



Aerosol Observations from Satellites: Brief Theory & Existing Products

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Satellite Remote Sensing of Air Quality, 18-19 November 2018



Objectives

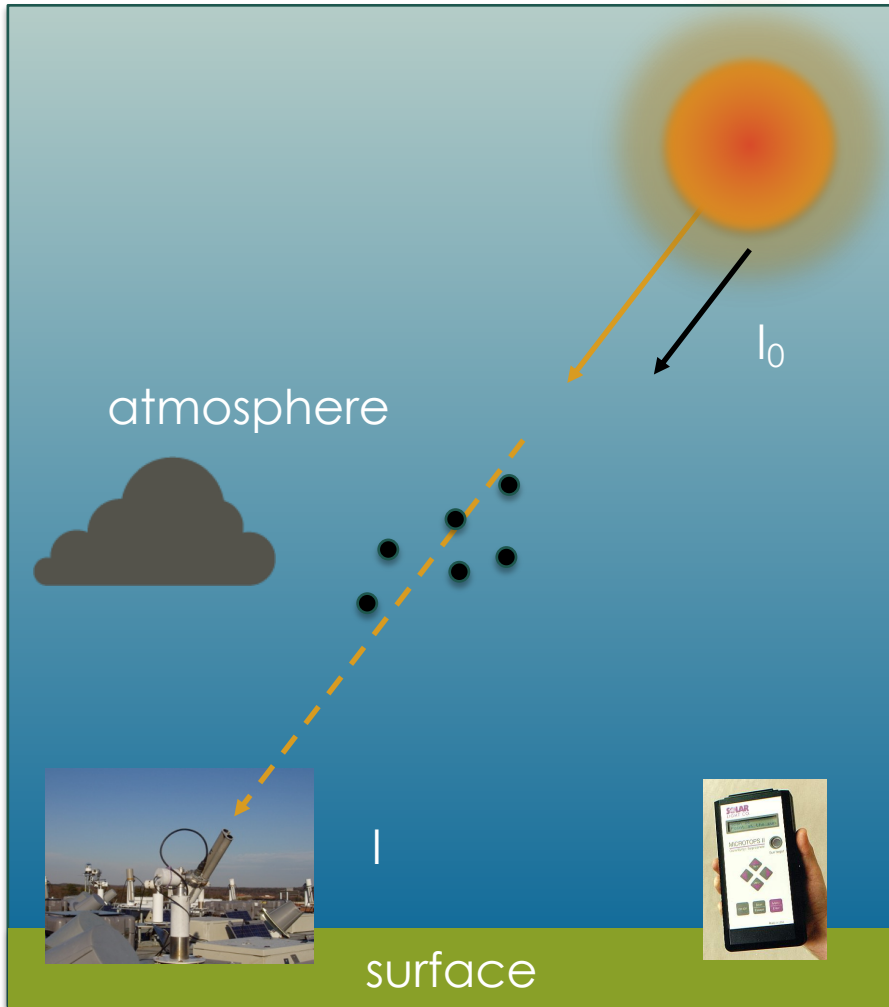
1. Gain a basic understanding of aerosol optical depth
2. Gain knowledge of and ability to access available aerosol products from NASA sensors

Aerosol Optical Depth

- AOD: Aerosol **Optical** Depth
- AOT: Aerosol **Optical** Thickness

- These **optical measurements** of light extinction are used to represent aerosol amounts in the entire column of the atmosphere

Optical Depth



The optical depth expresses the quantity of light removed from a beam by **scattering** or/and **absorption** during its path through a medium

optical depth τ as:

$$I = I_0 e^{-m\tau}$$

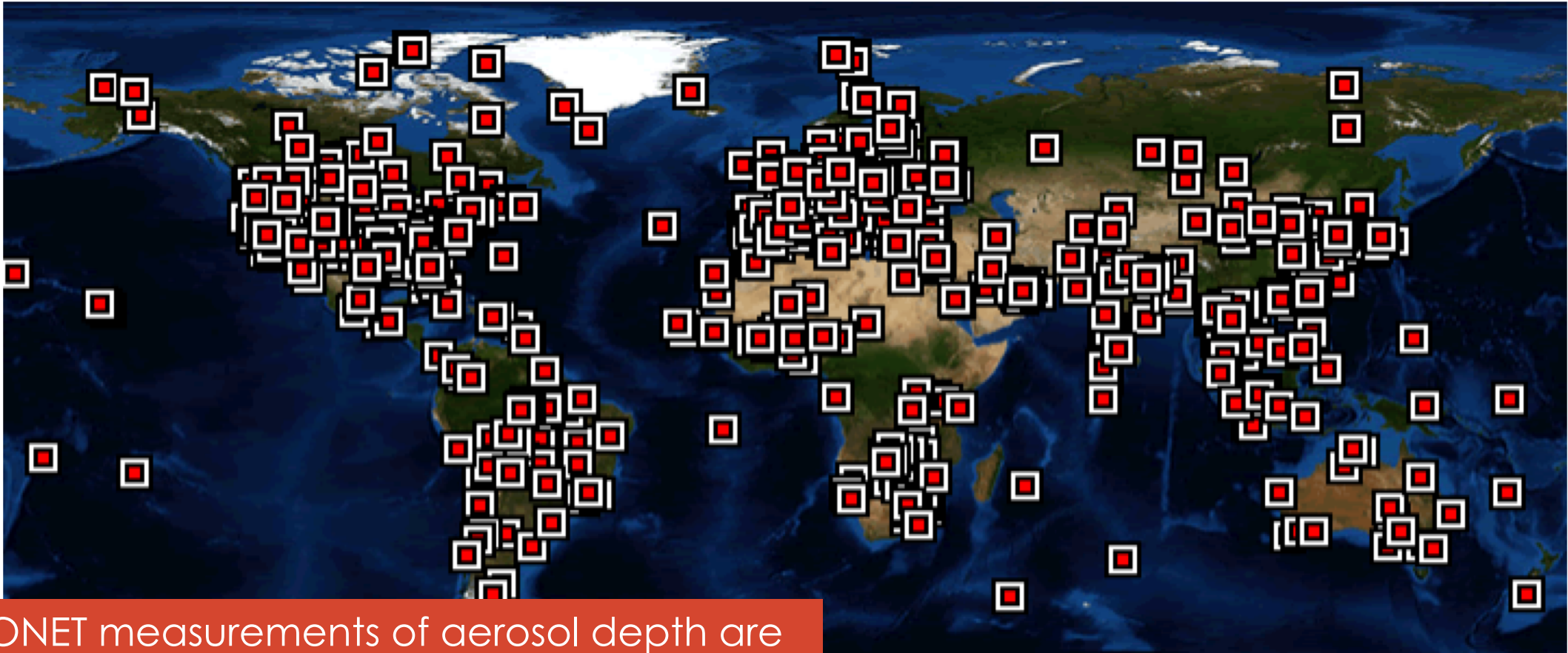
$$m = \sec \theta_0$$

$$\tau = \tau_{Rayl} + \tau_{aer} + \tau_{gas}$$



AERONET

<http://aeronet.gsfc.nasa.gov/>



AERONET measurements of aerosol depth are considered **ground truth** and are used to validate satellite aerosol retrievals



Satellites for Air Quality Data

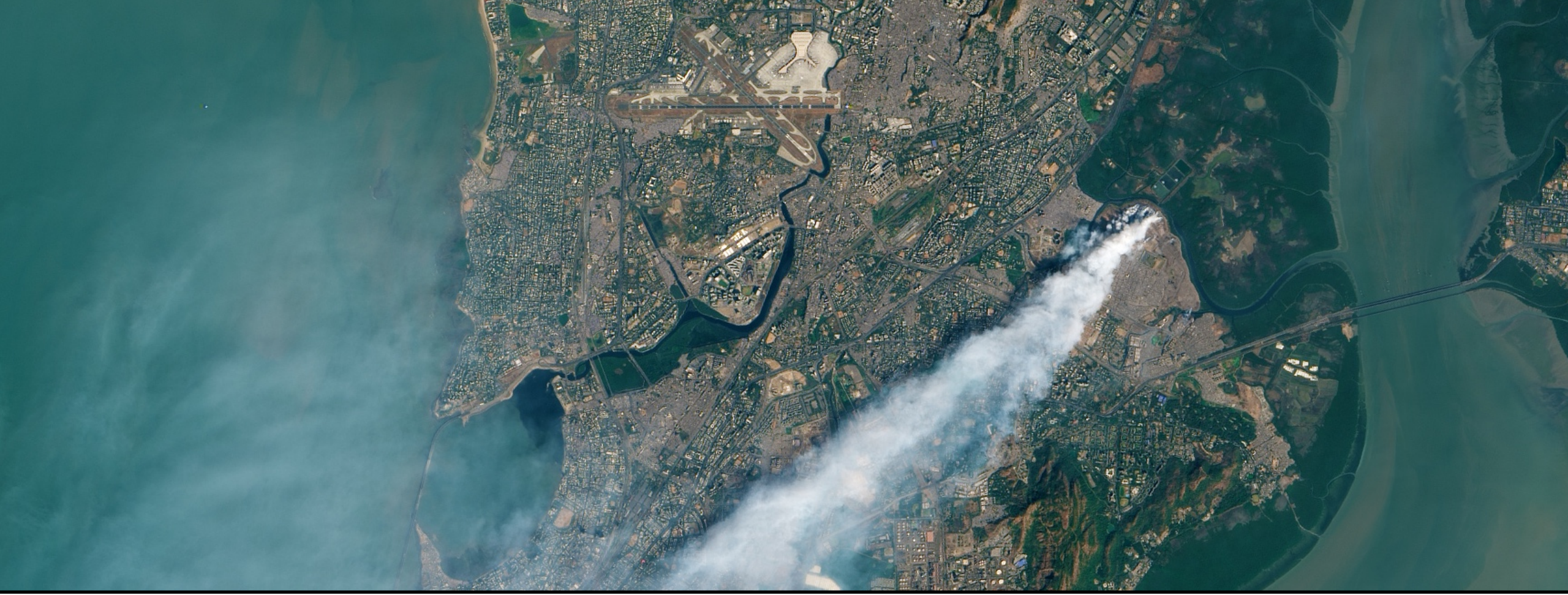
- MODIS (Terra and Aqua)
 - AOD: columnar aerosol loading – can be used to estimate $PM_{2.5}$ or PM_{10}
- MISR (Terra)
 - Columnar aerosol loading in different particle size bins
 - In some cases aerosol heights
- OMI (Aura)
 - Absorbing aerosols, total aerosols
 - Trace gases
- VIIRS (NPP, JPSS)
 - Aerosol optical depth
 - Aerosol type

