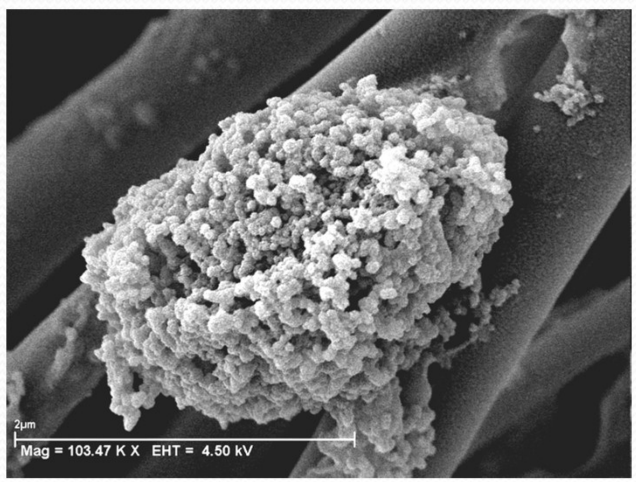
Wherever you have trees or vegetation, these particles are there.
These are from Brazil.

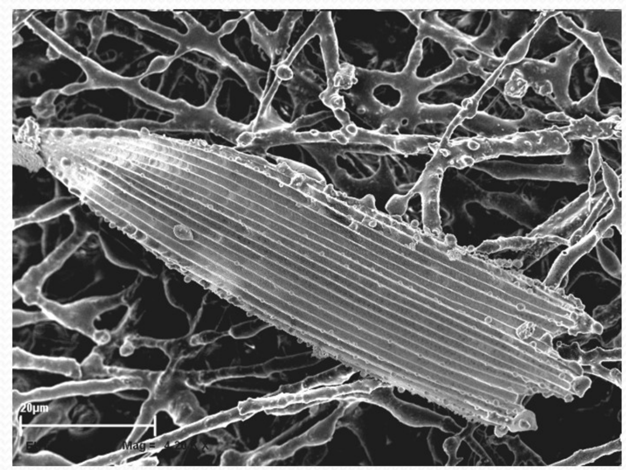












photos from Gunther Helas, MPIC

Aerosol Size Distribution

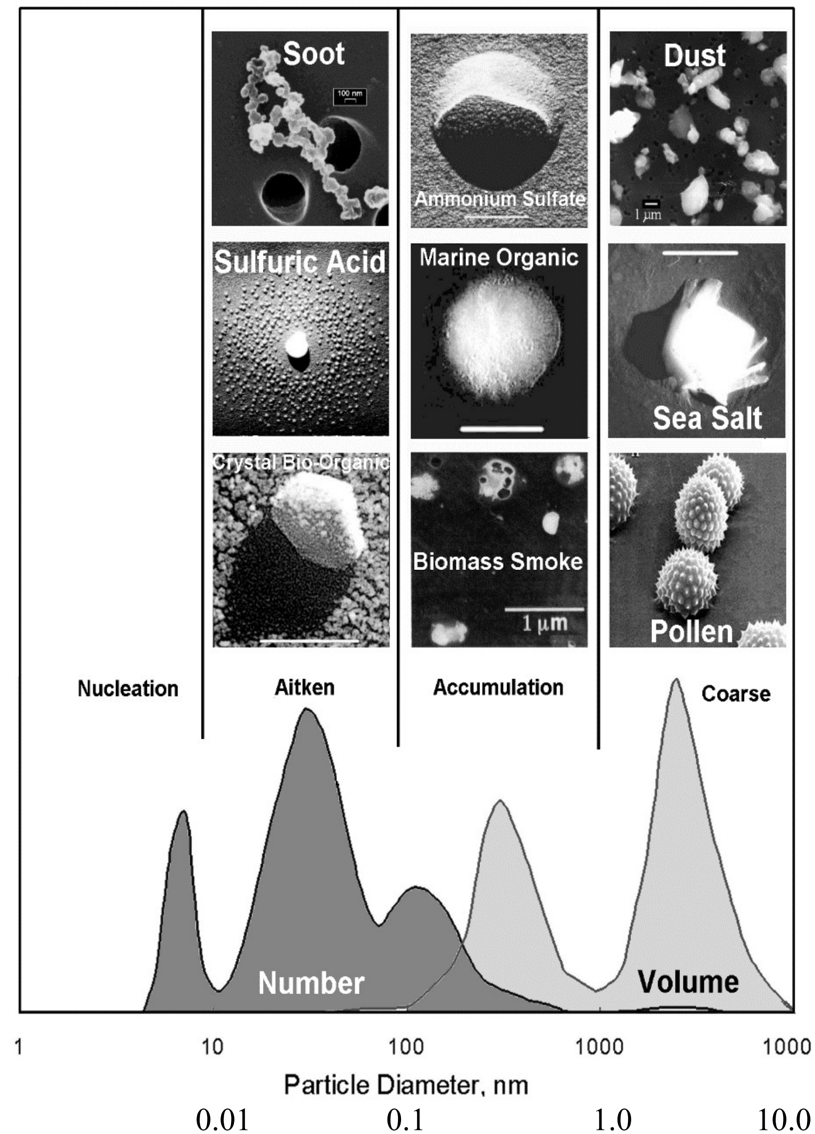
It presents 3 modes :

- « **nucleation** »: radius is between 0.002 and 0.05 µm. They result from combustion processes, photo-chemical reactions, etc.

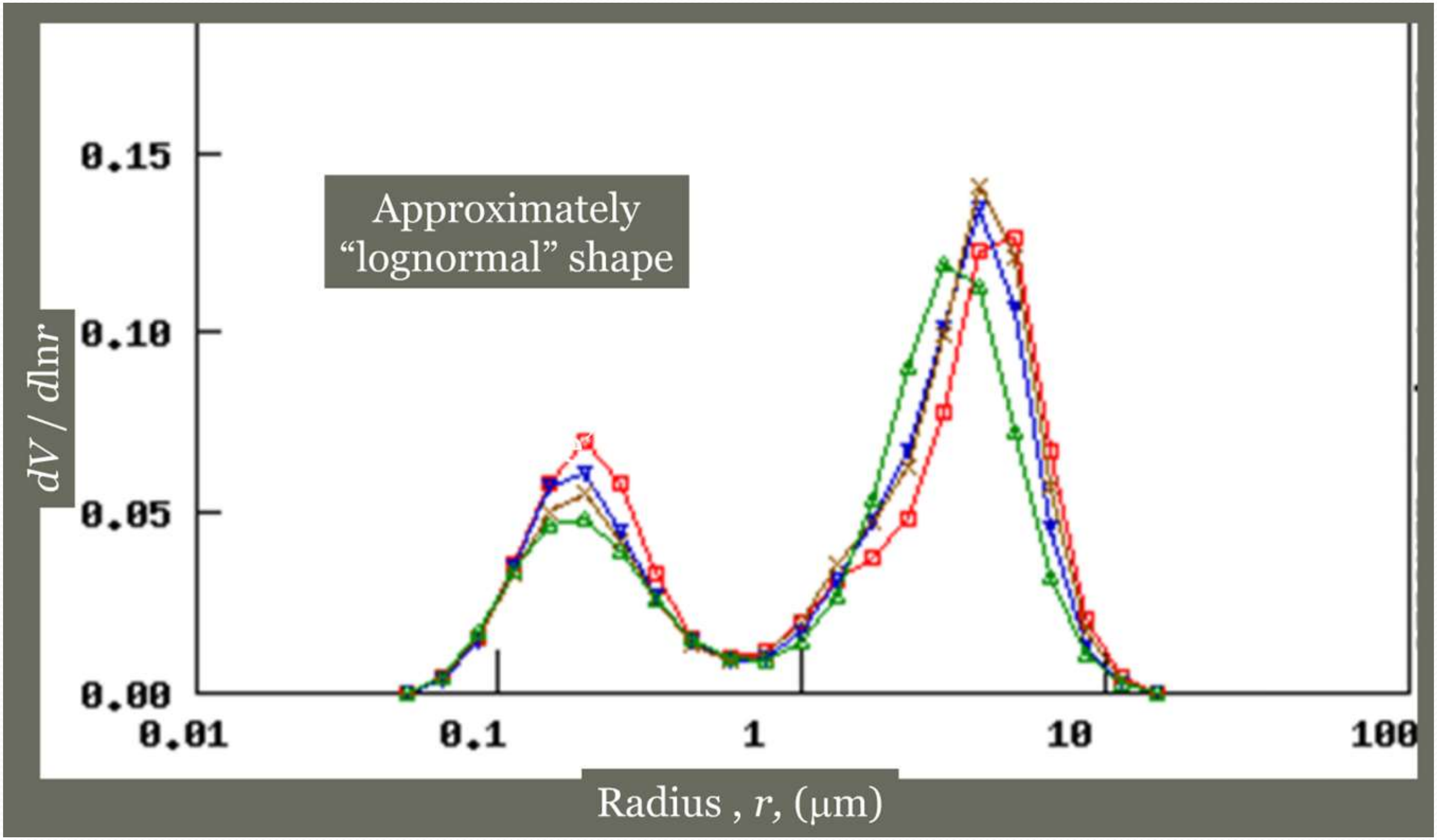
- « **accumulation** »: radius is between 0.05 µm and 0.5 µm. Coagulation processes.

- « **coarse** »: larger than 1 µm. From mechanical processes like aeolian erosion.

« fine » particles (nucleation and accumulation) result from anthropogenic activities, coarse particles come from natural processes.



Size Distribution



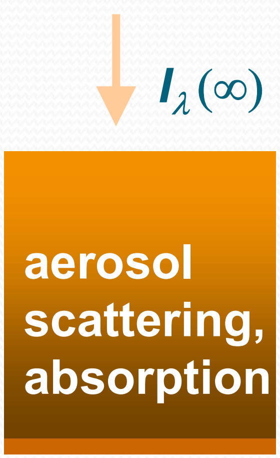
Aerosol from space by solar backscatter

Relatively easy to do qualitatively for thick plumes over dark ocean…

California fire plumes

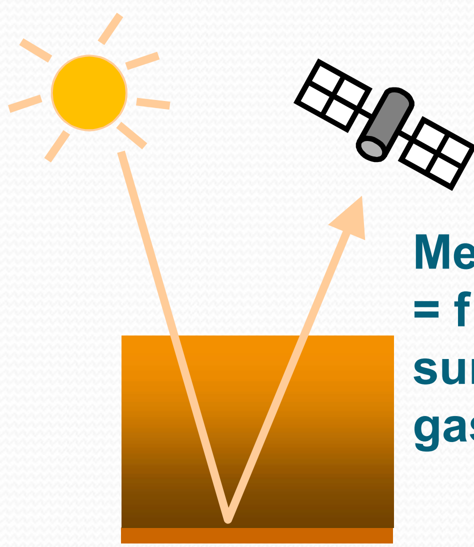
Pollution off U.S. east coast

Dust off West Africa



$I_\lambda(\infty)$

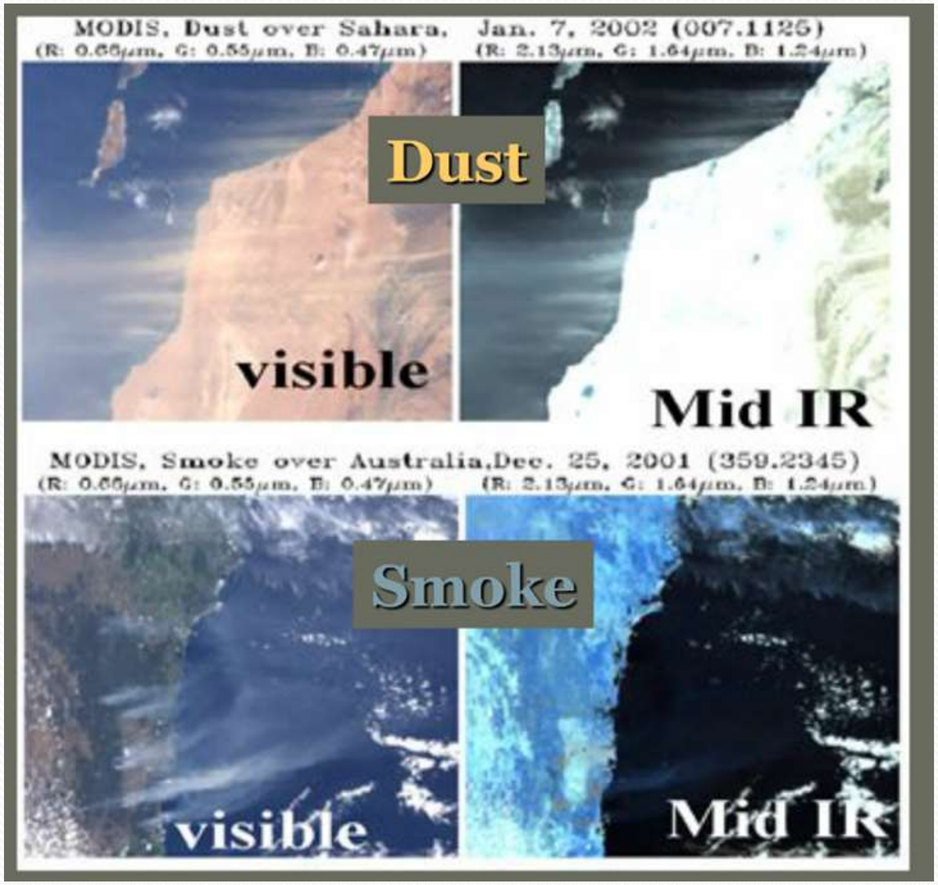
$I_\lambda(0)=I_\lambda(\infty)\exp[-AOD]$



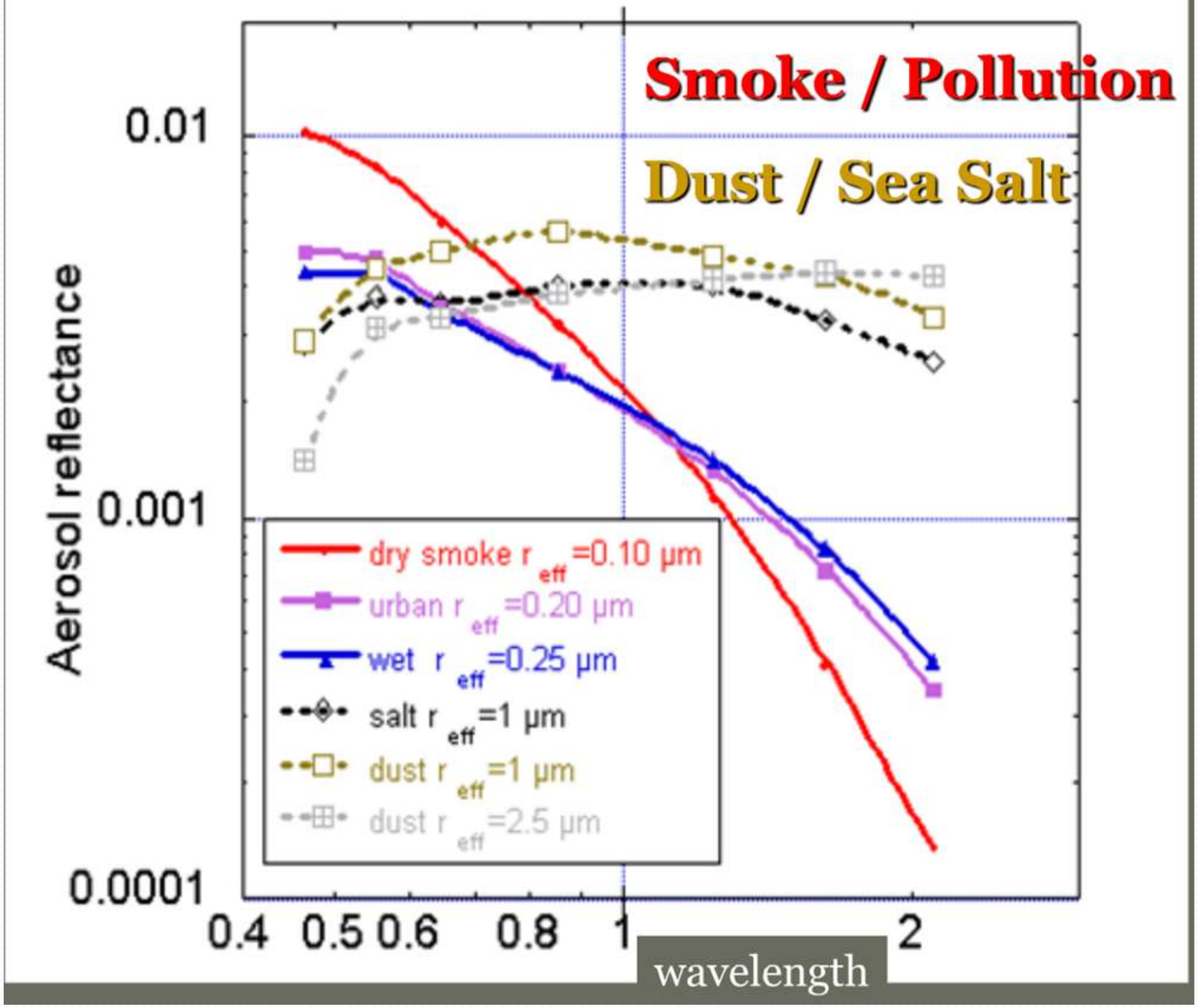
Measured top-of-atmosphere reflectance = f (AOD, aerosol properties, surface reflectance, air scattering, gas absorption, Sun-satellite geometry)