CALIPSO, POLDER, etc. and more recent are TROPOMI, GOES-R, GOES-S

Instrument Capabilities for Air Quality

Sensor Measurement: Spatial Resolution

MODIS:	250 m – 1 km
MISR:	275 m – 1.1 km
OMI:	13 x 24 km
VIIRS:	750 m



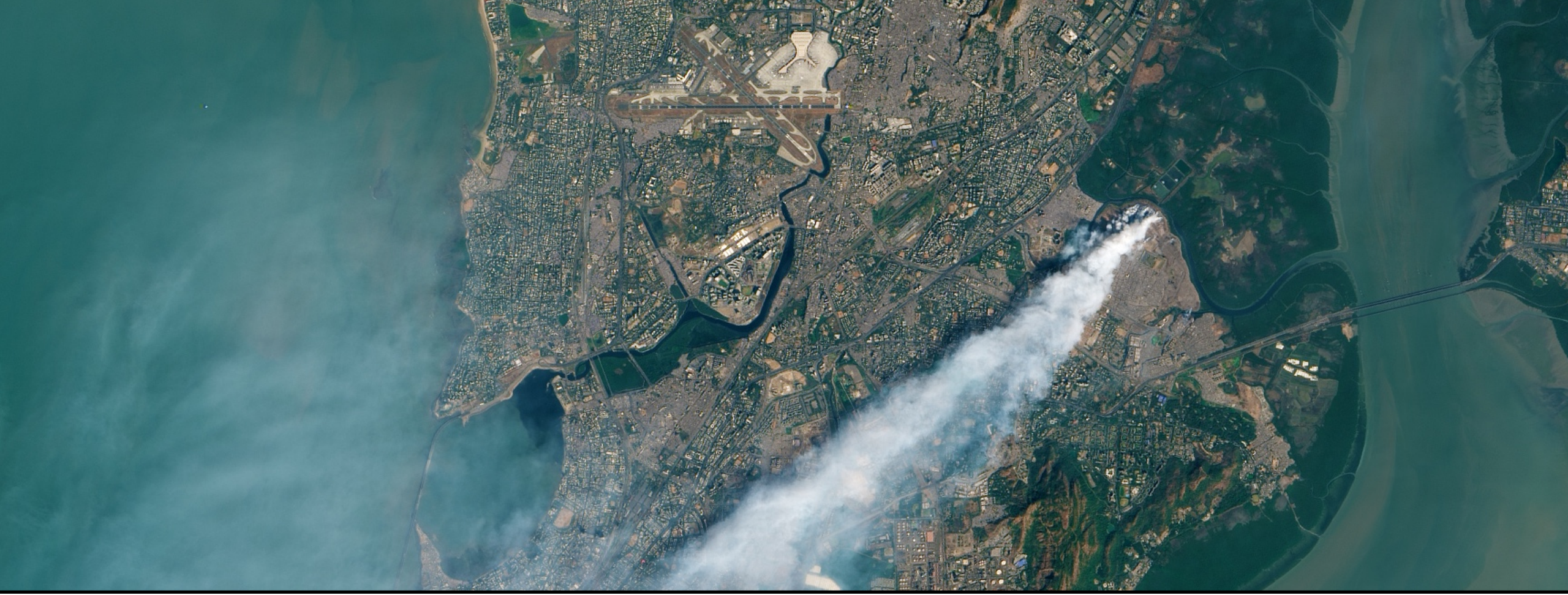
MODIS

MODerate resolution Imaging Spectroradiometer

- 2000 - present
- Spatial Resolution
 - 250 m, 500 m, 1 km
- Platform
 - Terra & Aqua
- Temporal Resolution
 - Daily, 8-day, 16-day, monthly, quarterly, yearly
- Data Format
 - Hierarchical Data Format – Earth Observing System Format (HDF-EOS)

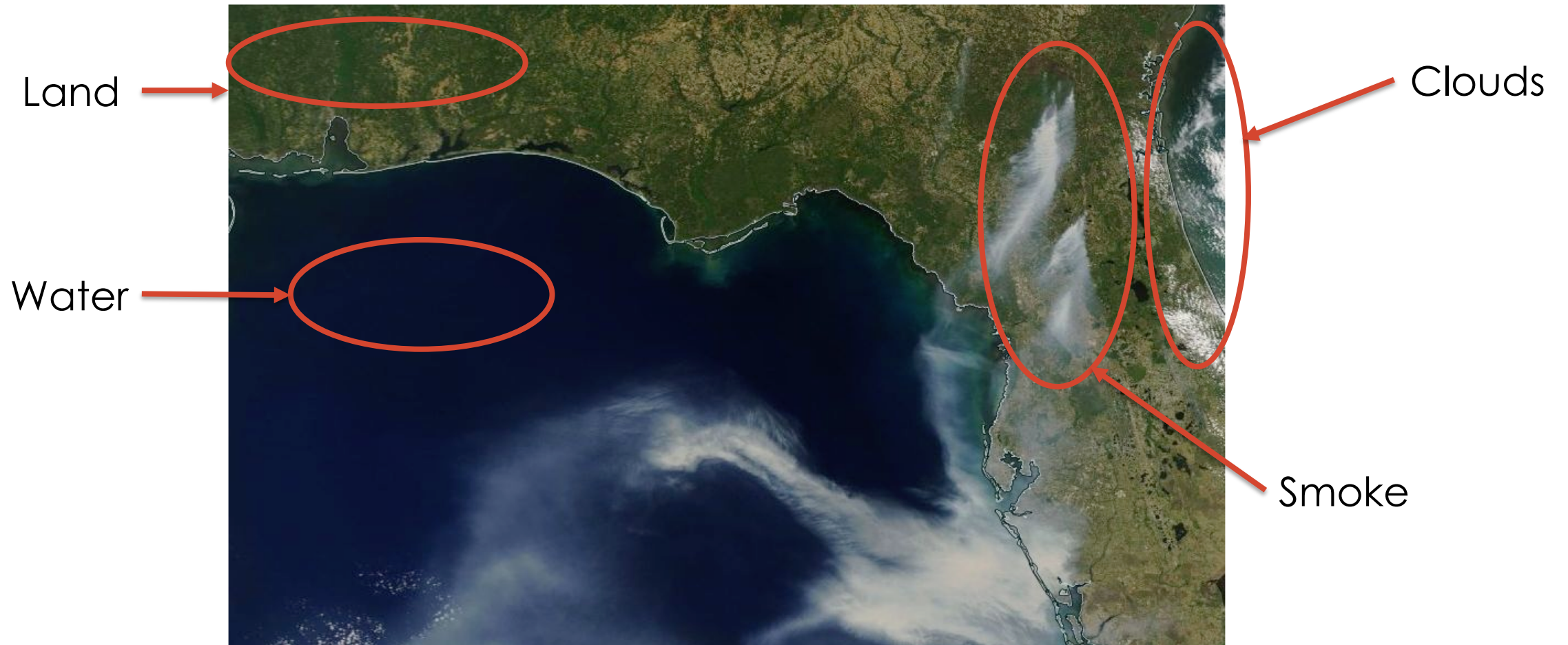


- Spectral Coverage
 - 36 bands (major bands include red, blue, IR, NIR, MIR)
 - Bands 1-2: 250 m
 - Bands 3-7: 500 m
 - Bands 8-36: 1,000 m



Aerosol Retrieval

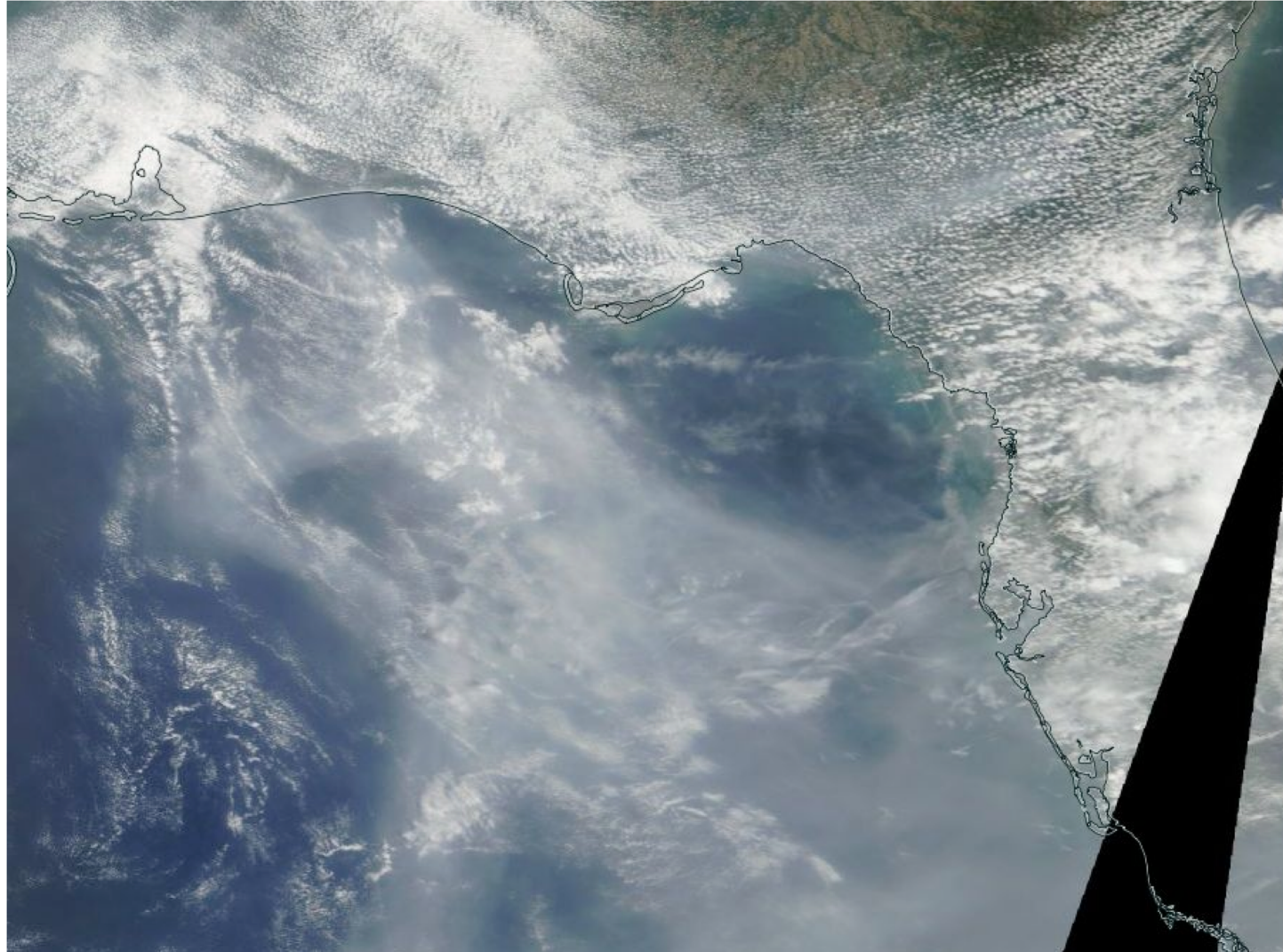
Aerosol Detection



Terra MODIS, May 8, 2007



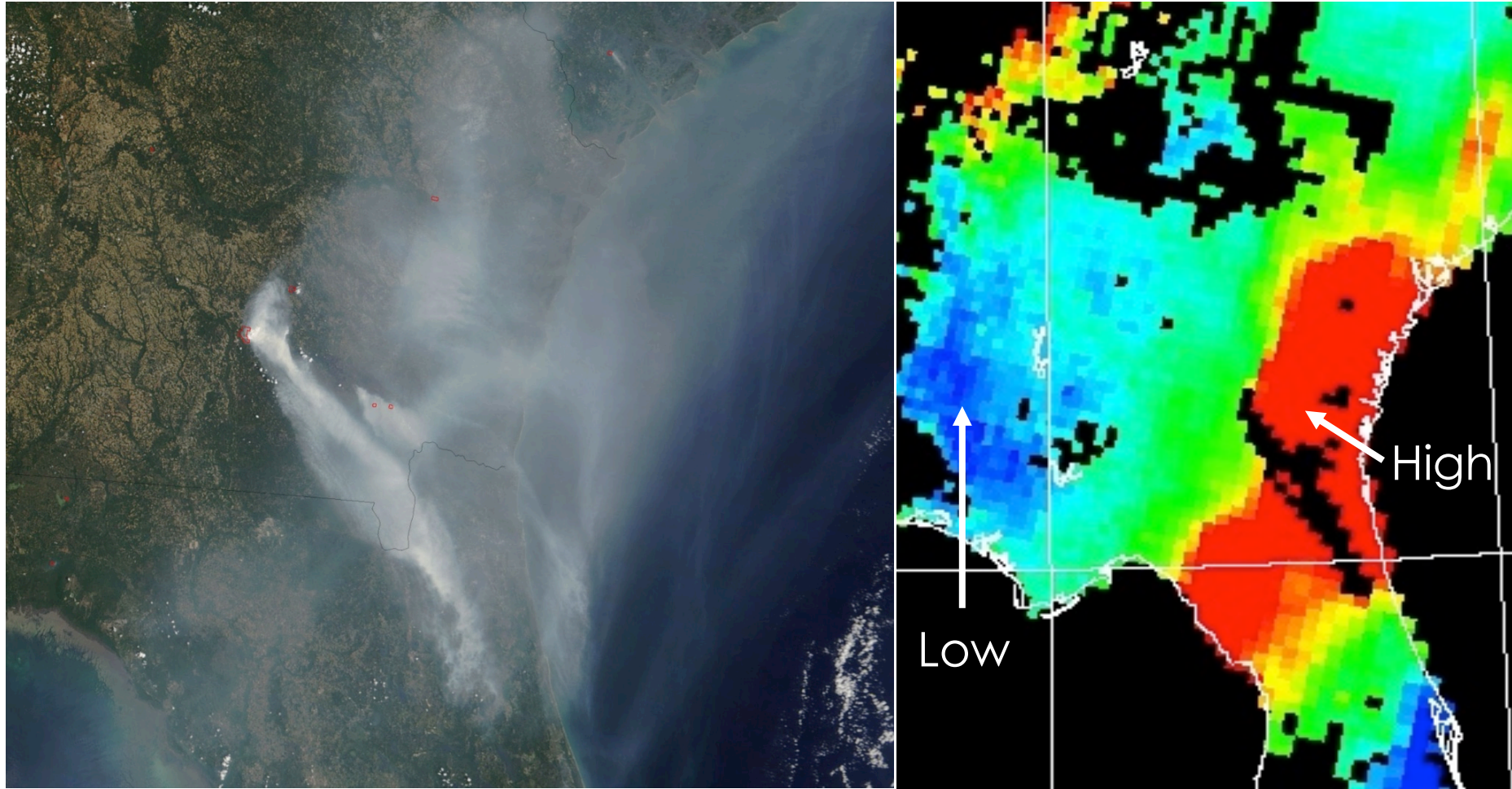
Complex Image: Smoke & Clouds



Terra MODIS, May 14, 2007



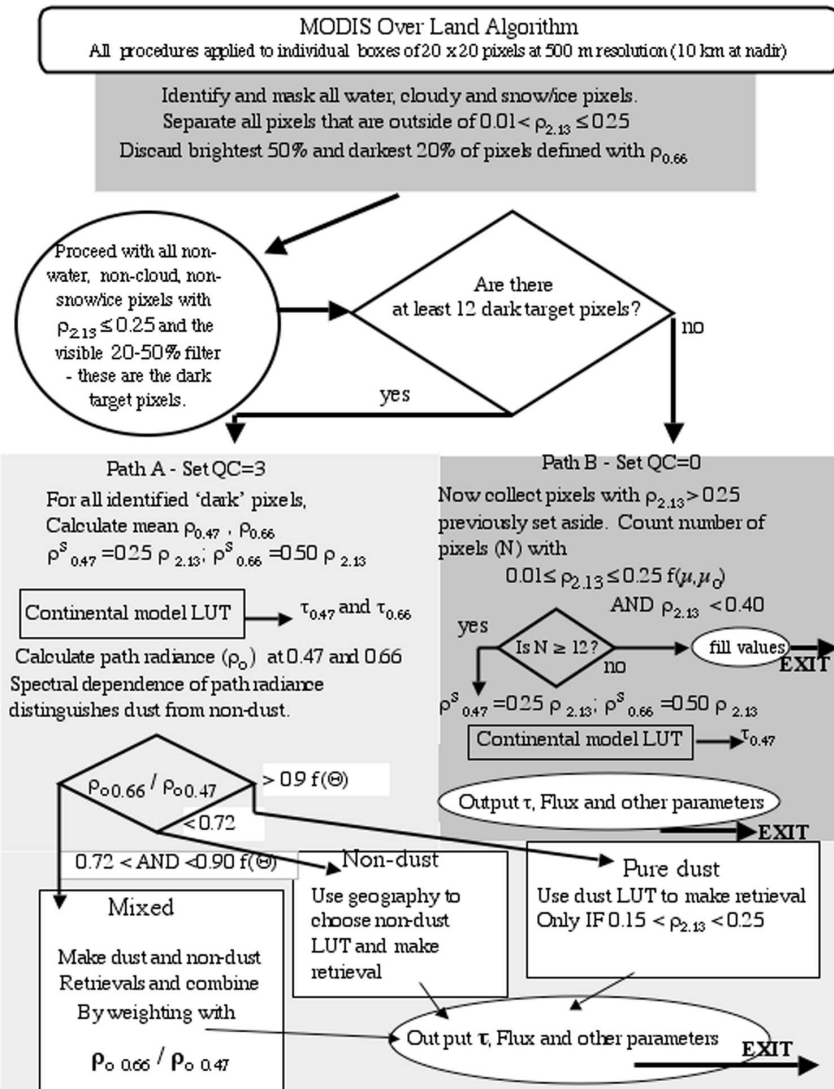
Radiance to Aerosol Products



Terra MODIS, May 2, 2007



Aerosol Retrieval Algorithm



Aerosol retrieval algorithm is a complex inversion scheme where assumptions are made in simulating satellite observations with advanced radiative transfer calculations to retrieve atmospheric aerosol properties

Sources: Remer et al., 2005, Levy et al., 2013



MODIS Products

MOD01 Level-1A Radiance Counts

MOD02 Level-1B Calibrated Geolocated Radiances – also Level 1B "subsampled" 5kmx5km pro

MOD03 Geolocation Data Set

MOD04 Aerosol Product

MOD05 Total Precipitable Water

MOD06 Cloud Products

MOD07 Atmospheric Profiles

MOD08 Gridded Atmospheric Product (Level 3)

MOD09 Atmospherically-corrected Surface Reflectance

MOD10 Snow Cover

MOD11 Land Surface Temperature & Emissivity

MOD12 Land Cover/Land Cover Change

MOD13 Vegetation Indices

MOD14 Thermal Anomalies, Fires & Biomass Burning

MOD15 Leaf Area Index & FPAR

MOD16 Surface Resistance & Evapotranspiration

MOD17 Vegetation Production, Net Primary Productivity

MOD18 *Normalized Water-leaving Radiance

MOD19 Pigment Concentration

MOD20 Chlorophyll Fluorescence

MOD21 *Chlorophyll_a Pigment Concentration

MOD22 Photosynthetically Active Radiation (PAR)

MOD23 Suspended-Solids, Conc, Ocean Water

MOD24 Organic Matter Concentration

MOD25 Coccolith Concentration

MOD26 *Ocean Water Attenuation Coefficient

MOD27 Ocean Primary Productivity

MOD28 *Sea Surface Temperature

MOD29 Sea Ice Cover

MOD32 Processing Framework & Match-up Database

MOD33 Gridded Snow Cover

MOD34 Gridded Vegetation Indices

MOD35 Cloud Mask

MOD36 Total Absorption Coefficient

*MOD37 Ocean Aerosol Optical Thickness

MOD39 Clear Water Epsilon

MOD43 Albedo 16-day L3

MOD44 Vegetation Cover Conversion

MYD – MODIS Aqua

MOD – MODIS Terra



A Few More Things About MODIS Data...