Spectral Properties of Aerosol

- Particles of different size respond to different wavelengths.
- **Big** Particles (e.g. Dust) reflect in the IR
- **Small** Particles (e.g. smoke/polltuion) do not



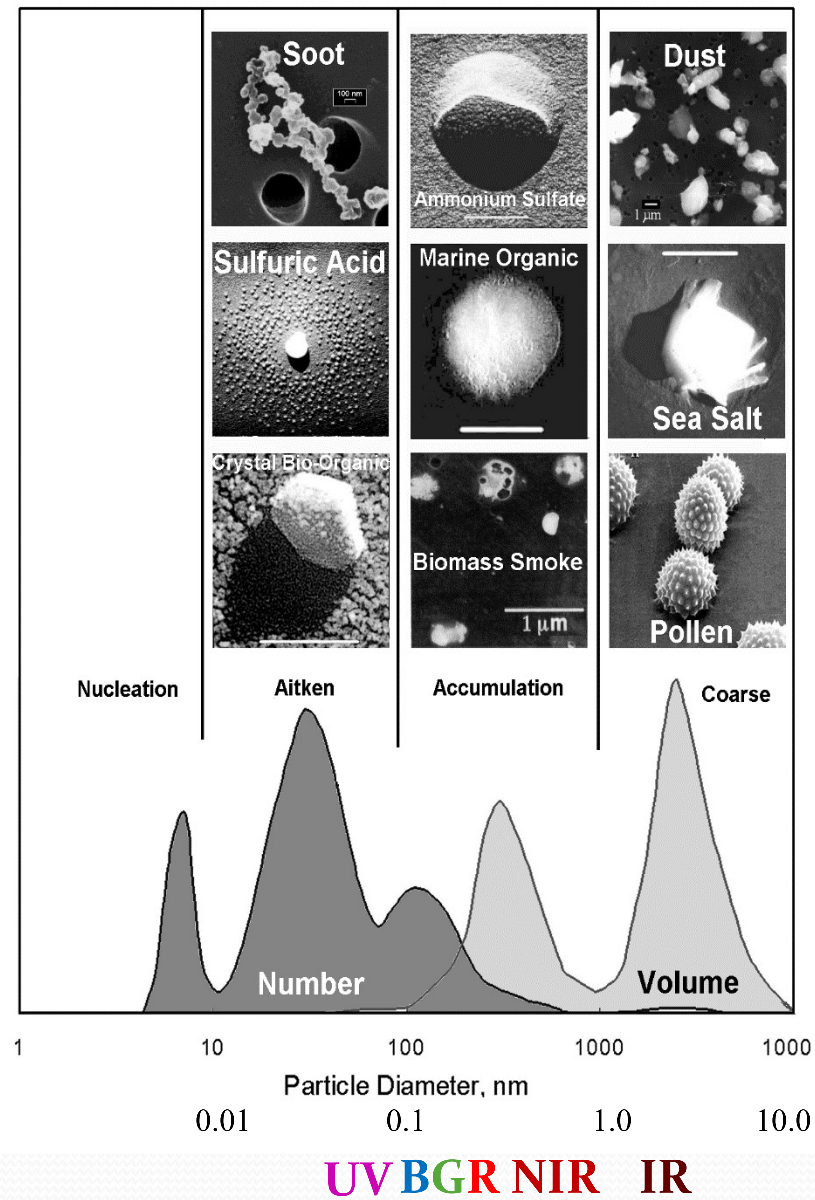
Spectral Optical Properties of Aerosol



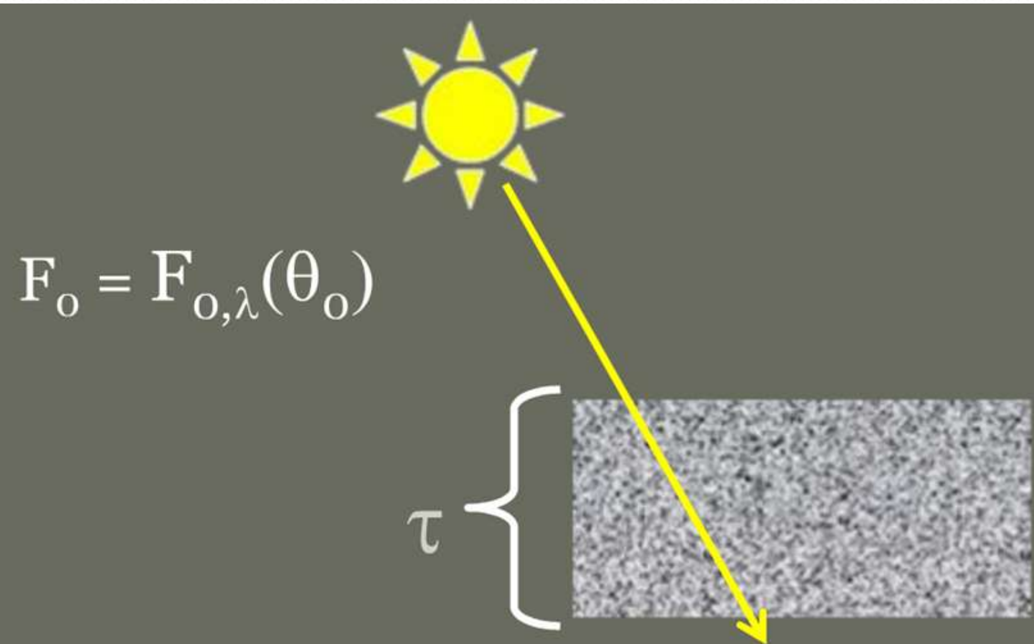
- Particles of different size respond to different wavelengths.

Aerosol Size and Optical Properties

- These aerosols have the largest impacts on:
  - radiative budget
  - visibility
  - cloud processes
  - health issues



τ - Aerosol Optical Depth



Beer-Bouguer-Lambert's extinction law

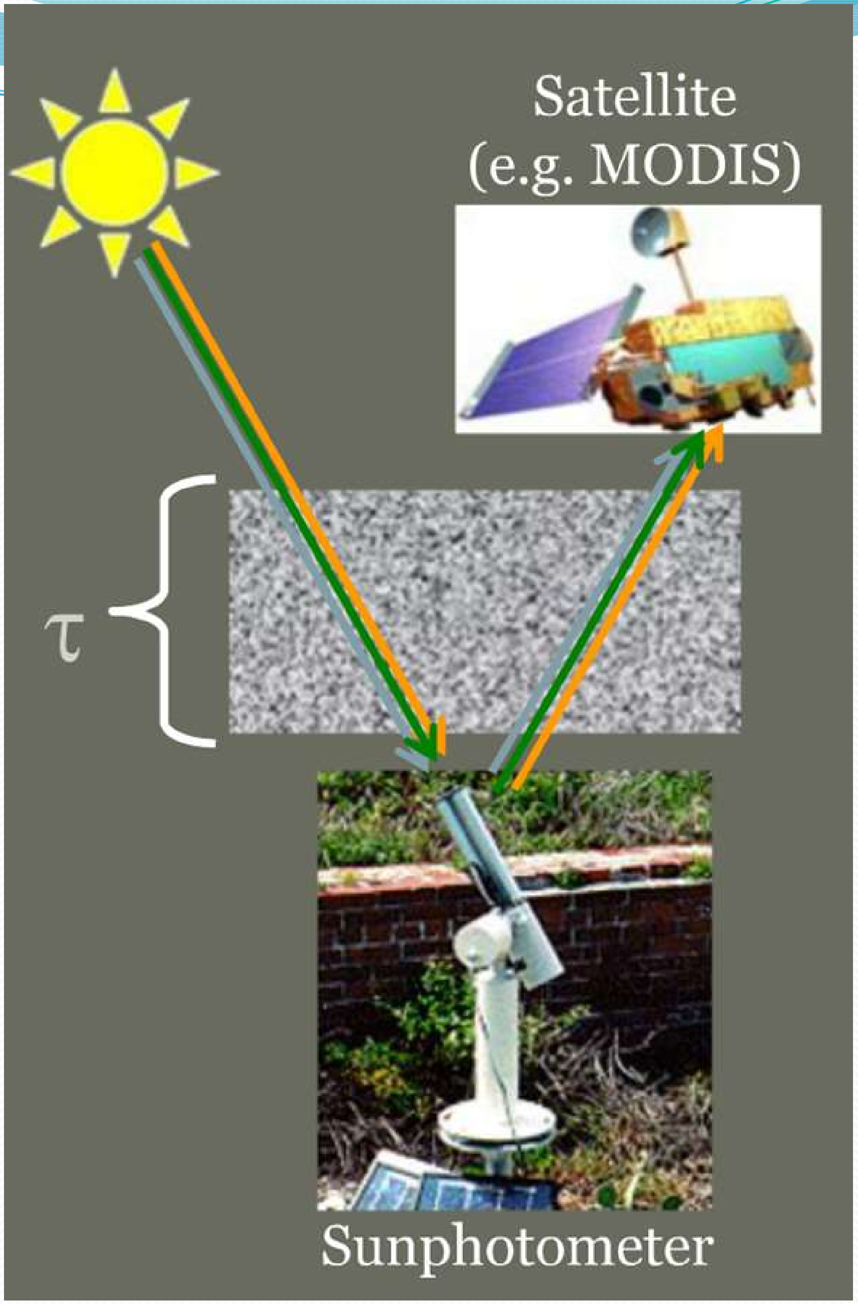
$$L_\lambda = F_{o,\lambda} \exp[-\tau_\lambda m]$$

where λ is wavelength, $m=m(\theta_o)$ is "air mass" (function of solar zenith angle, θ_o), $L=L(\theta_o)$ is radiance, $F_o=F_o(\theta_o)$ is solar irradiance and τ is total optical depth.

figures from a talk by Y. Kaufman

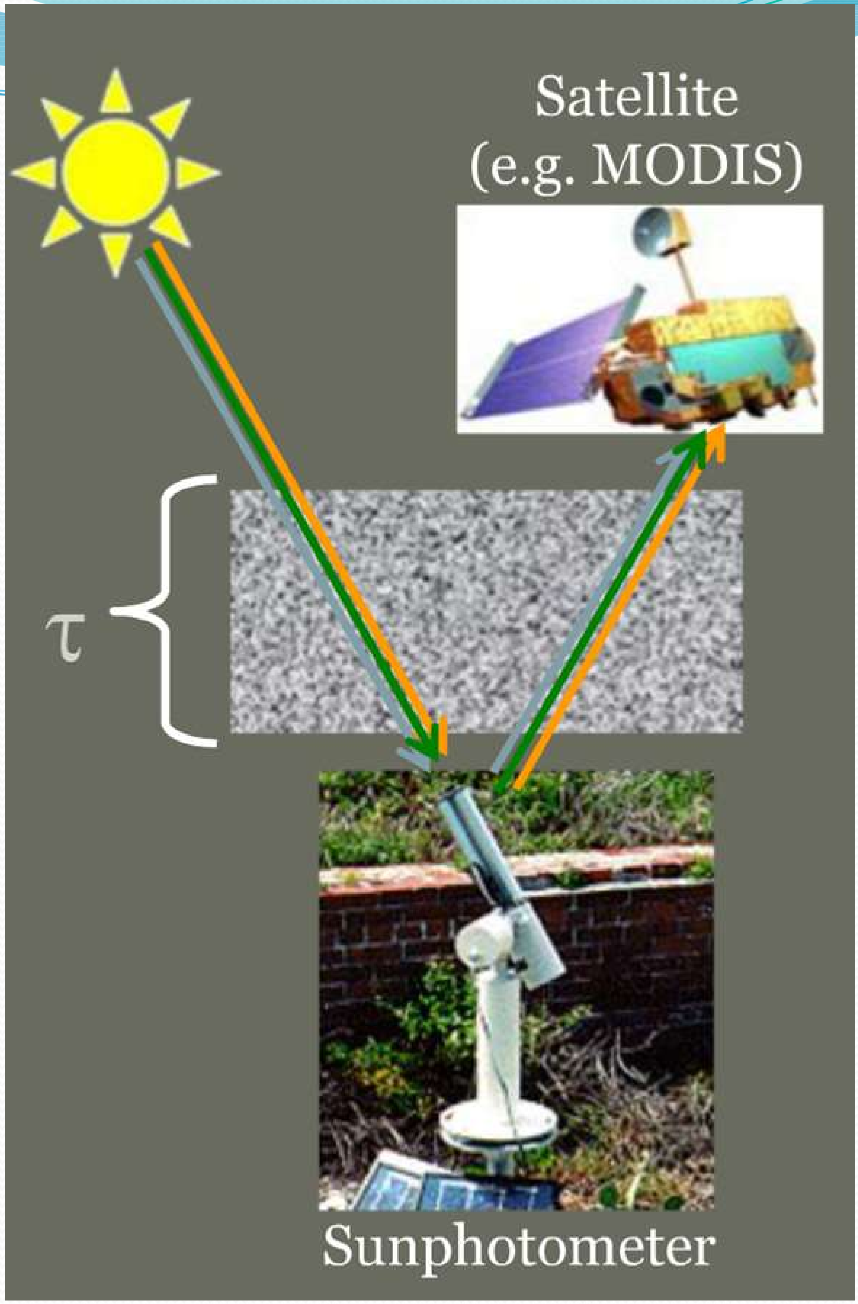
Passive Remote Sensing (Scattering)

- If we can measure spectral light extinction or scattering
- And we can separate the aerosol signal (from the total that includes molecular, surface, etc)
- Then we can retrieve aerosol optical properties (find a solution that fits the measurements)
- Which then can be related to aerosol physical properties (type and loading)
- We can do this from the ground (sunphotometer) or from space (satellite).