- MOD: Terra product
- MYD: Aqua product

- All MODIS products come in **HDF** format

- In HDF format each file contains both data and metadata

- **Scientific Data Set (SDS)**: each parameter within a MODIS HDF file is referred to as a SDS
 - Each SDS must be referenced precisely according to name when analyzing the data within your own computer code



Things That Change with Each Instrument

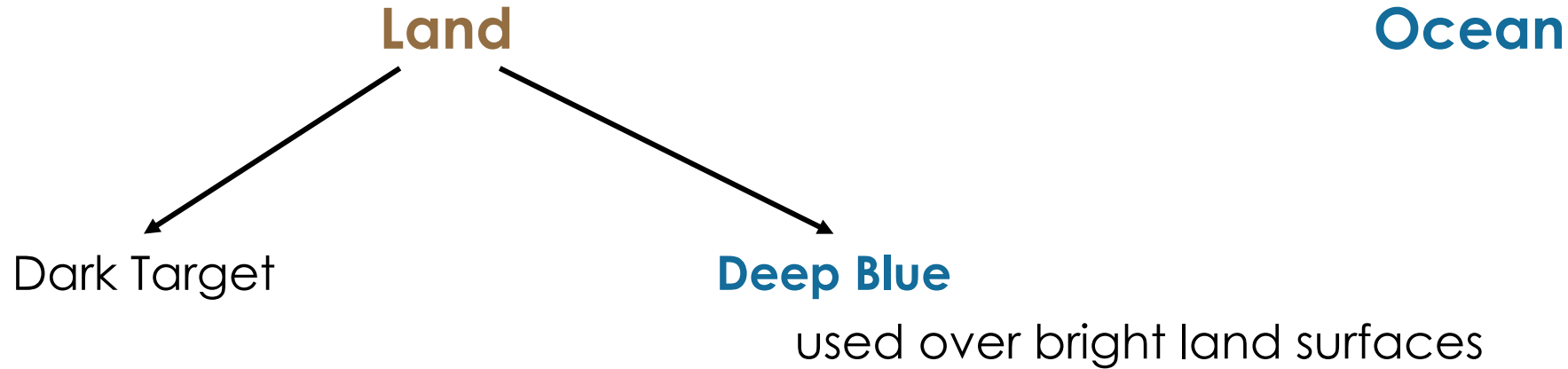
(So you need to learn them!)

- Calibration Accuracy
- Quality Assurance – quality of the data
- Data Formats
- Product Resolutions
- Creating Level 3 products from Level 2
 - temporal and spatial averaging
- Current data release and data history



MODIS Aerosol Products

Three Separate Algorithms

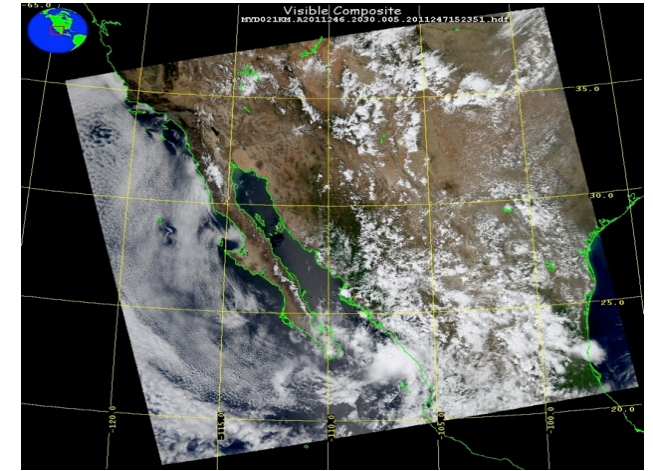


- The dark target and deep blue products are separate and when both are available, the user must select which to use
- In collection 6, there is a joint product that uses an automated procedure to select the appropriate product

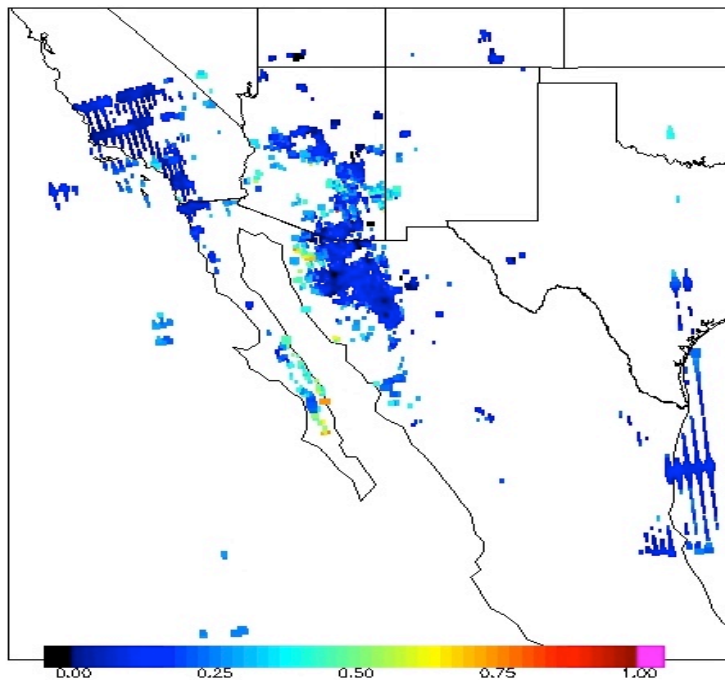


MODIS Aerosol Products

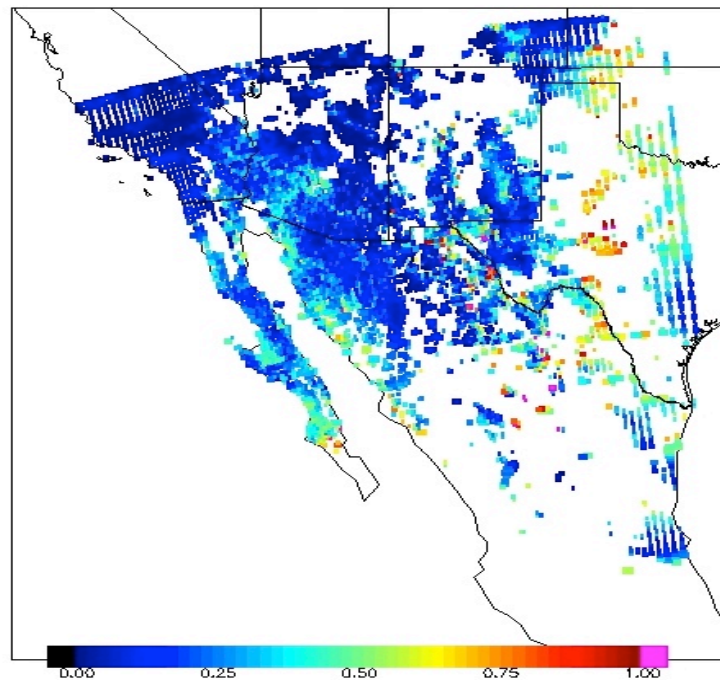
Two Algorithms



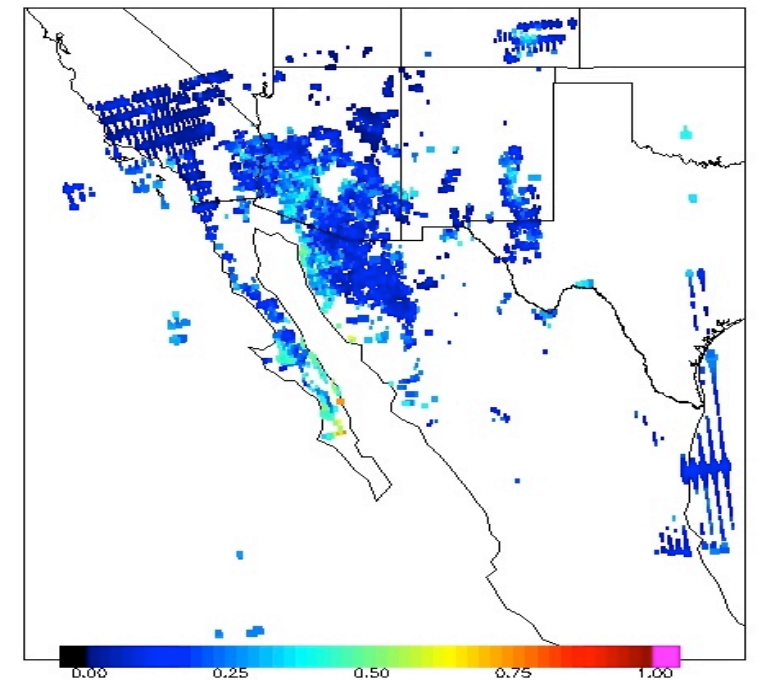
Dark Target



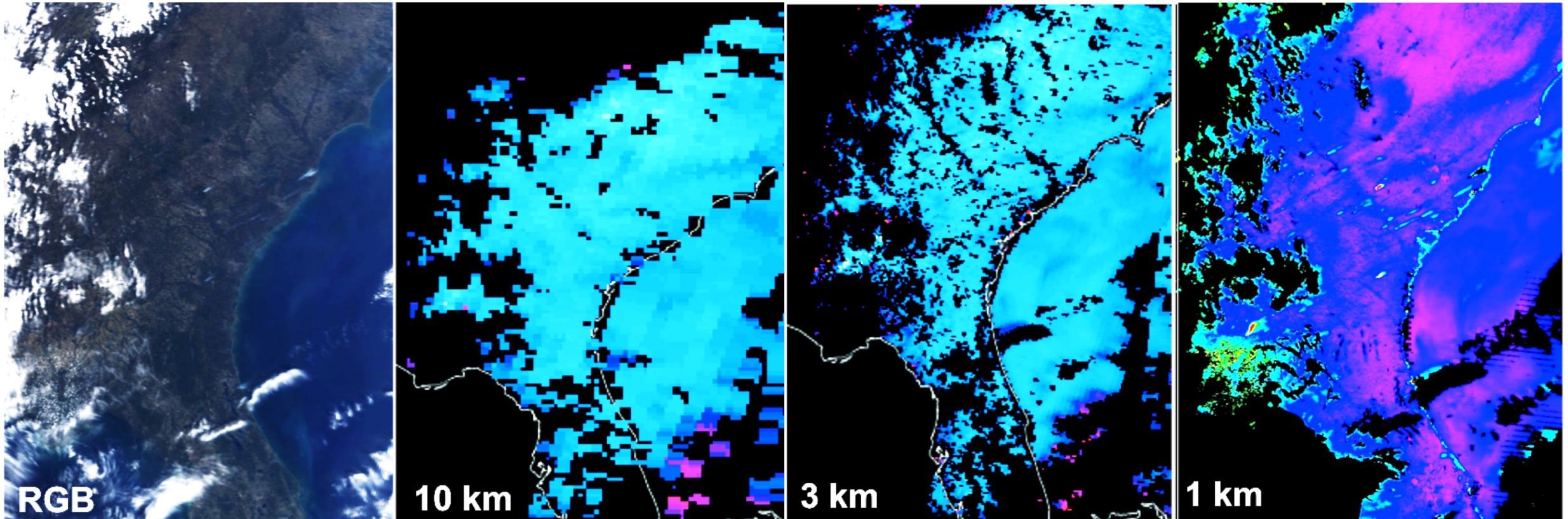
Deep Blue



Deep_Dark_Combined



High Resolution Aerosol Product



Quality Assurance is Extremely Important

QA indicates confidence in the quality of the retrieval

Quality_Assurance_Ocean

- Scale is 0 – 3
- Recommended Ocean QA above 1, 2, 3
- Factors:
 - number of pixels
 - error fitting
 - **how close to glint**

Quality_Assurance_Land

- Scale is 0 – 3
- Recommended Land QA of 3
- Factors:
 - number of pixels
 - error fitting
 - **surface reflectance**

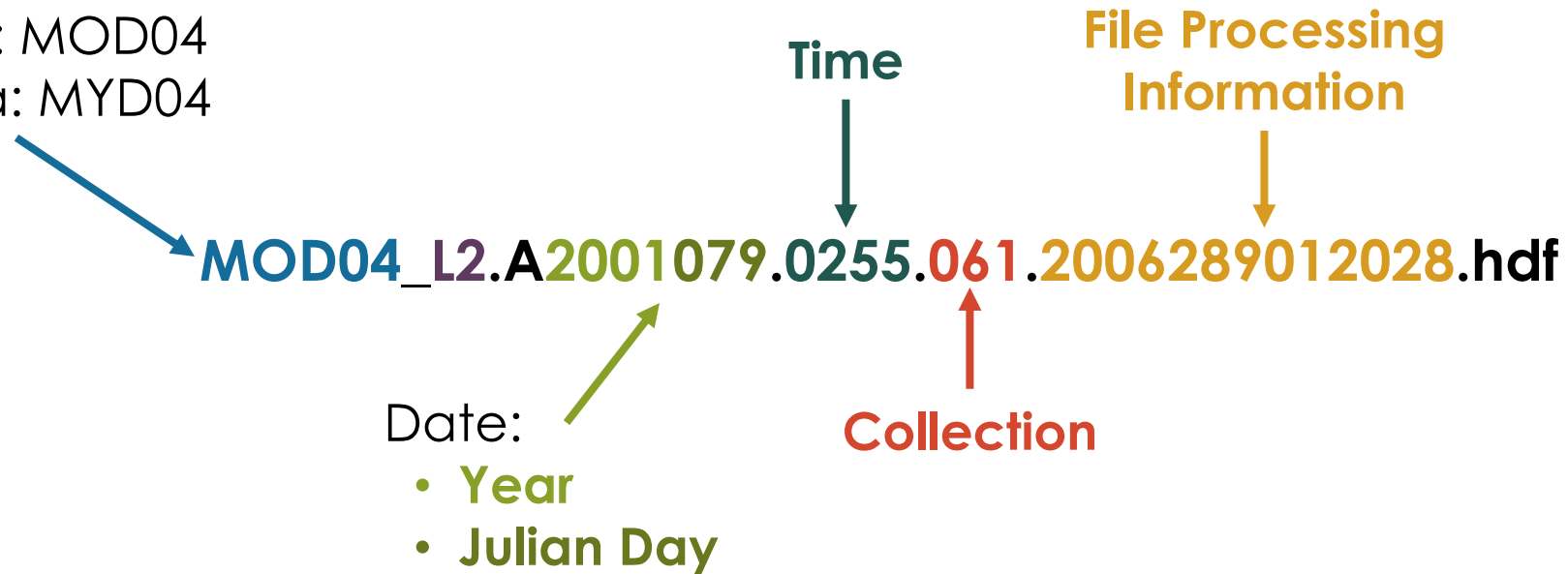


Understanding a MODIS File Name

Level 2, 10 km, Aerosol Product

Product Name:

- Terra: MOD04
- Aqua: MYD04



HDFLook, Panoply, IDL, Python, Fortran, MatLab, and more can be used to read the data

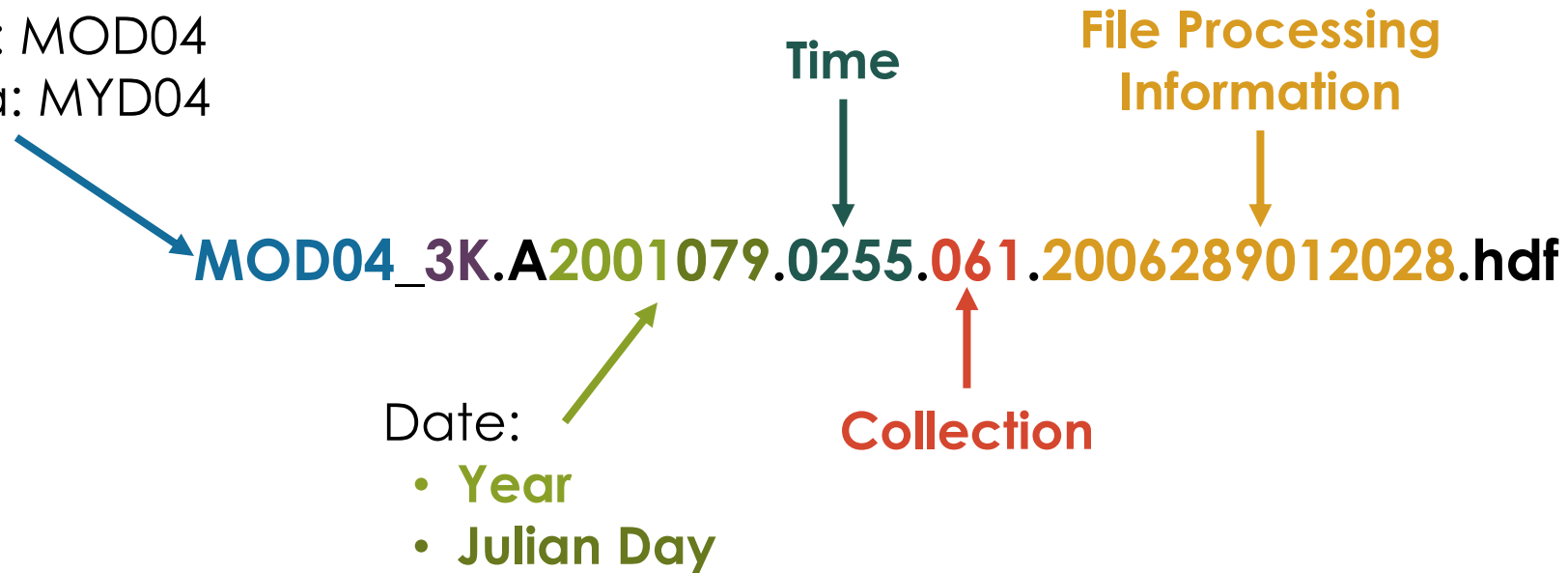


Understanding a MODIS File Name

Level 2, 3 km, Aerosol Product

Product Name:

- Terra: MOD04
- Aqua: MYD04



HDFLook, Panoply, IDL, Python, Fortran, MatLab, and more can be used to read the data