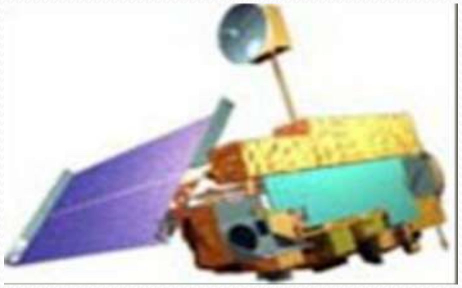
Passive Remote Sensing (Scattering)

- **Unit of measure =**
  - Aerosol Optical Depth
  - AOD
  - τ
- **What is τ?**
  - τ depends on wavelength (λ)
  - τ represents "total column light extinction"



MODIS Aerosol Retrieval Bands

- **7 Bands** for Aerosol Retrieval
- All are found in "Atmospheric Windows"



Band	Band (μm)	Central Wavelen	Resoln (m)
1	0.620 - 0.670	0.646	250
2	0.841 - 0.876	0.855	250
3	0.459 - 0.479	0.466	500
4	0.545 - 0.565	0.553	500
5	1.230 – 1.250	1.243	500
6	1.628 – 1.652	1.632	500
7	2.105 – 2.155	2.119	500

MODIS "Observations"

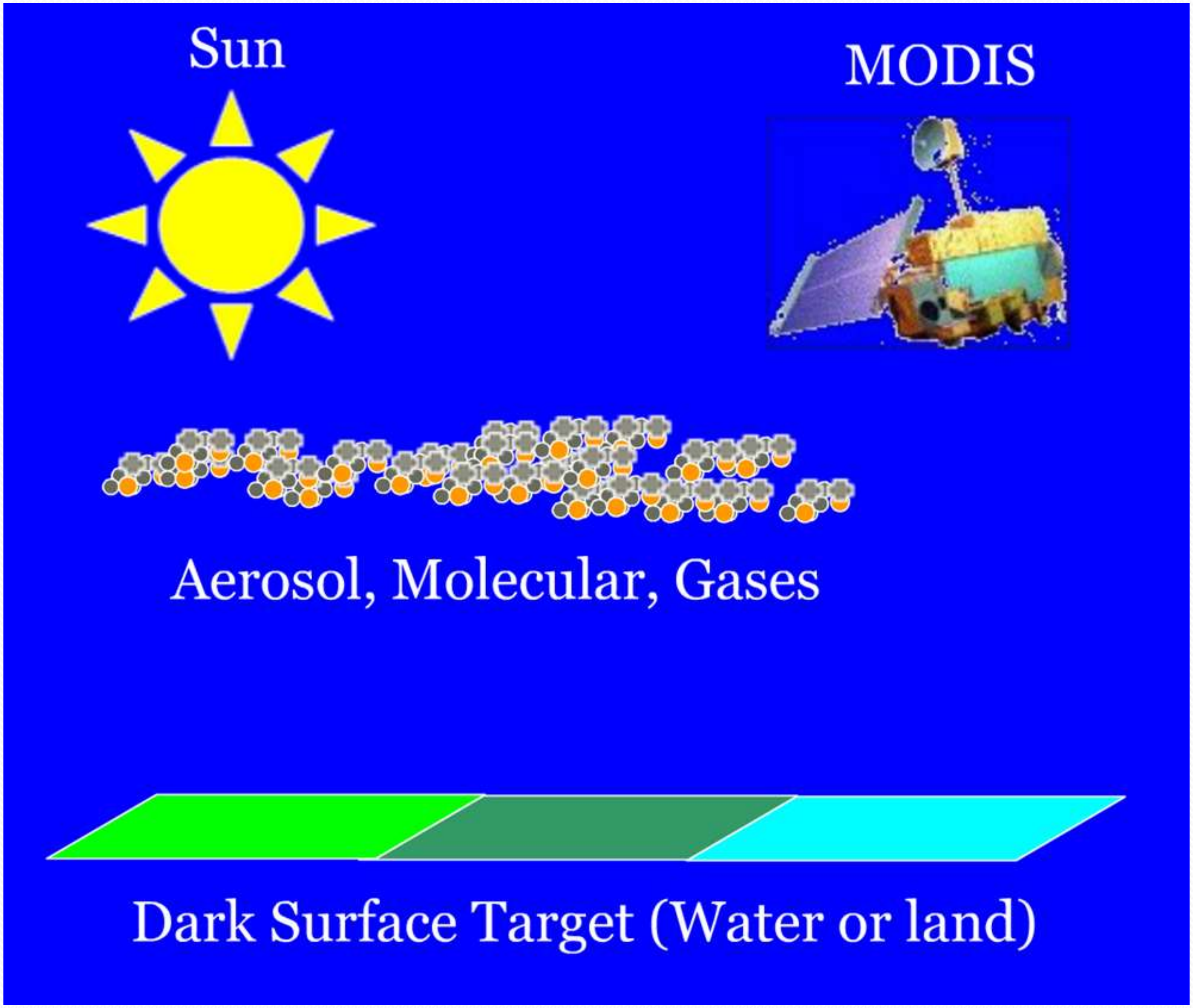
- MODIS observes reflectance in **7 bands at 500 m (or 250 m)**
- These data are "**noisy**"
- These data must be:
  - Cloud "cleared"
  - Decided whether over ocean or over land
  - Screened for glint and other surfaces that are too bright
  - Massaged, averaged to yield…

- One set of spectral reflectance that best represents average conditions in **10 km x 10 km box**

- The MODIS dark target algorithm is actually two separate algorithms, one **over ocean** and one **over land**

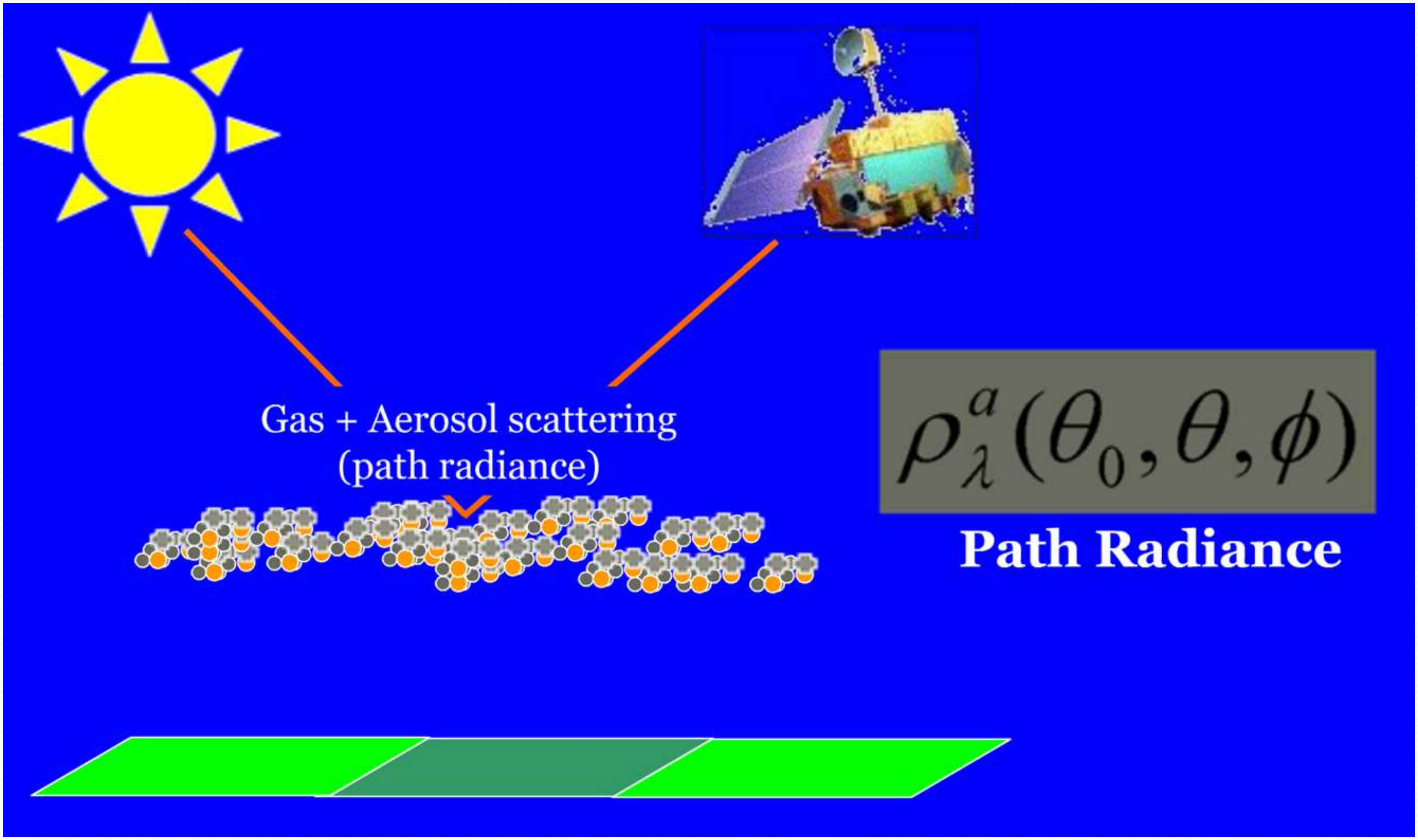
- More about separate algorithms later.