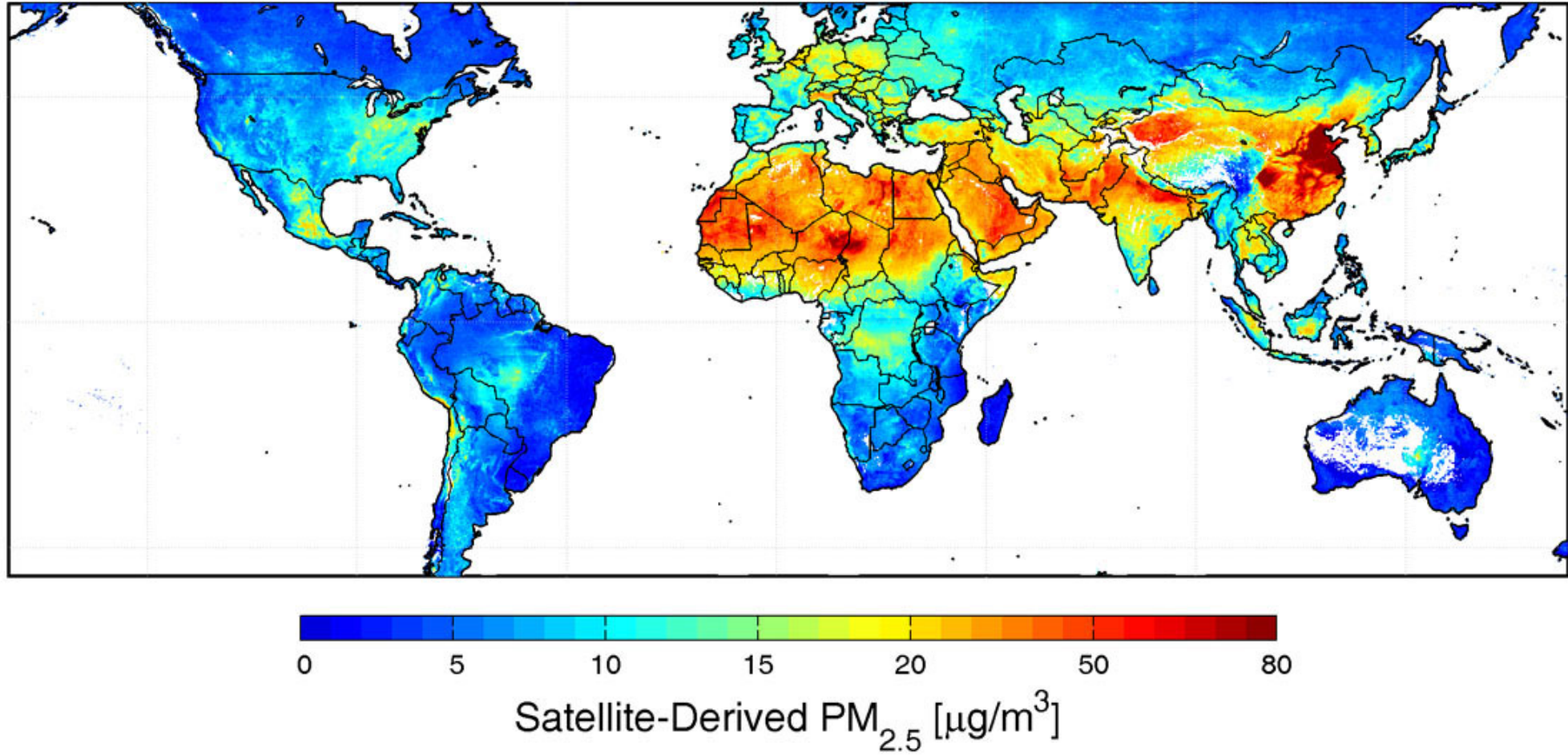


MODIS Aerosol Parameters (SDS)

- Optical_Depth_Land_and_Ocean
 - Retrieved using Dark Target Algorithm
 - Only high quality data
 - Over land QA = 3
 - Over ocean QA = 1, 2, 3
 - 10 km and 3km
- Dark_Target_Deep_Blue_Optical_Depth_550_Combined
 - Deep Blue & Dark Target Algorithm Merged Product
 - 10km only
- Dark_Target_Deep_Blue_Optical_Depth_550_Combined_QA
 - Quality flag associated with DD product



Application of MODIS Aerosol Product



Source: van Donkelaar et al., 2006, 2009



Access to MODIS Aerosol Products

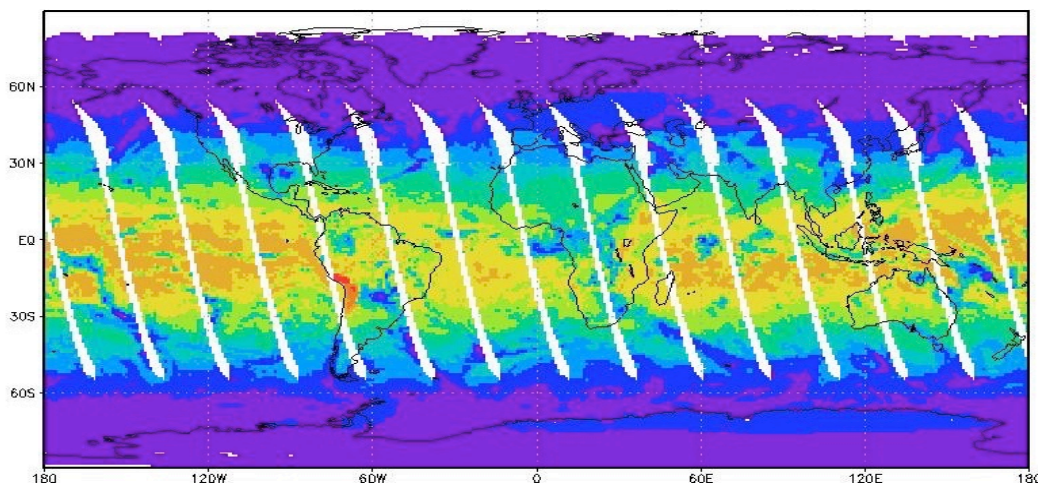
- NASA LAADSWeb
 - Searchable database, FTP access
 - <https://ladsweb.modaps.eosdis.nasa.gov/>
- MODIS-Atmos Site
 - Complete RGB archive with Level 3 product imagery
 - <http://modis-atmos.gsfc.nasa.gov/>
- Giovanni for Level 3 data sets
 - Web tool for imagery visualization and analysis
 - <https://giovanni.gsfc.nasa.gov/giovanni/>
- Dark Target Algorithm Site
 - <http://darktarget.gsfc.nasa.gov/>
- Deep Blue Algorithm Site
 - <http://deepblue.gsfc.nasa.gov/>





OMI -- and OMPS

Ozone Monitoring Instrument (OMI)



Instrument Characteristics

- Nadir solar backscatter spectrometer
- Spectral Range: 270-500 nm
 - Resolution ~1 nm
- Swath Width: 2,600 km
 - Global daily coverage with 13x24 km spatial resolution

- One of four sensors on the EOS-Aura platform
 - OMI, MLS, TES, HIRDLS
- An international project
 - Netherlands, USA, Finland
- Launched July 15, 2004

Retrieval Products

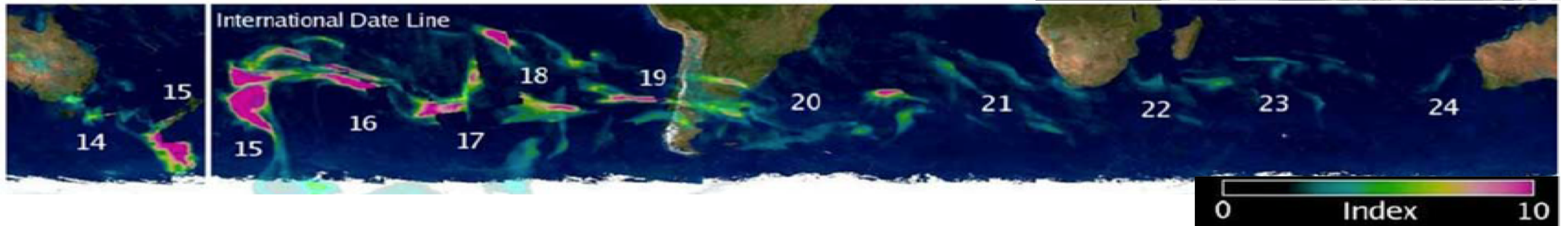
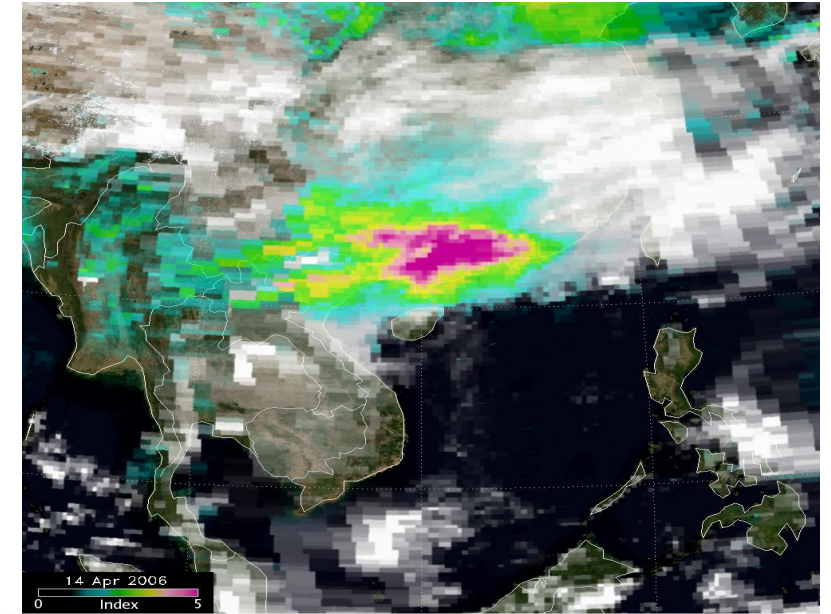
- Column Amounts
 - Ozone (O_3)
 - Nitrogen Dioxide (NO_2)
 - Sulfur Dioxide (SO_2)
 - Others
- Aerosols



Applications of the Aerosol Index

- Validation tool for transport models
- Separation of carbonaceous from sulfate aerosols
- Tracking of aerosol plumes above clouds and over ice and snow

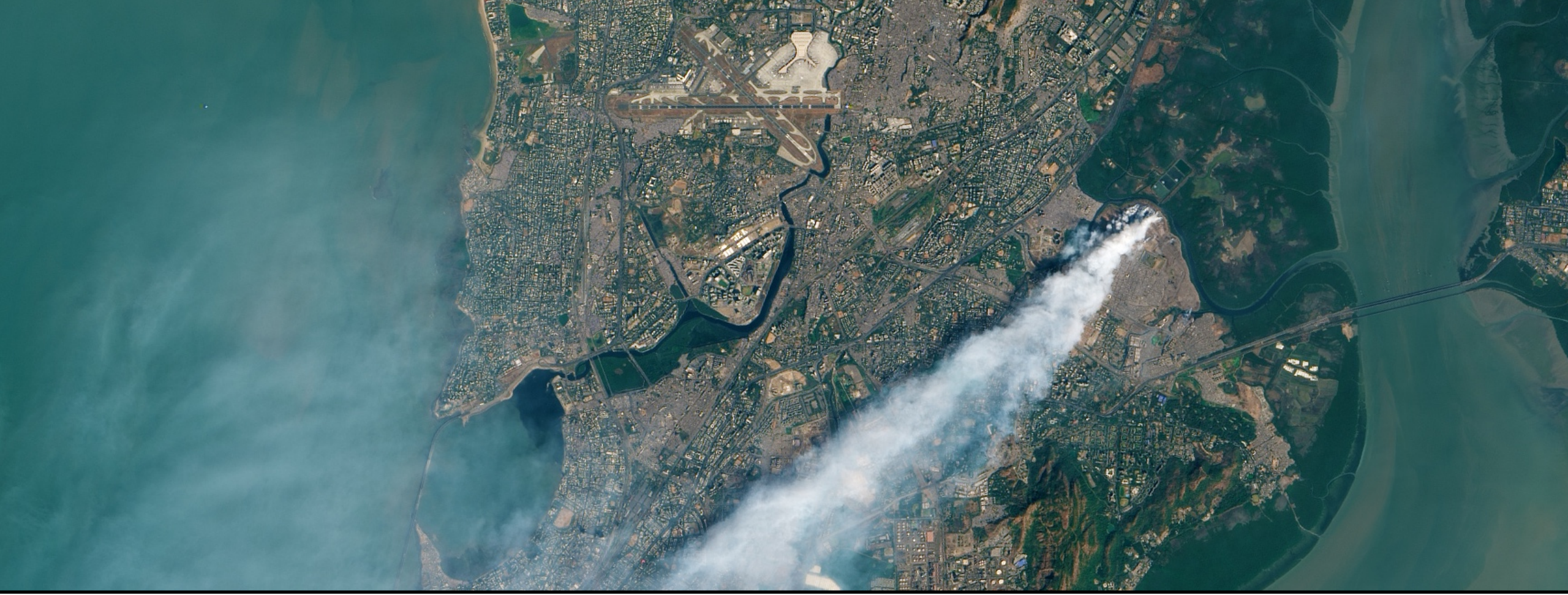
Aerosols Over Clouds, April 14, 2006



Above: Transport around the globe of a high altitude smoke layer generated by the Dec 2006 Australian fires. Numbers indicate the day of the month.