Deconstructing the Clear Sky Signal



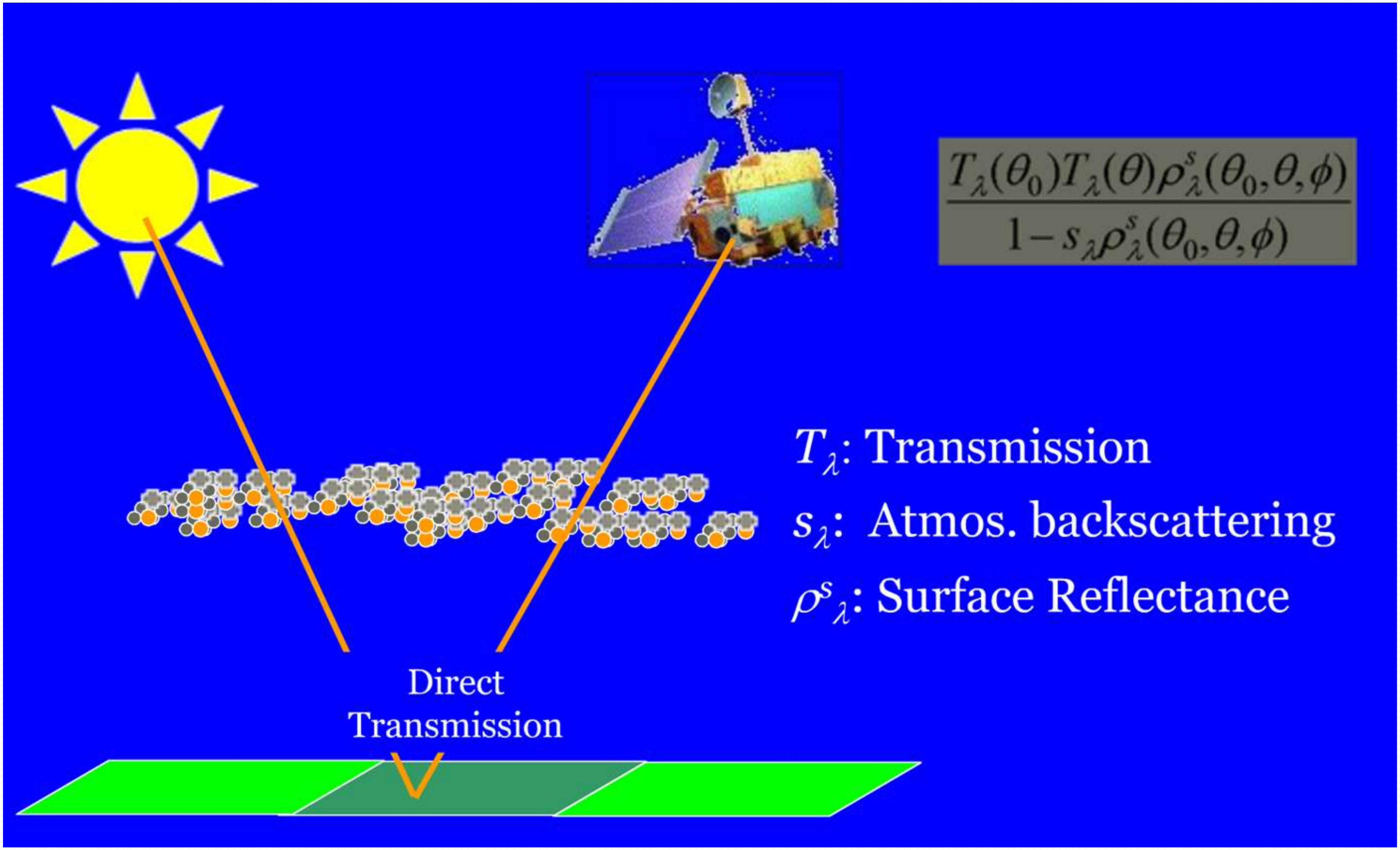
cartoons from a talk by Y. Kaufman

Atmospheric Path Reflectance



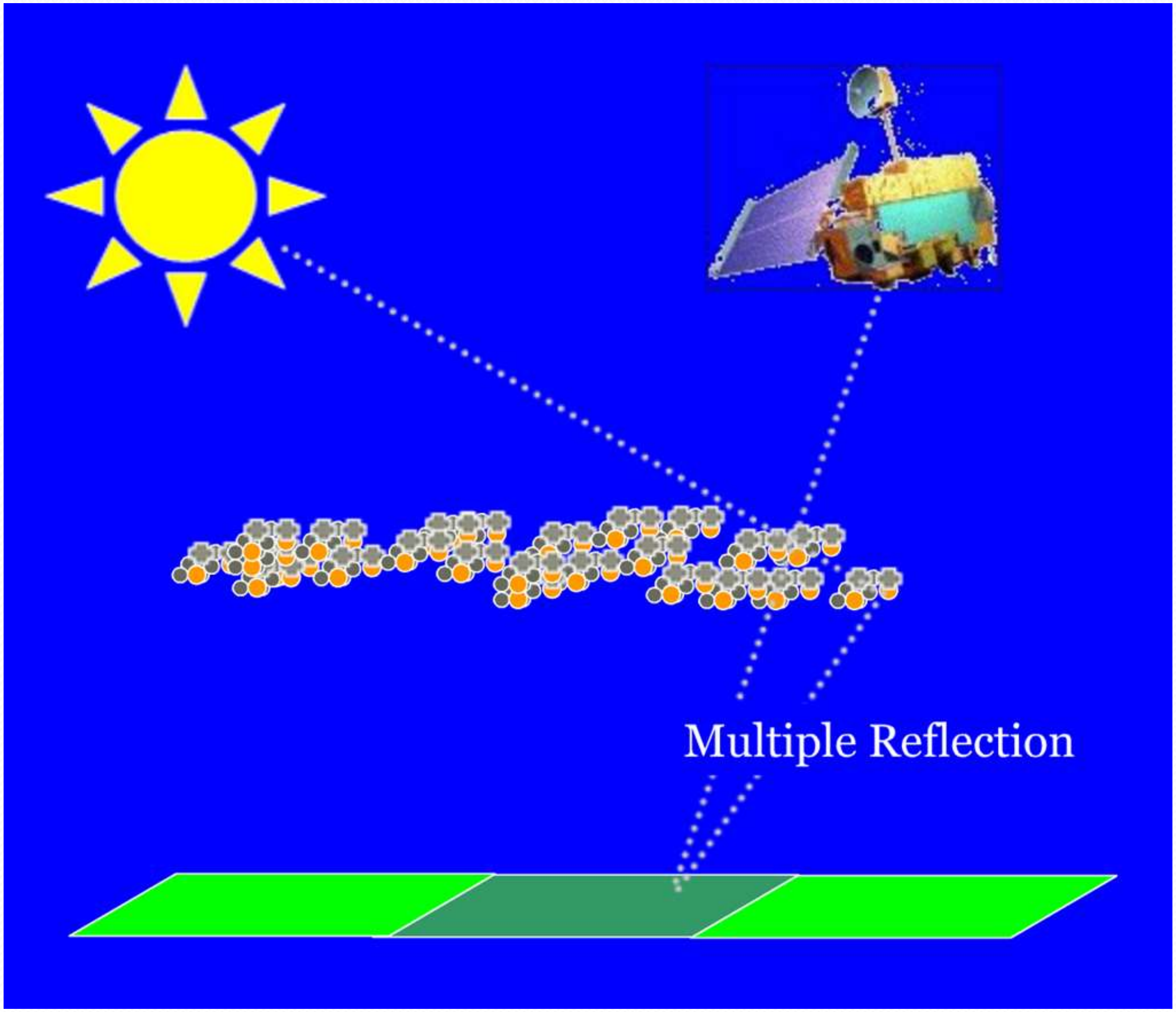
cartoons from a talk by Y. Kaufman

Transmission of Surface Reflectance

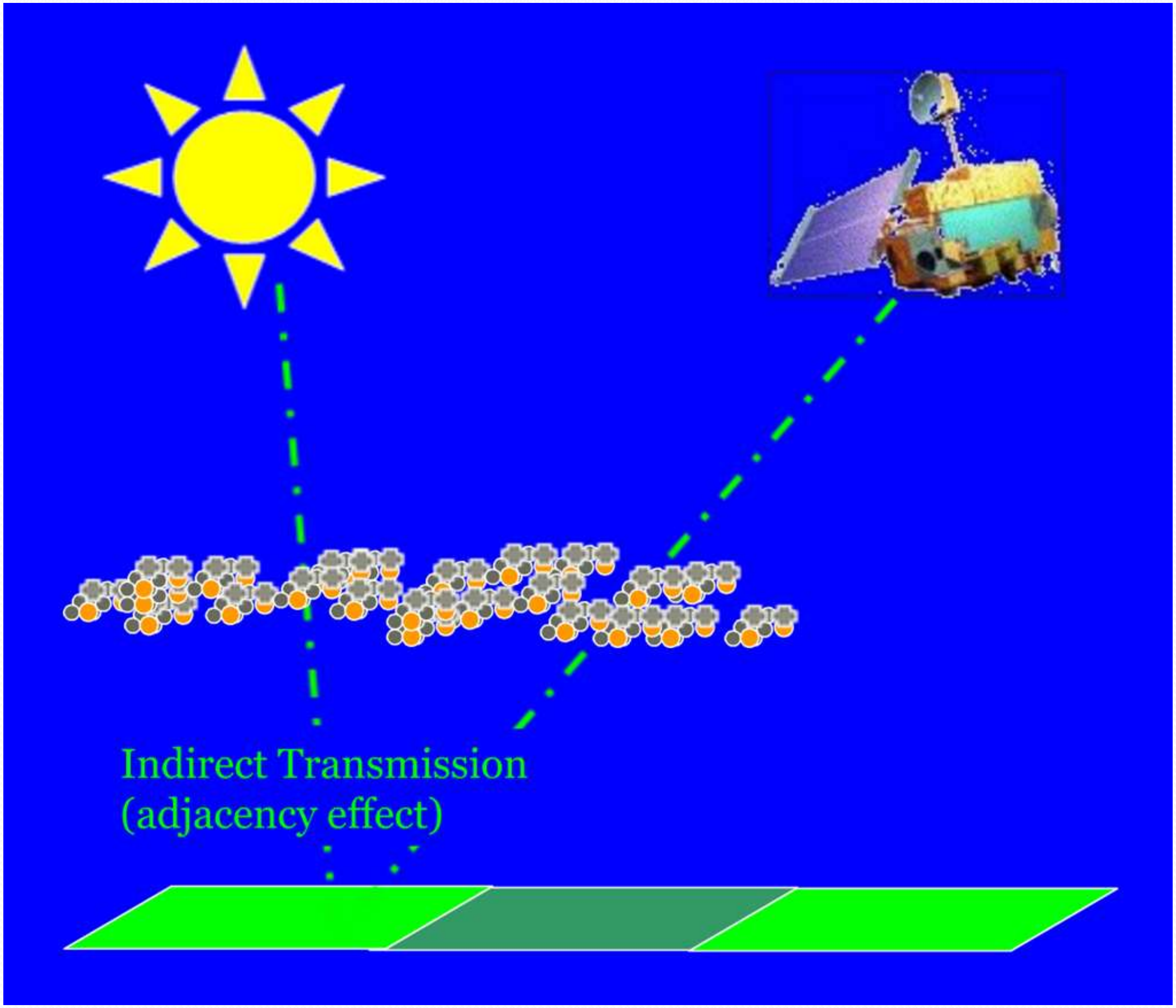


cartoons from a talk by Y. Kaufman

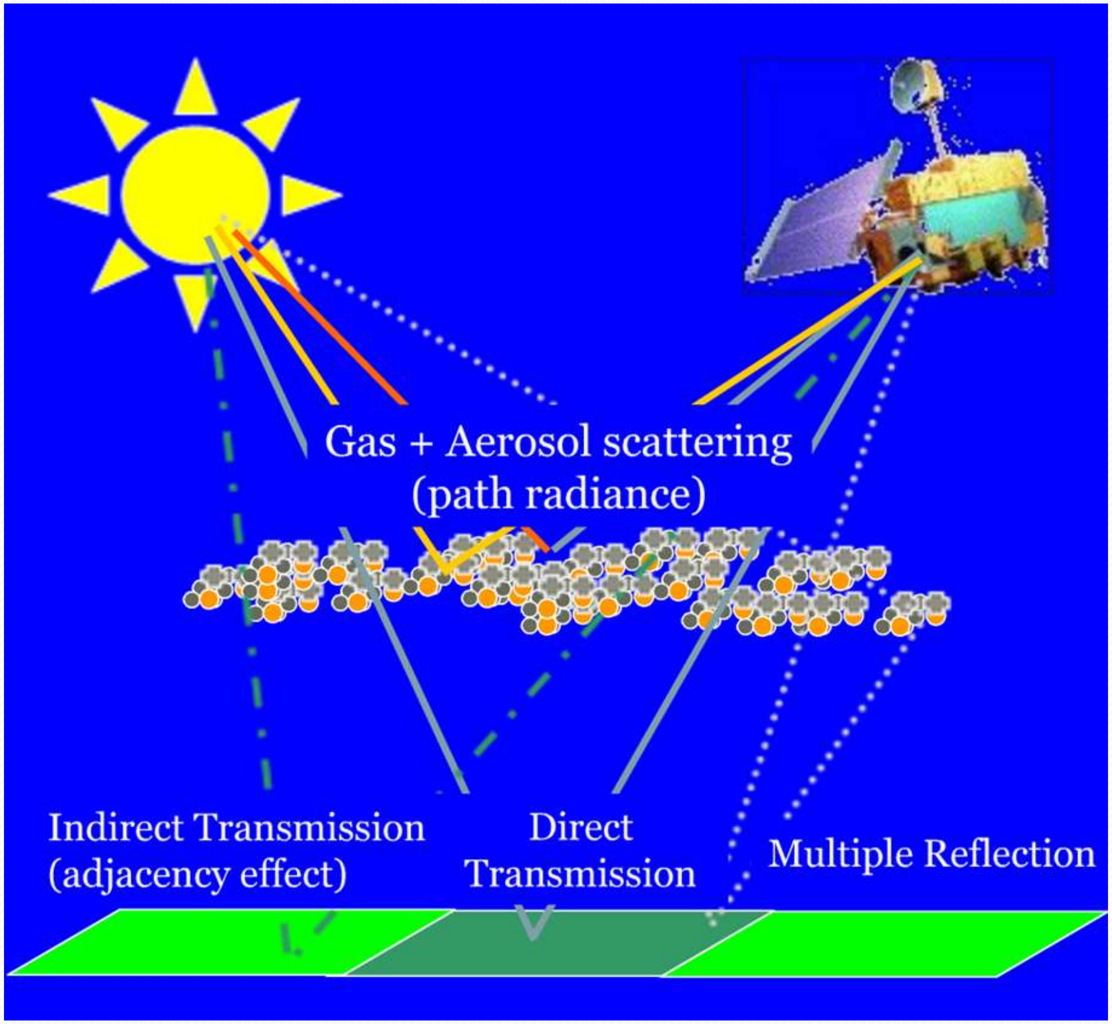
Multiple Reflection



Adjacency Effect (etc)



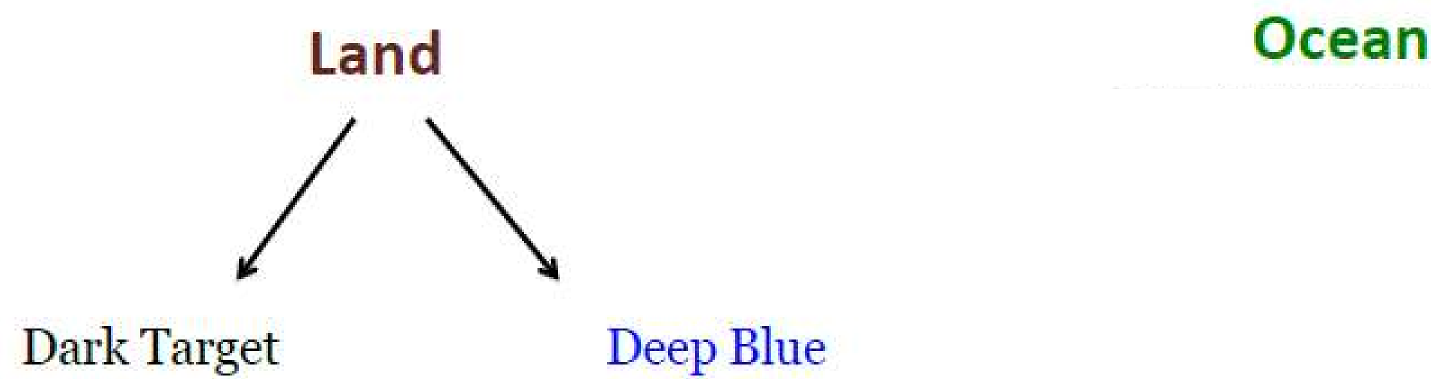
Complicated "Clear Sky" TOA Signal



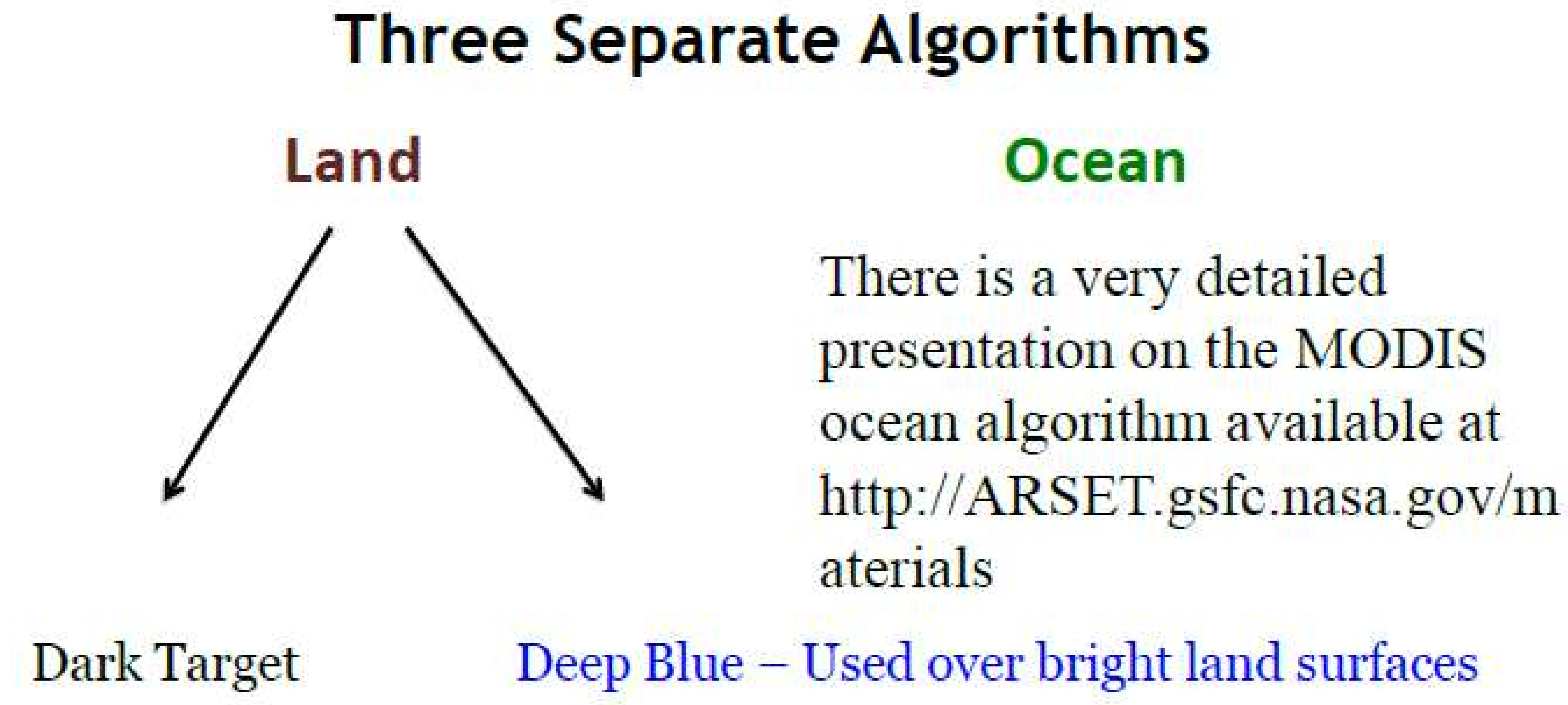
- Contributions From:
  - Gas absorption (O_3, CO_2, etc)
  - H_2O absorption
  - Rayleigh (molecular scattering)
  - Aerosol scattering and absorption
  - Surface reflection
  - Atmosphere/Surface interaction
  - Contamination from neighboring pixels (clouds, etc).

MODIS Aerosol Products

Three Separate Algorithms



MODIS Aerosol Products



Dark target and Deep Blue products are separate and the user can decide which one to use.

In Collection 6 there is a joint product that uses an automated procedure to select the appropriate product

MODIS Aerosol Products

- All three algorithms create a 10 km product
- Land and Ocean – 400 half kilometer pixels
- **Deep Blue – 100 one kilometer pixels**
- Ocean and Land (dark target) algorithms are based on the assumption that aerosols brighten the scene
- Retrievals can only occur where there are a sufficient number of spectrally dark pixels.

Aerosol SDS and What They Really Mean

- The **Ocean** and **Land** algorithms each produce their own SDS's.

- When both algorithms retrieve the same parameter they may be combined into a joint **Land_And_Ocean** SDS.

- The individual **Land** or **Ocean** SDS is generally preferred because
  - it contains more wavelengths
  - gives more information about quality
  - at level 3 it gives a quality weighted product that screens out anomalies

- **Land_And_Ocean** is useful if you need both together but may not give the same results as **Land** or **Ocean**.

MODIS Aerosol Products

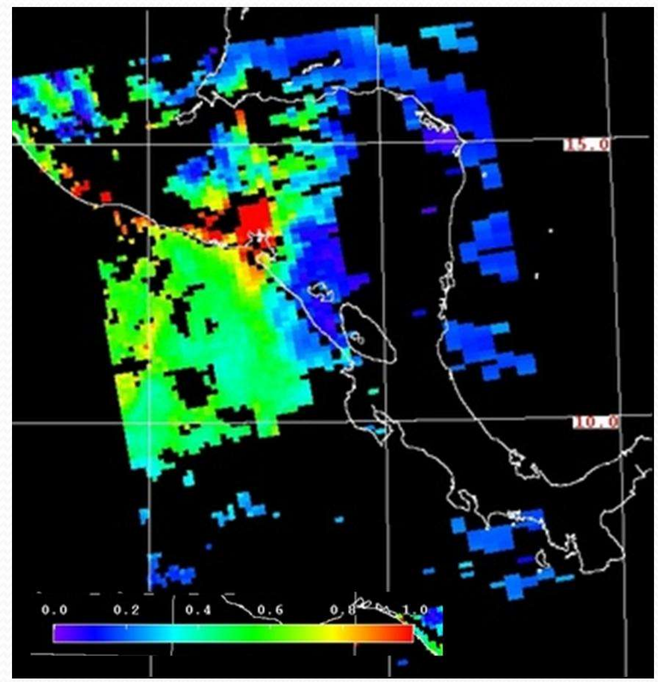
- Important to remember for MODIS Aerosol Products
  - **Ocean** and **Land** Products are produced using totally separate and distinct algorithms.
  - All current aerosol products are 10 km x 10 km
  - The most important products are **Aerosol Optical Depth** and **Fine Fraction**.
    - These exist for both **Ocean** and **Land**
    - Fine Fraction over land should be seen as a qualitative indicator not as a quantitative measurement

Quality Assurance

- QA is our indication of how much confidence we have in the quality of the retrieval.

- Quality_Assurance_Ocean – Scale is 0-3
  - We use Ocean QA above 0
  - Factors
    - Number of pixels
    - Error fitting
    - How close to glint

- Quality_Assurance_Land – Scale is 0-3
  - We use Land QA of 3
  - Factors
    - Number of pixels
    - Error fitting
    - Surface reflectance



Main Products - Ocean

- Effective_Optical_Depth_Average_Ocean
  - Retrieved AOD at 0.47, 0.55, 0.66, 0.86, 1.24, 1.63, 2.13
- Optical_Depth_Ratio_Small_Ocean_0.55*
  - Fraction of Fine Mode AOD at 0.55
- Optical_Depth_Small_Average_Ocean
  - AOD * Fine Mode Ratio

Additional Products - Ocean

- **Optical_Depth_Large_Average_Ocean**
  - (1-Fine Fraction)*AOD for the 7 ocean wavelengths

- **Mass_Concentration_Ocean***
  - Total column mass per unit area in unis of $1.0e^{-6}g/cm^2$

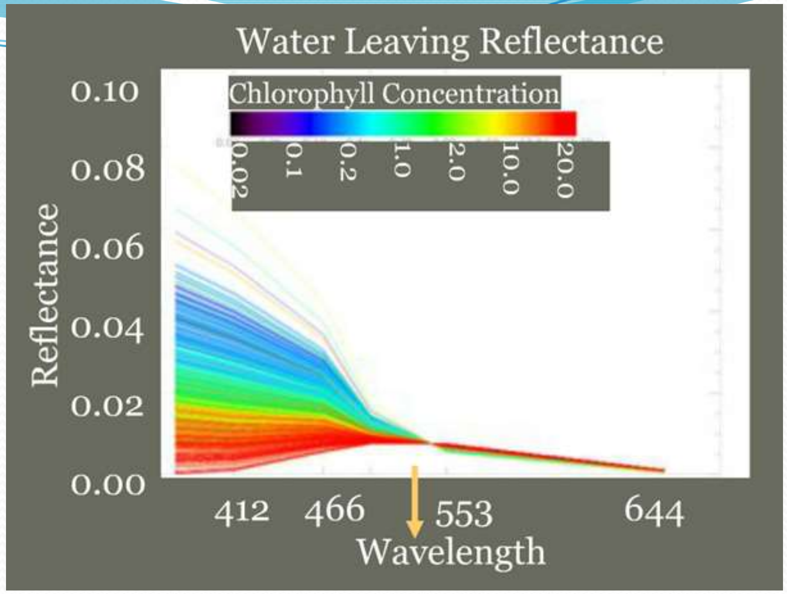
- **Angstrom_Exponent_1_Ocean*** 0.55/0.86
- **Angstrom_Exponent_2_Ocean*** 0.86/2.1

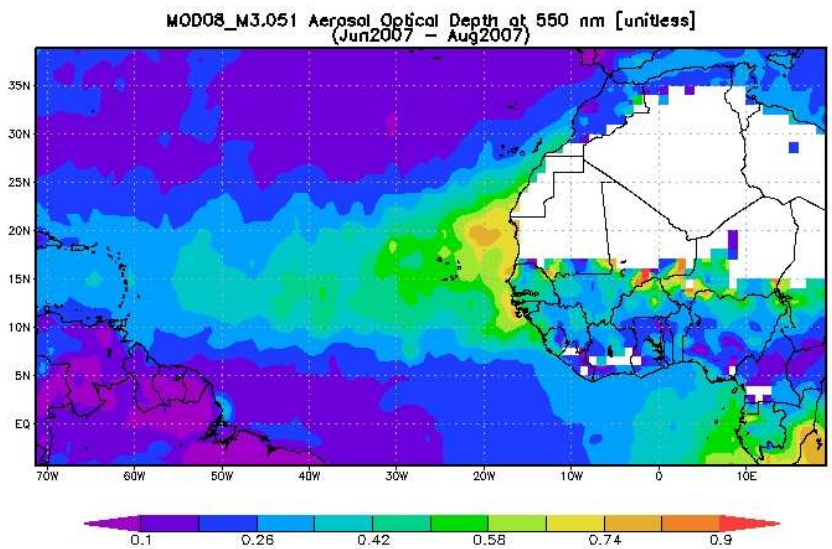
- **Optical_Depth_by_Models_Ocean**
  - Retrieval AOT per model. This information is carried into the level 3 products

- **Effective_Radius_Ocean**
  - Effective Radius at 0.55 for both the fine and coarse modes

Dark Target

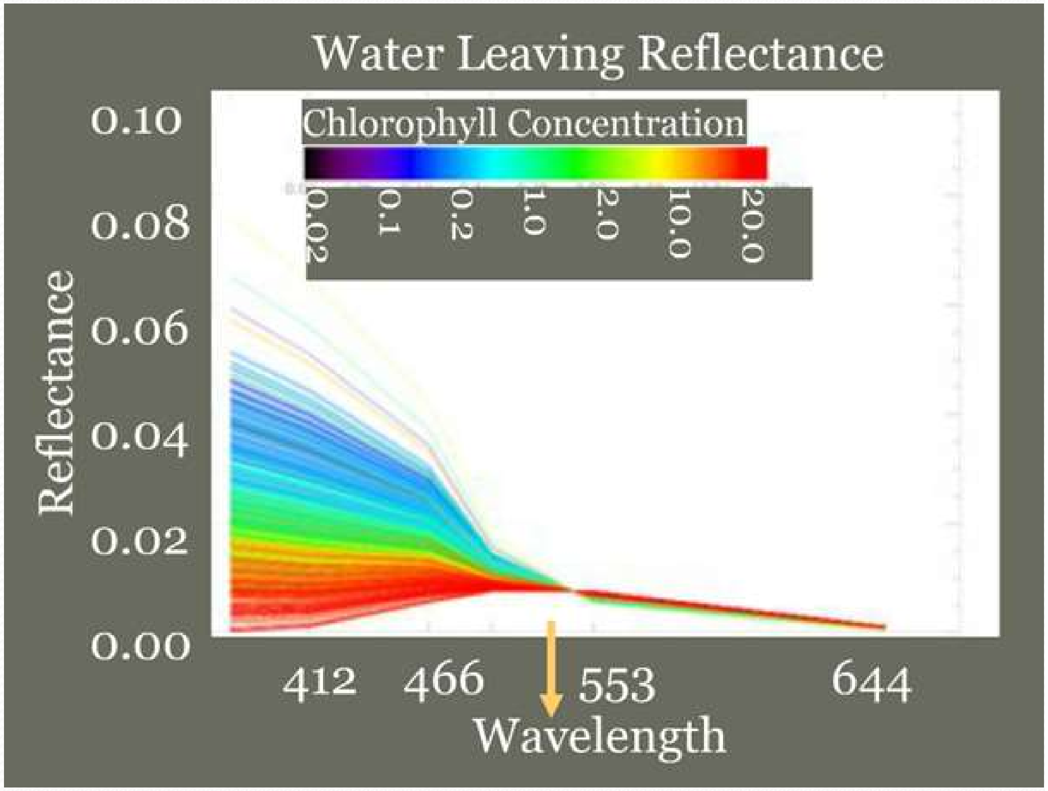
- What is a dark target algorithm and why do we use it?
  - We have a mixed signal of aerosol and surface
  - If we remove the surface signal (our noise) we are left with aerosol (our signal)
  - Choosing dark targets helps to minimize our error from the surface signal
  - Will need to consider if we are over land or over ocean.
  - Discard the brightest 50% and darkest 20% of pixels.... Apply retrieval algorithm if sufficient pixels remain





Over Oceans

- We can choose the wavelengths that give little or no surface signal.
- The 0.55 channel is assumed to have a water leaving radiance 0.005
- Longer wavelengths have no signal at all
- We account for the effects in the 0.55 channel in our radiative transfer calculations



→ Dark λ ≥ 553 nm

Aerosol Models over Ocean

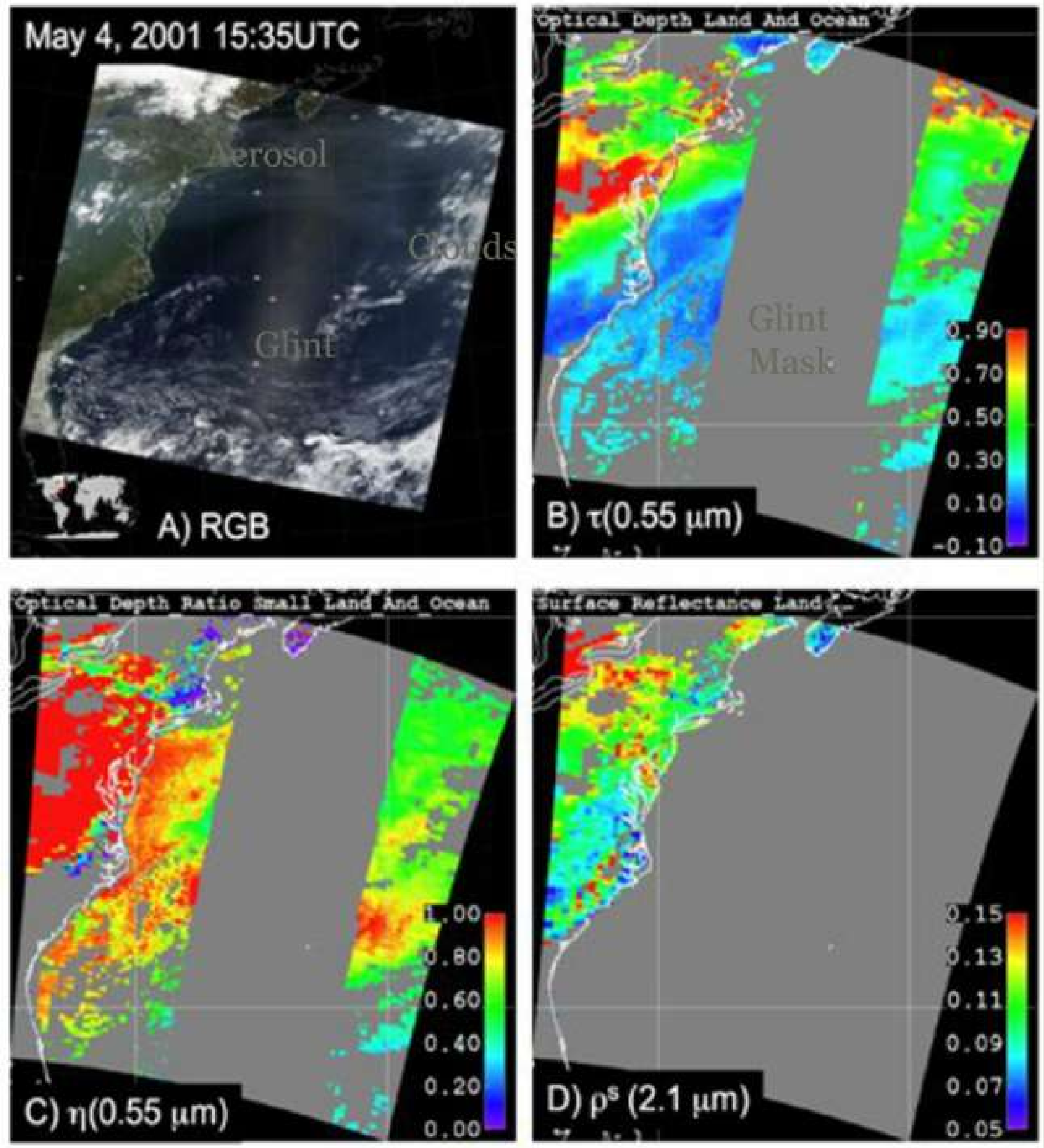
- Represented by "MODES" – Fine & Coarse

Fine (Small) Mode	Refractive Index λ=0.47-->0.86μm	r_g	σ	r_{eff}	Comments
1	1.45-0.0035i	0.07	0.40	0.10	Water Soluble
2	1.45-0.0035i	0.06	0.60	0.15	Water Soluble
3	1.40-0.0020i	0.08	0.60	0.20	Water Soluble with humidity
4	1.40-0.0020i	0.10	0.60	0.25	Water Soluble with humidity

Coarse (Big) Mode	Refractive Index λ=0.47-->0.86μm	r_g	σ	r_{eff}	Comments
5	1.35-0.001i	0.40	0.60	0.98	Wet sea salt type
6	1.35-0.001i	0.60	0.60	1.48	Wet sea salt type
7	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)	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)	0.50	0.80	2.50	Dust-like type

Aerosol Retrieval Combined (Land/Ocean)

- **Retrieved**
  - τ – 0.55 μm
  - η – 0.55 μm
  - ε – fitting error
  - ρ^s – over land
- **Derived**
  - τ_λ
  - α – Column Mass
  - Diagnostics



Land Retrieval

- How is the land retrieval different than ocean?

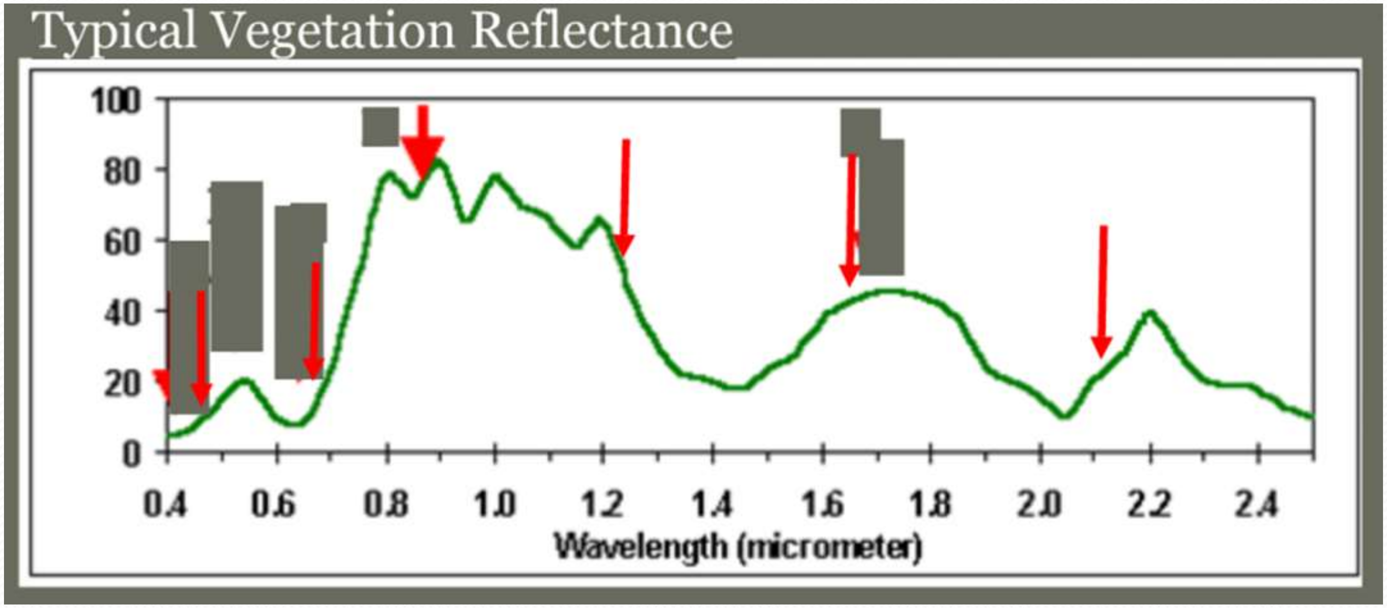
- **Scenes are screened to remove**
  - Water
  - Snow, Ice, Melting Snow

- **Aerosol models are fixed and determined only by**
  - Location
  - Season

- **Only 3 wavelengths are used in the retrieval**
  - 0.44, 0.66 and 2.1

We Require "Dark Targets" Over Land

LAND



- Vegetation Reflectance: → Dark $\lambda \leq 644$ nm
  - $\rho^s_{0.66} \approx 0.55\rho^s_{2.1}$
  - $\rho^s_{0.47} \approx 0.50\rho^s_{0.66}$
- Depends on:
  - $\rho_{0.86}, \rho_{1.2}, \rho_{2.1}$ and θ