Image Credit: Torres, Omar & Tanskanen, Aapo & Veihelmann, Ben & Ahn, Changwoo & Braak, Remco & Bhartia, Pawan & Veefkind, Pepijn & Levelt, P. (2007).

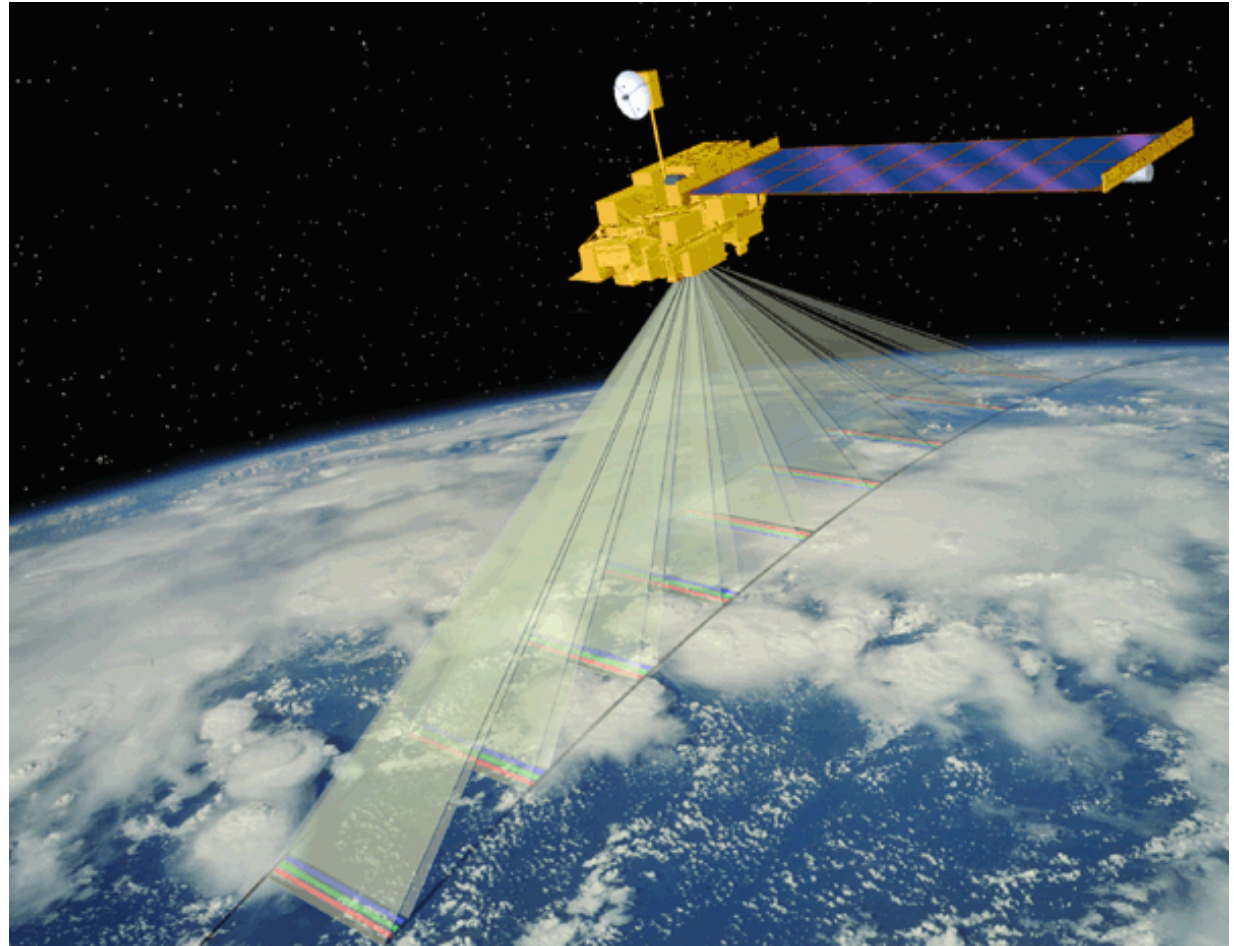




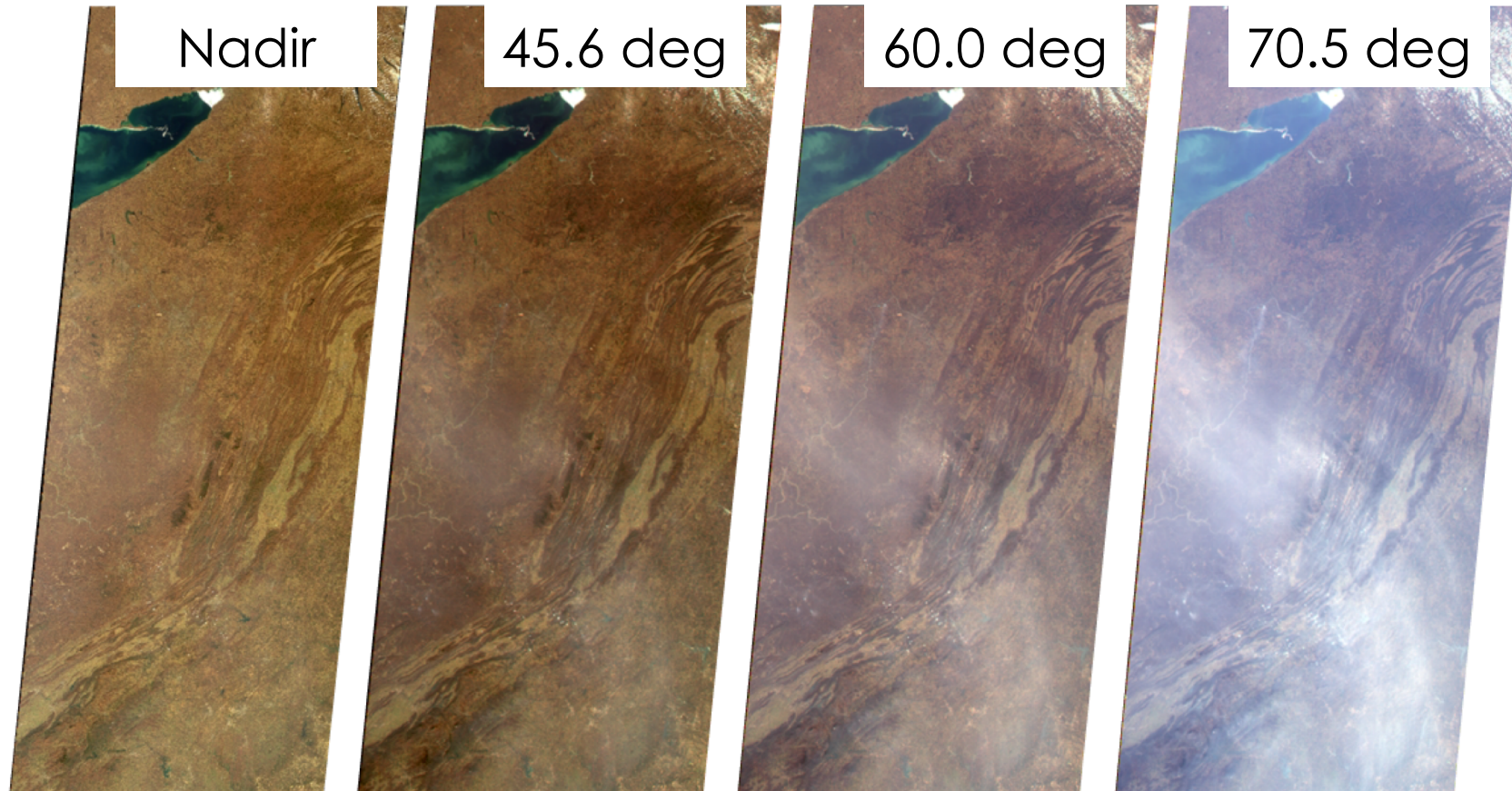
MISR

Multi-angle Imaging Spectro-Radiometer (MISR)

- 9 View angles
- 7 minutes to view each scene from all 9 angles
- 275 m spatial resolution
- Swath Width ~ 400 km
- 4 Spectral Bands
 - 446 nm
 - 558 nm
 - 672 nm
 - 866 nm



MISR Instrument



Angular observations (which are not available in MODIS) make MISR capable of providing additional information on particle size, shape and aerosol height under specific cases