	True Reflectance	Measured Reflectance	Surface Error 10%	Error in AOT
Pixel 1	0.2	0.22	.02	0.2
Dark Target Pixel 2	0.02	0.022	.002	0.02

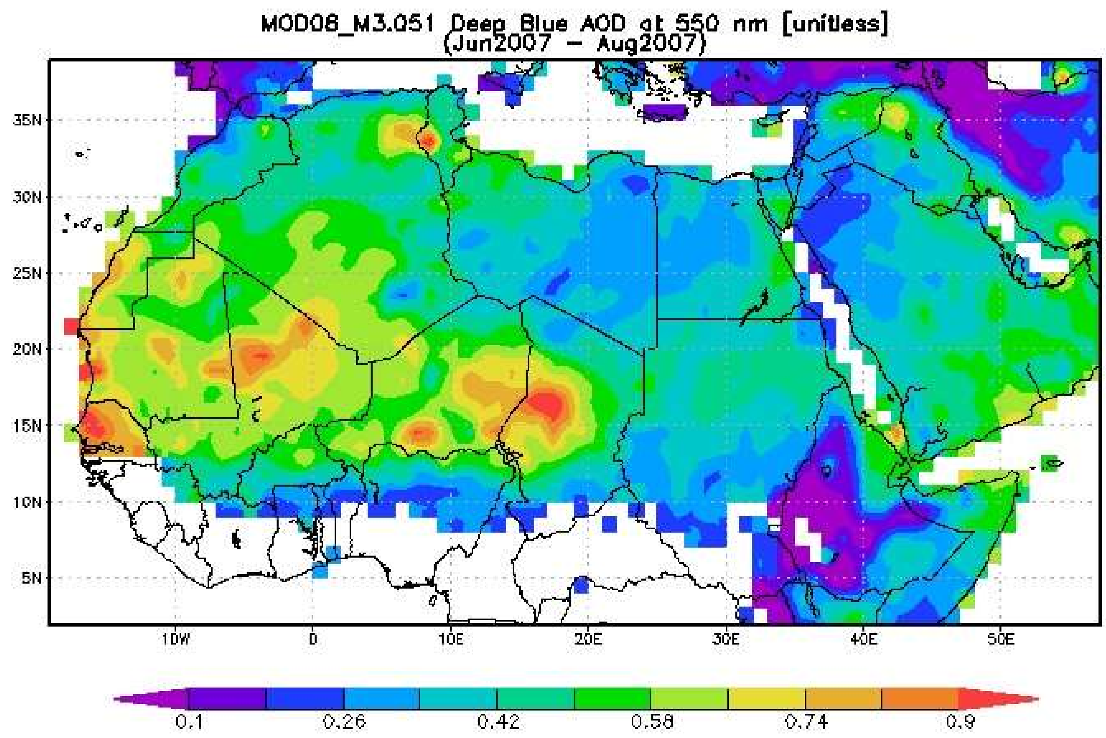
AERONET based Aerosol Modes (land)

Model	Mode	r_v (μm)	σ	V_0 ($\mu m^3 / \mu m^2$)	ω_0 (0.47/0.55/0.66/2.1 μm)
Mod-absorb (Developing)					0.93 / 0.92 / 0.91 / 0.87
	1	$0.0203\tau + 0.145$	$0.1365\tau + 0.3738$	$0.1642\ \tau^{0.7747}$	
	2	$0.3364\tau + 3.101$	$0.098\tau + 0.7292$	$0.1482\ \tau^{0.6846}$	
Weak-absorb (Industrial)					0.95 / 0.95 / 0.94 / 0.90
	1	$0.0434\tau + 0.1604$	$0.1529\tau + 0.3642$	$0.1718\ \tau^{0.8213}$	
	2	$0.1411\tau + 3.3252$	$0.1638\tau + 0.7595$	$0.0934\ \tau^{0.6394}$	
Strong-Absorb (Biomass)					0.88 / 0.87 / 0.85 / 0.70
	1	$0.0096\tau + 0.1335$	$0.0794\tau + 0.3834$	$0.1748\ \tau^{0.8914}$	
	2	$0.9489\tau + 3.4479$	$0.0409\tau + 0.7433$	$0.1043\ \tau^{0.6824}$	
Spheroid (Dust)					0.94 / 0.95 / 0.96 / 0.98
	1	$0.1416\ \tau^{-0.0519}$	$0.7561\ \tau^{0.148}$	$0.0871\ \tau^{1.026}$	
	2	2.2	$0.554\ \tau^{-0.0519}$	$0.6786\ \tau^{1.0569}$	

- Each “model” has two or more “modes.” Size of modes depends on τ

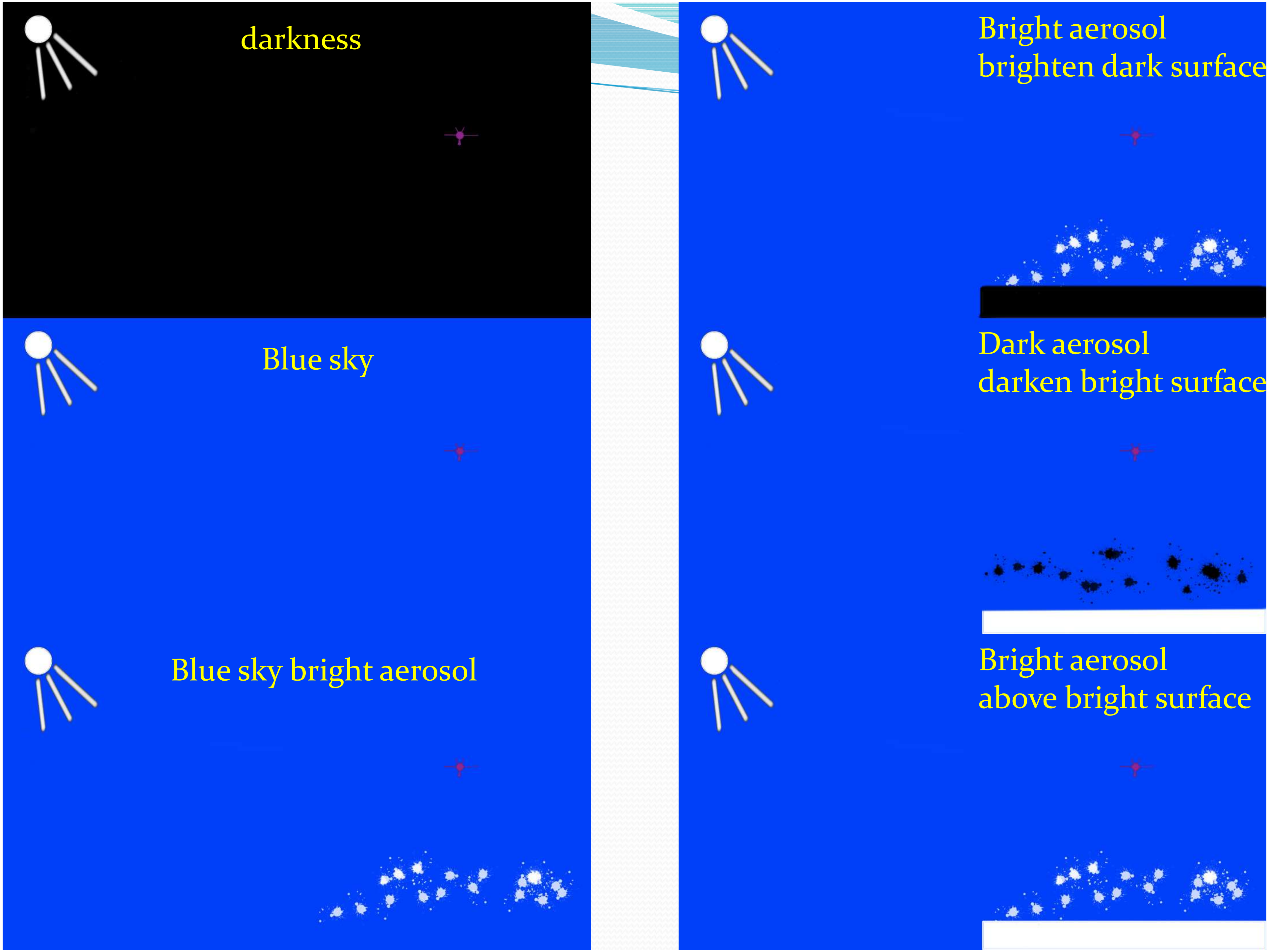
Aerosol Optical Depth MODIS data obtained over bright surfaces

- Deep Blue Algorithm!

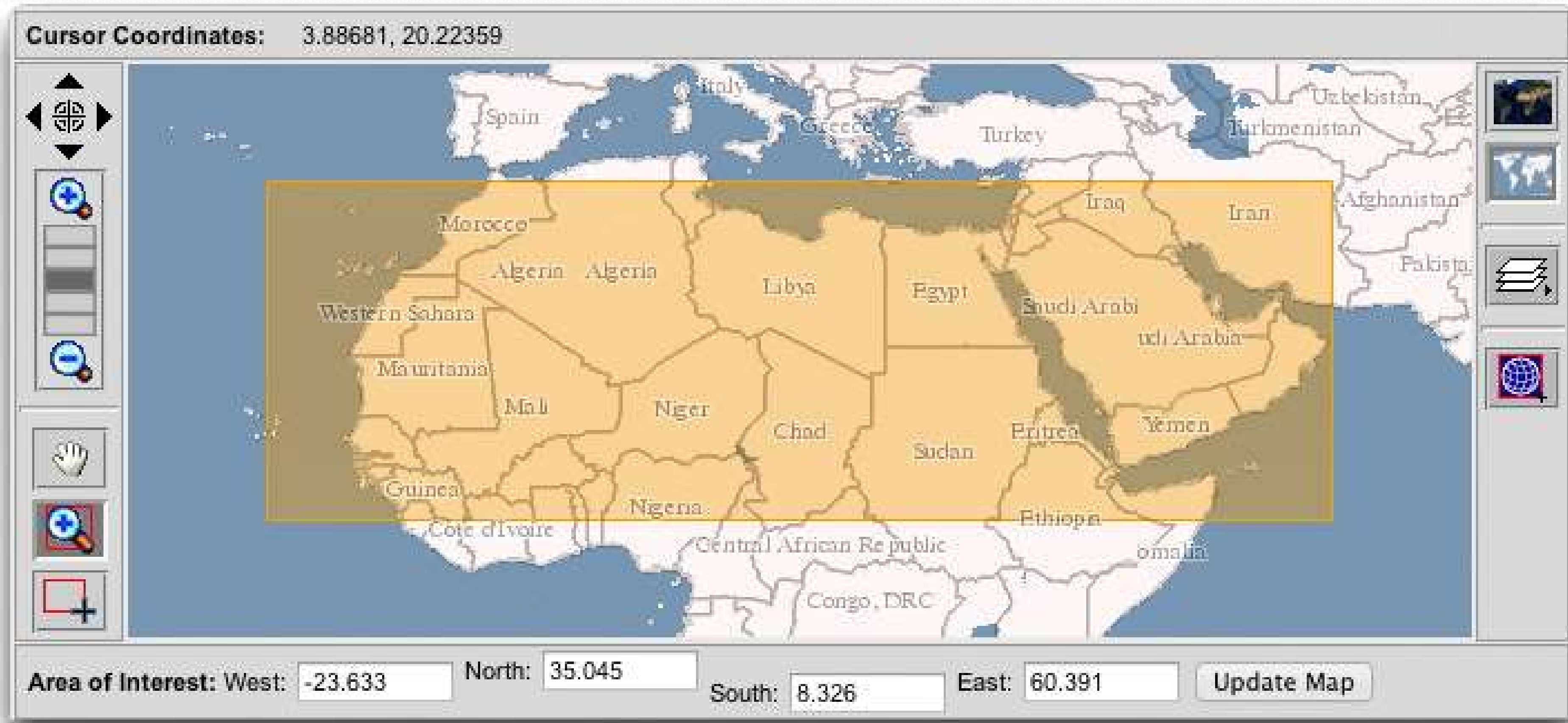


Deep Blue Summary

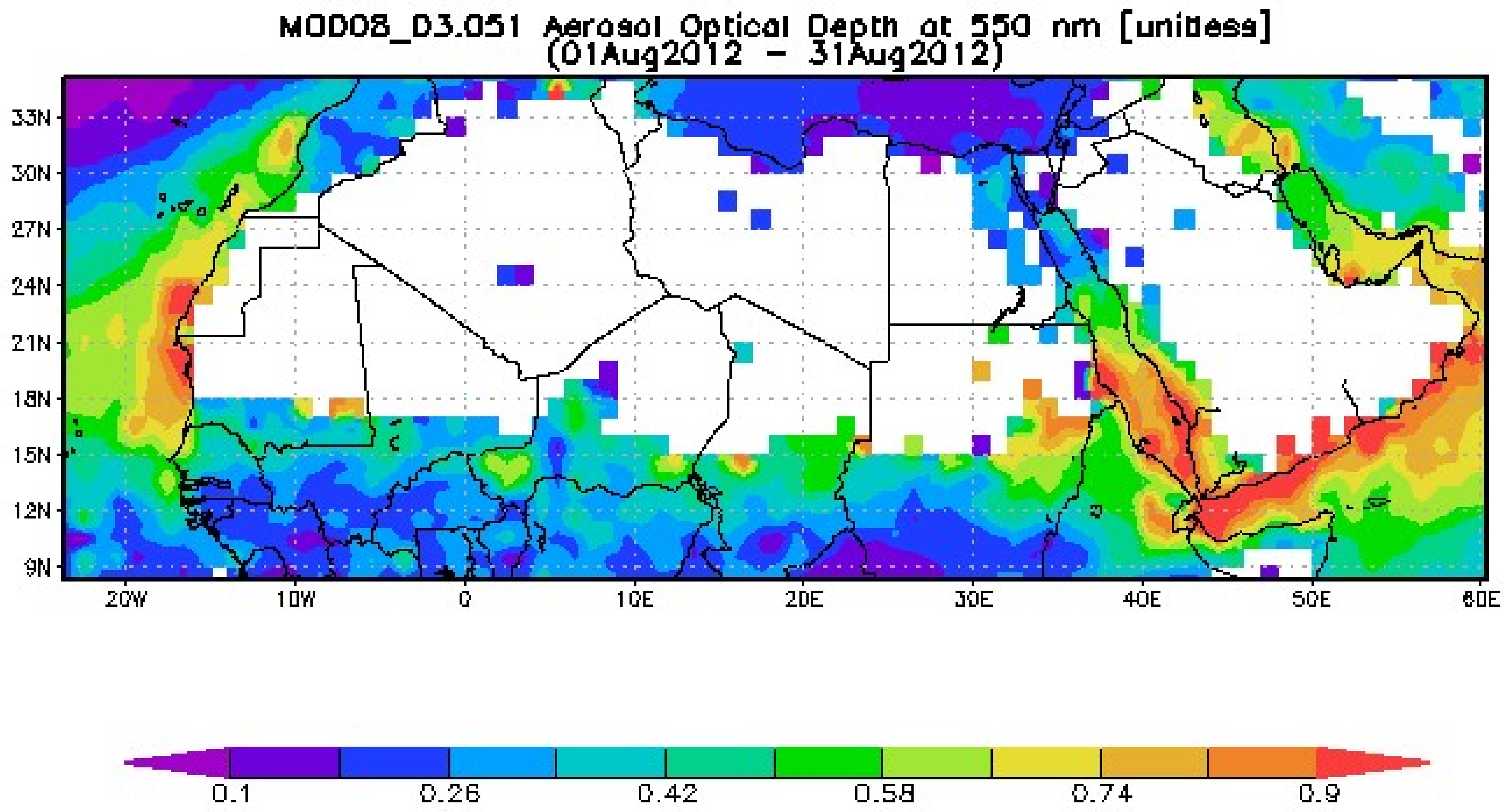
- **Screen out unwanted features** (e.g. clouds, water, snow/ice, and vegetated pixels).
- **Estimate surface reflectance from seasonally-varying global data base.**
- **Apply retrieval algorithm**
  - Maximum likelihood method to determine optimal aerosol model
  - 2-channel algorithm for low-to-moderate aerosols
  - 3-channel algorithm for heavy dust aerosols
- **Deep Blue aerosol products**
  - AOT, Angstrom exponent, and SSA for dust
  - AOT and Angstrom exponent for fine mode and mixed aerosols


darkness
Blue sky
Blue sky bright aerosol
Bright aerosol
brighten dark surface
Dark aerosol
darken bright surface
Bright aerosol
above bright surface

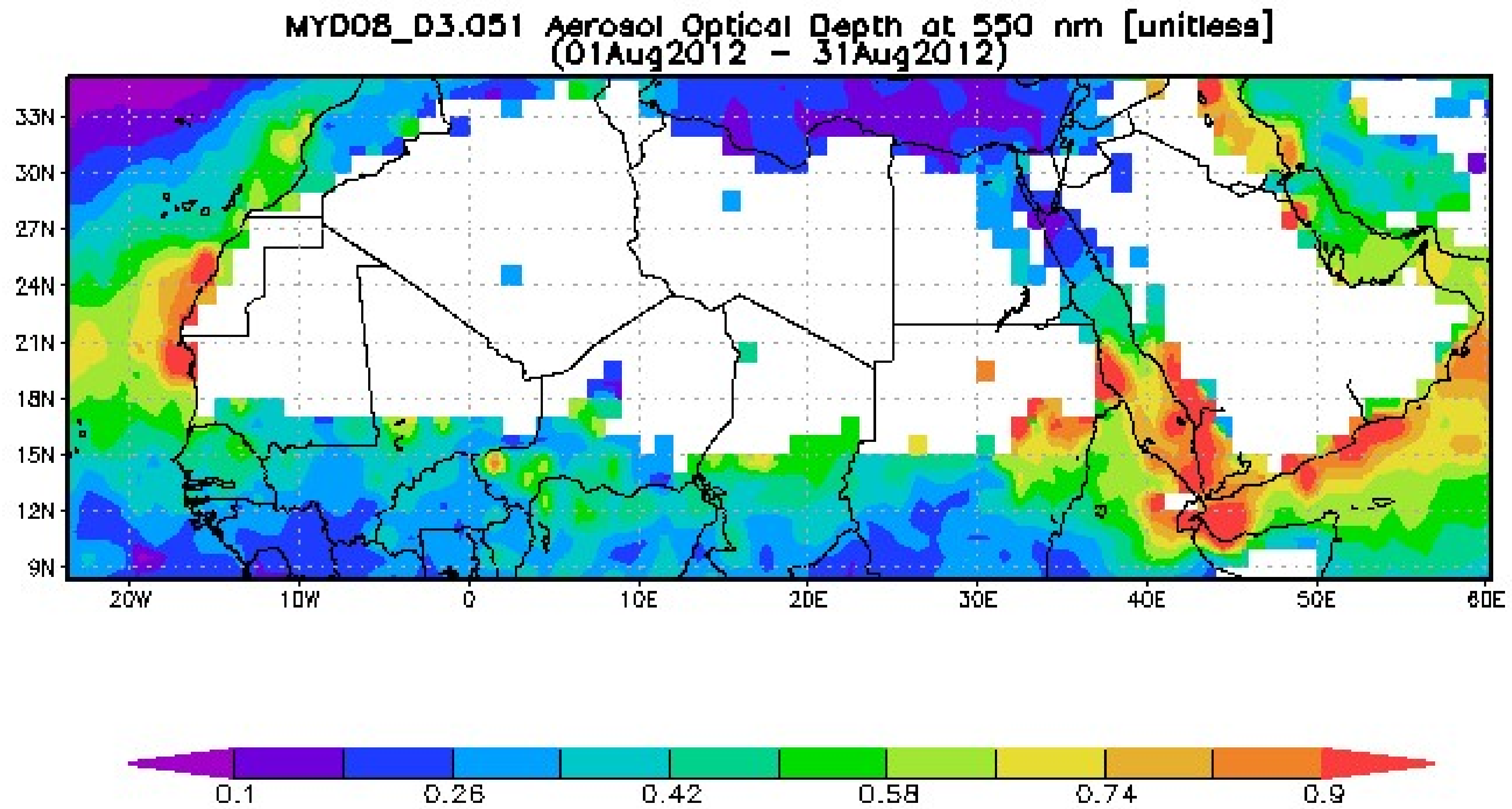
Suppose we want the AOD for this important region of the world …



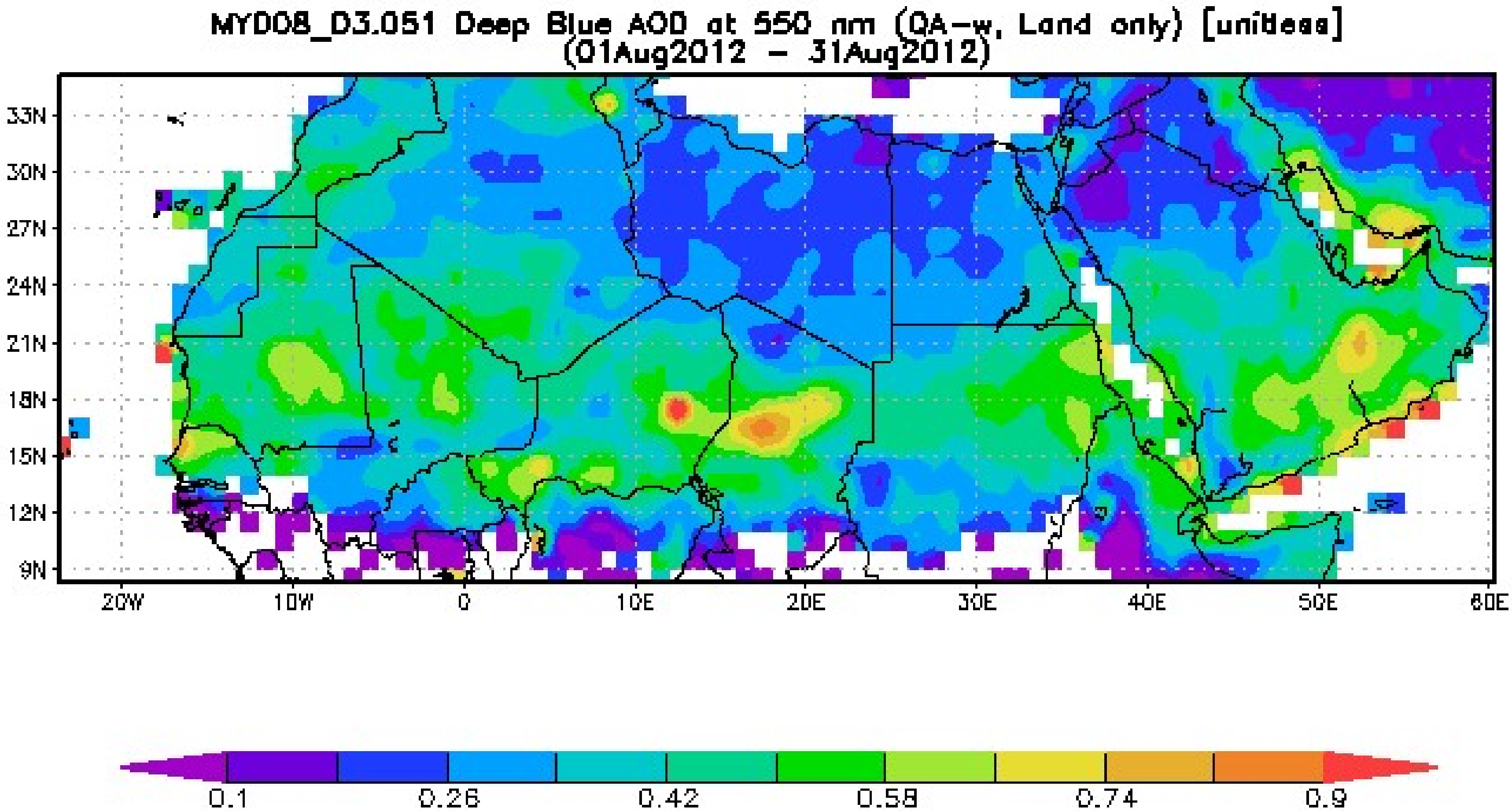
MODIS/TERRA, Standard 'Dark Target' Algorithm, provides no data for most of the region because the surface of the Saharan Desert is so bright.



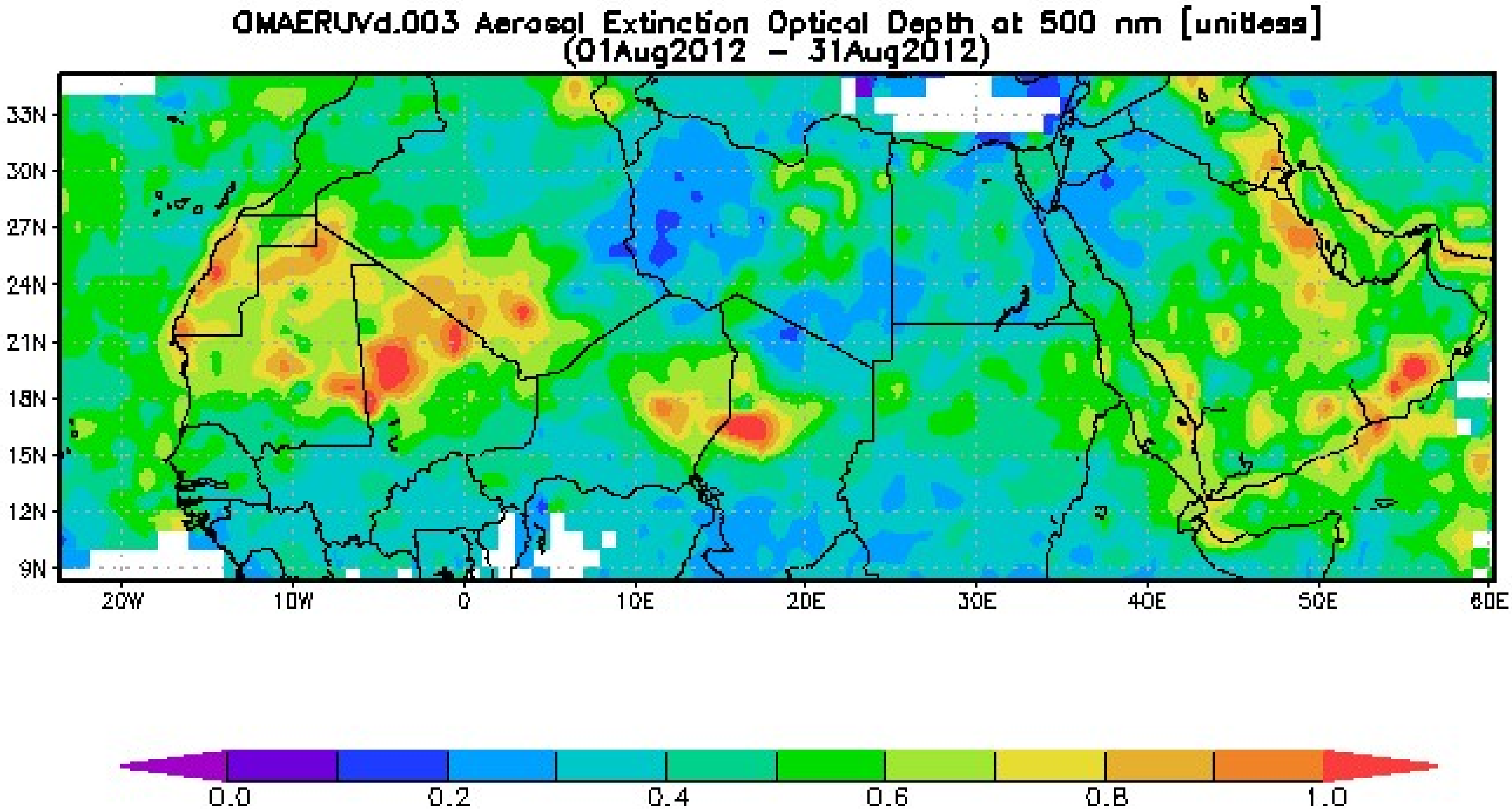
Same for MODIS/AQUA.



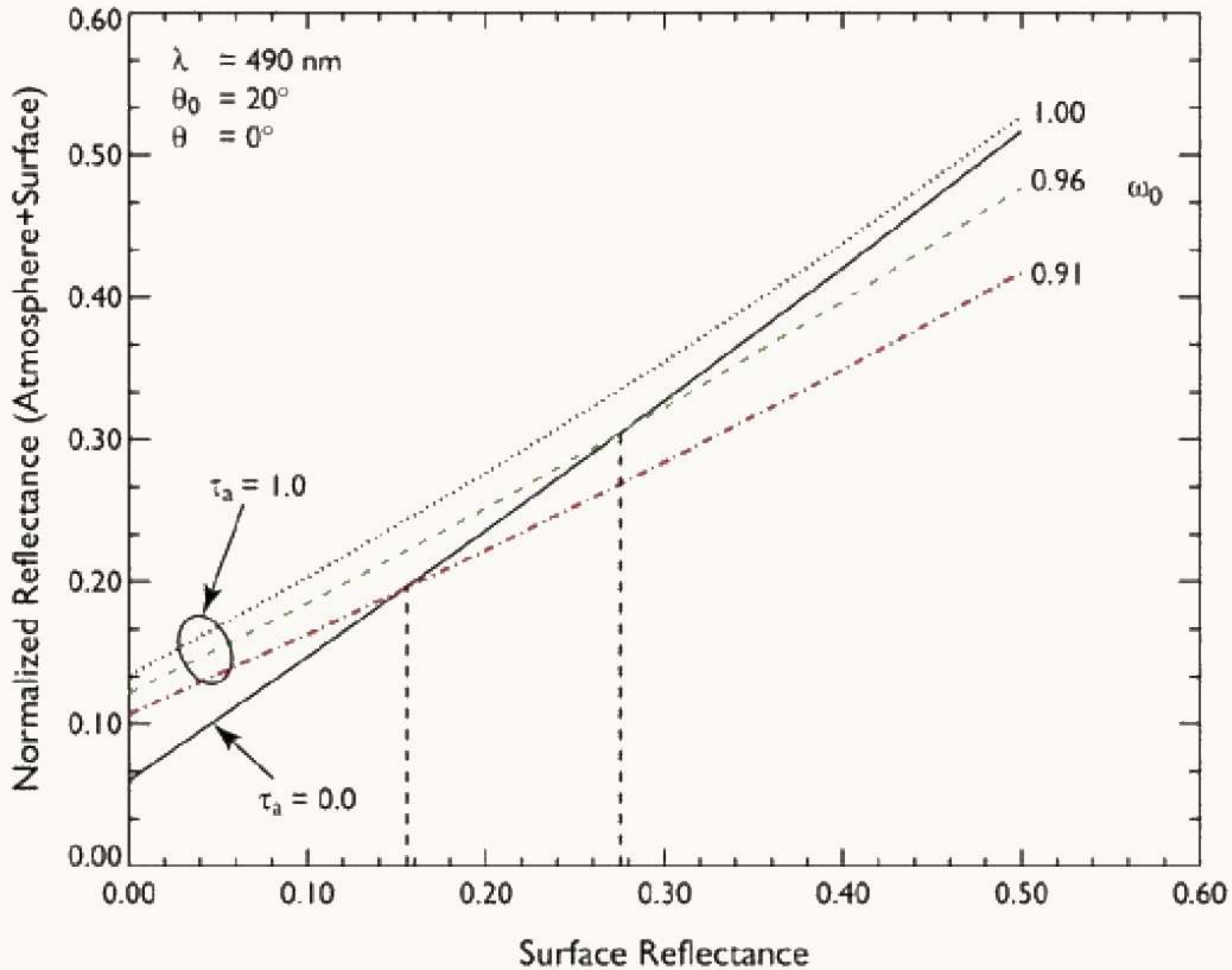
The Deep Blue Algorithm applied to MODIS/AQUA data does provide AOD retrievals ☺



Compare: Aerosol Optical Depth from the Ozone Monitoring Instrument data set retrieval.



Radiative Transfer Model Calculations for Combined Reflectivity by Surface and Atmosphere: Illustrates the problem.



Dashed lines are where clear sky and aerosol laden sky reflectivities are the same: Unique retrieval not possible. Solution(s) for the problem? Use wavelengths where the surface reflectivity is lowest, near UV, e.g. 412 nm.

Review: MODIS 'Dark Target' Aerosol Retrievals Over Land Algorithm

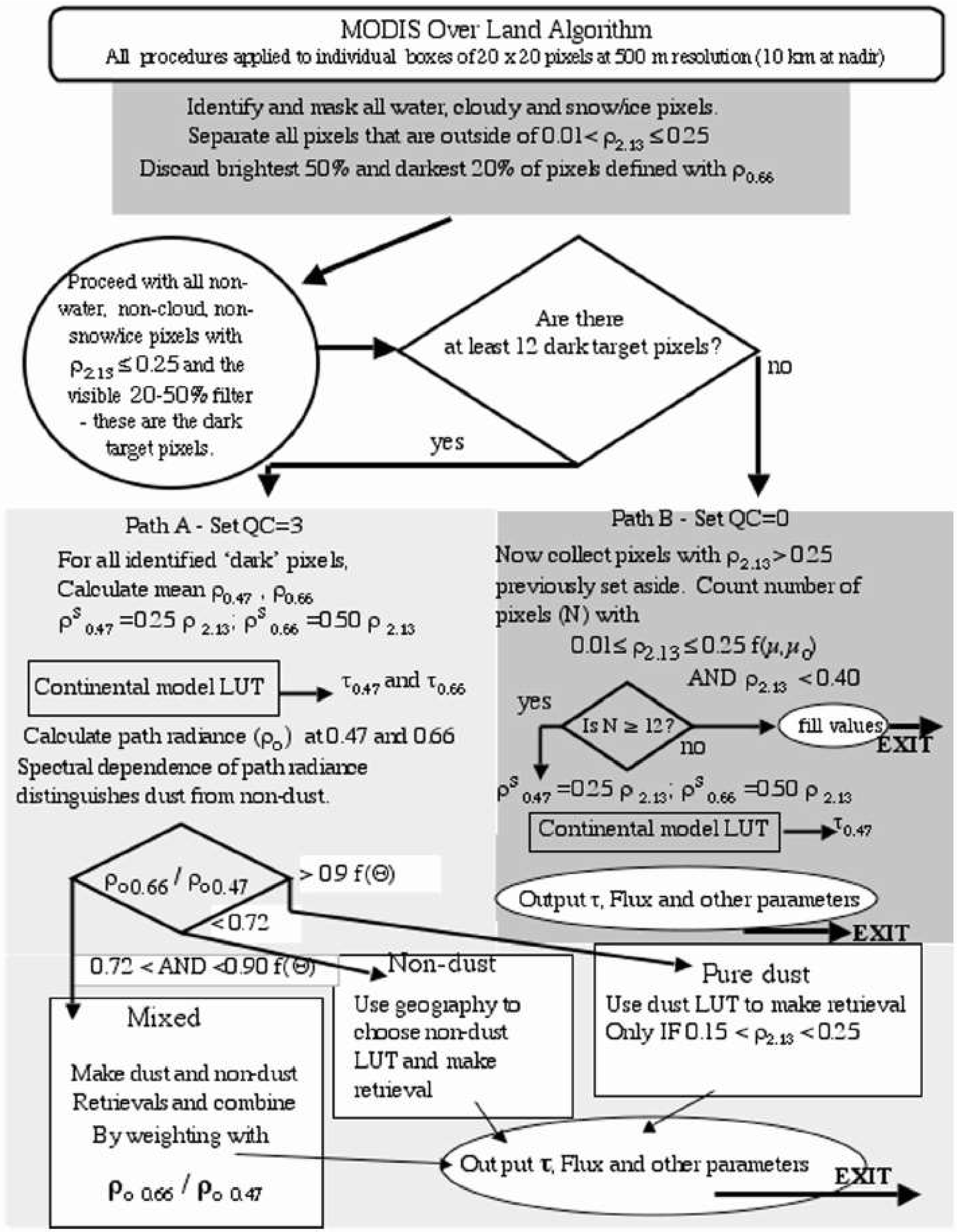


FIG. 1. Flowchart illustrating the derivation of aerosol over land.

Deep Blue AOD Algorithm

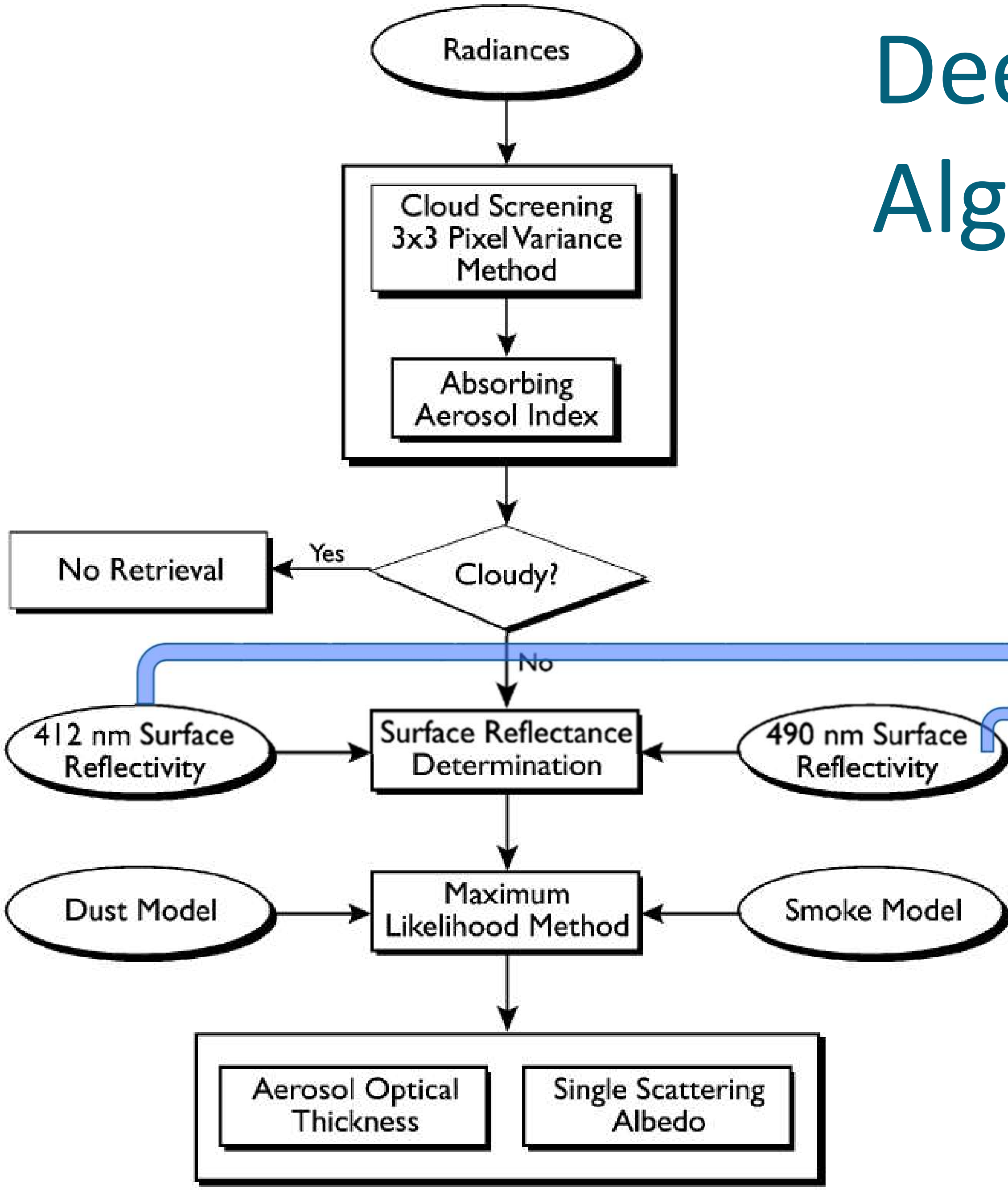


Fig. 4. Flowchart for aerosol optical property retrieval over bright surfaces.

Database from measurements under clear sky conditions, and during different seasons.

Basic Idea: Desert regions are darker at shorter wavelengths so aerosol show up better.

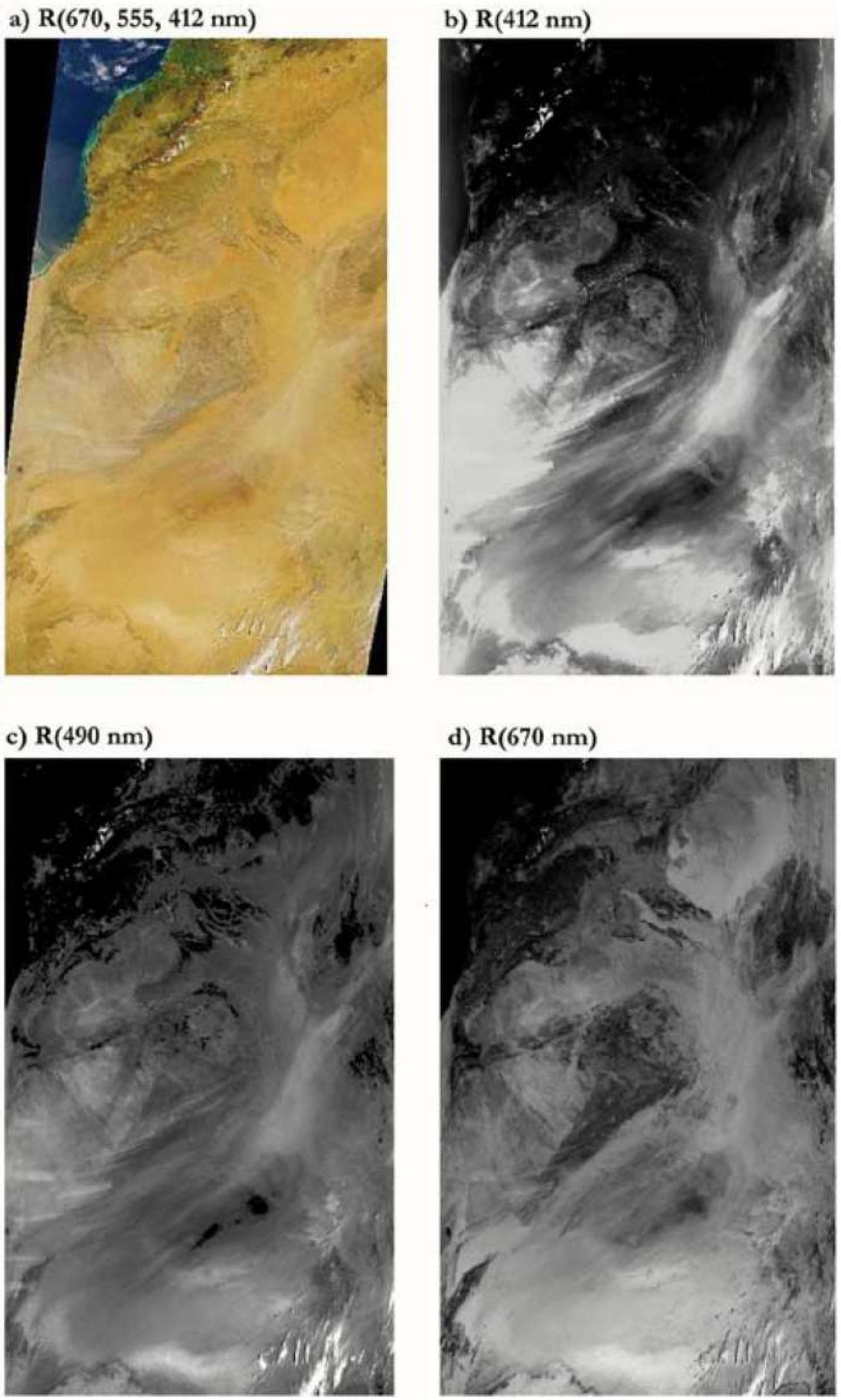
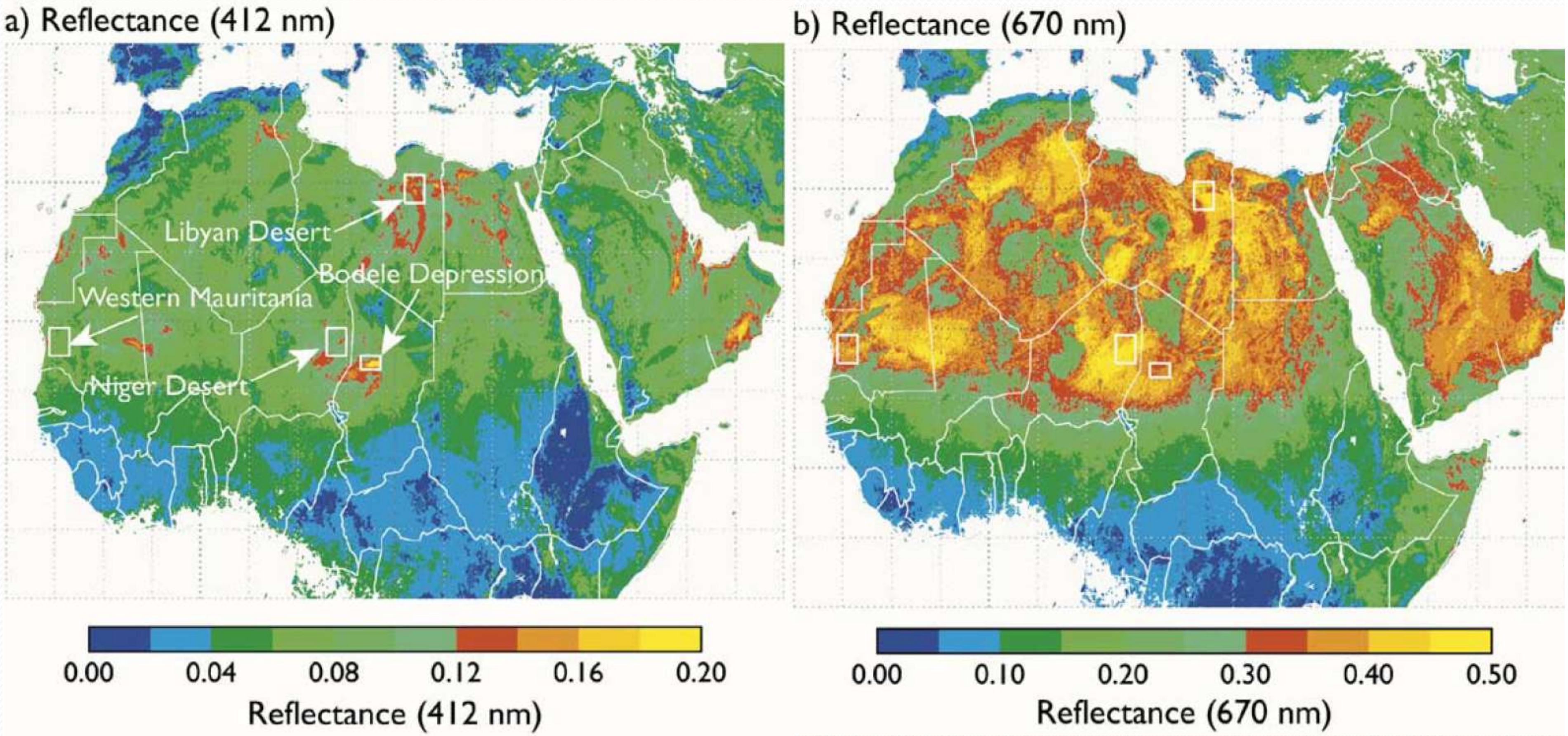


Fig. 2. SeaWiFS images over northeast Africa on February 10, 2001. The dynamical ranges of the grayscale used in (b)–(d) are individually adjusted to optimize the appearance of atmospheric features against the background surfaces.

Surface Reflectance Values Used in The Algorithm



Rapid changes of Vegetation may cause issues.