Appalachian Mountains, Terra MISR, April 18, 2000

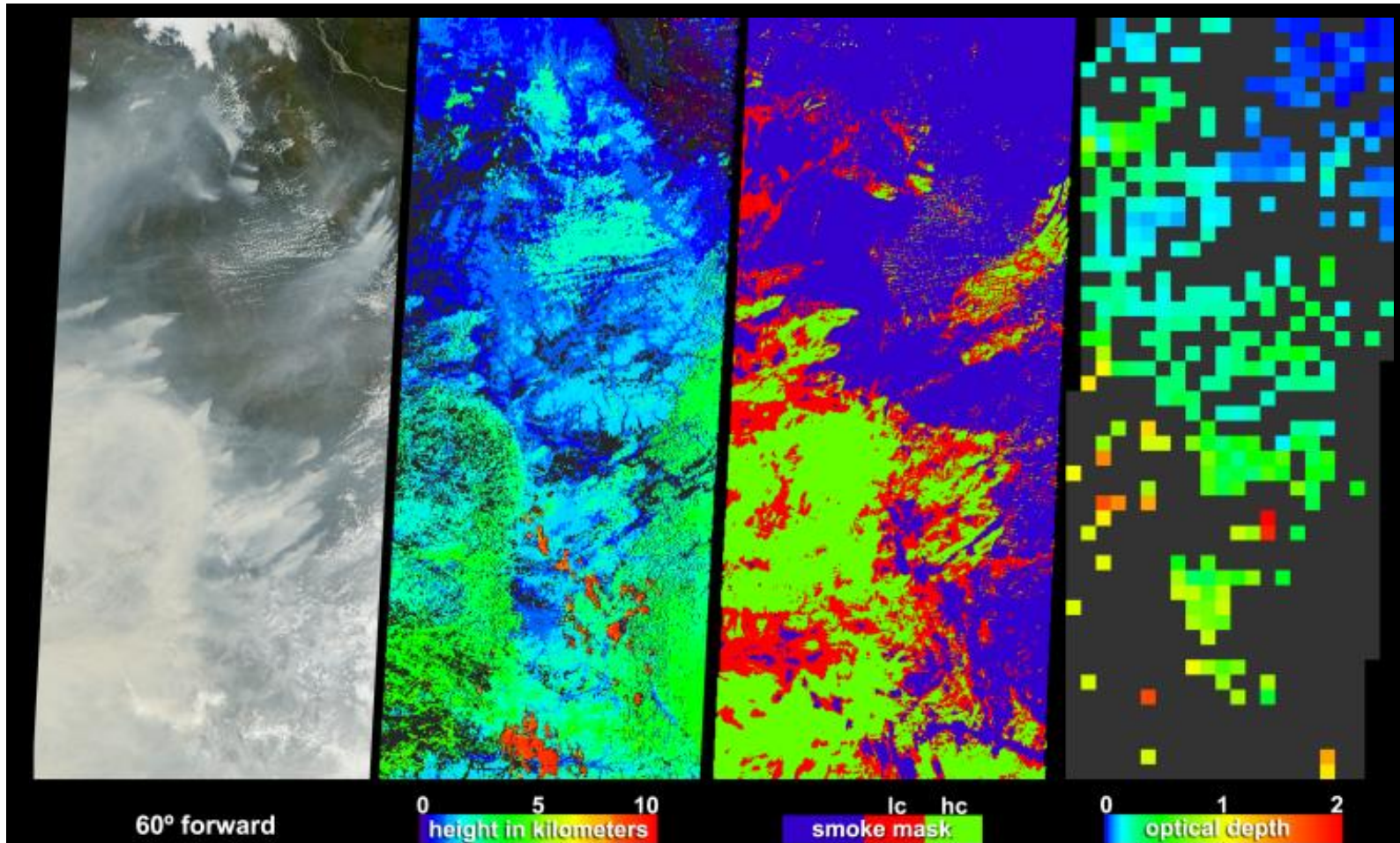


MISR Global Daily Coverage



Applications of MISR Data

Smoke signals from the July 2004 Alaska and Yukon Fires





VIIRS

Visible Infrared Imaging Radiometer (VIIRS)

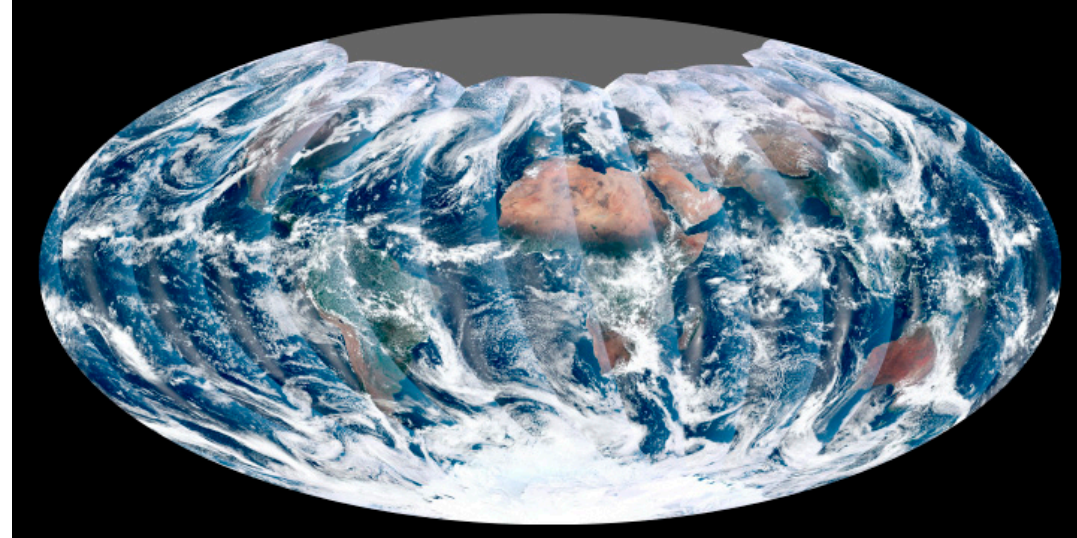
A multi-wavelength imager like MODIS with similar wavelength bands

	MODIS	VIIRS
Orbit Altitude	690 km	824 km
Equator Crossing Time	13:30 LT	13:30 LT
Granule Size	5 min	86 sec
Swath	2,330 km	3,000 km
Pixel Nadir	0.5 km	0.75 km
Pixel Edge	2 km	1.5 km

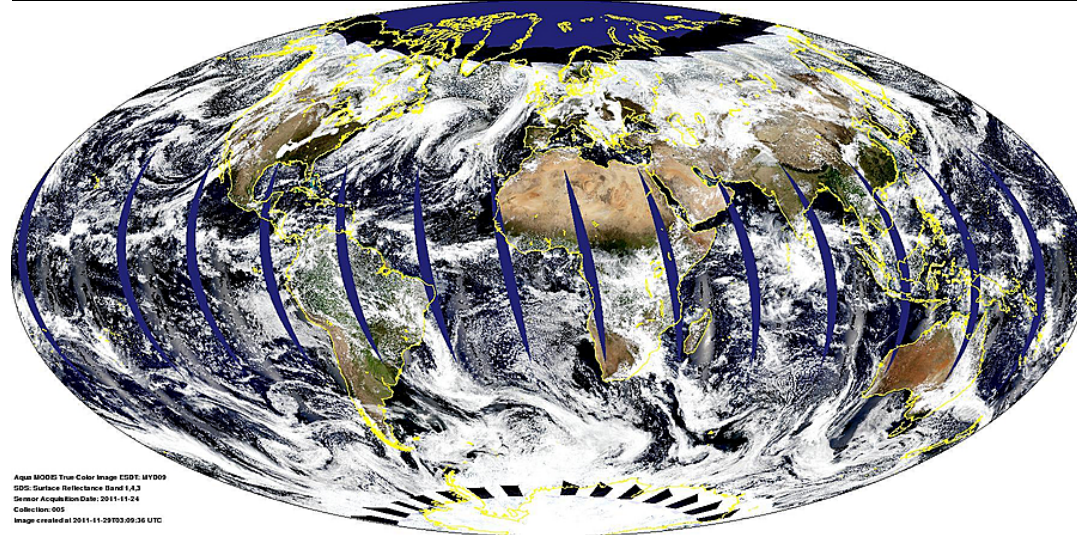


VIIRS & MODIS

VIIRS
Nov 24, 2011



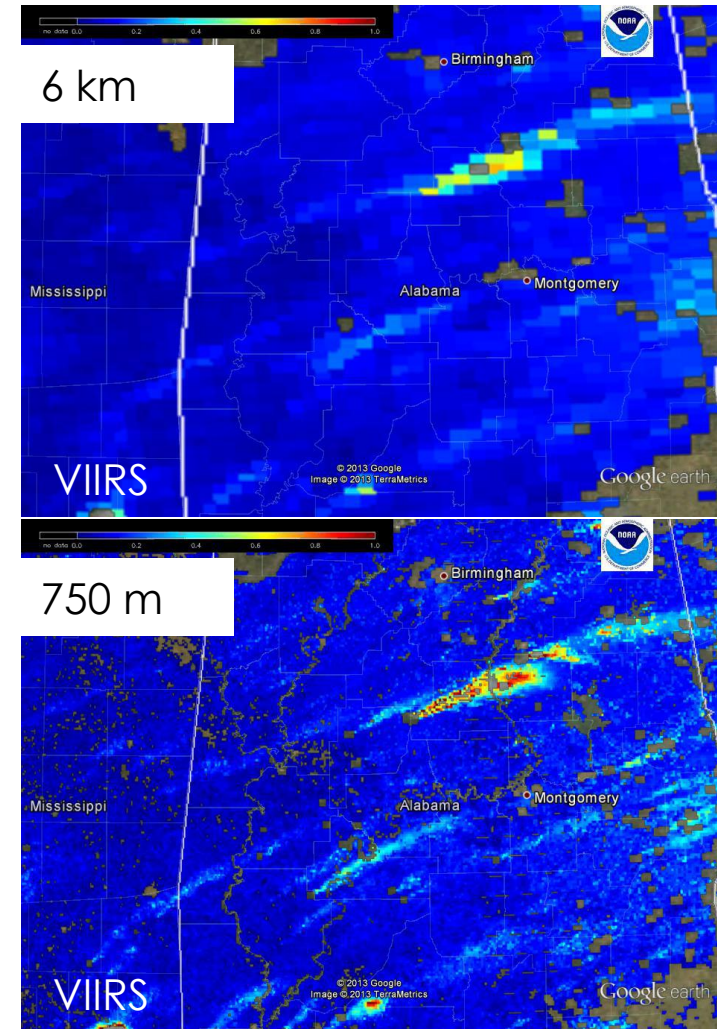
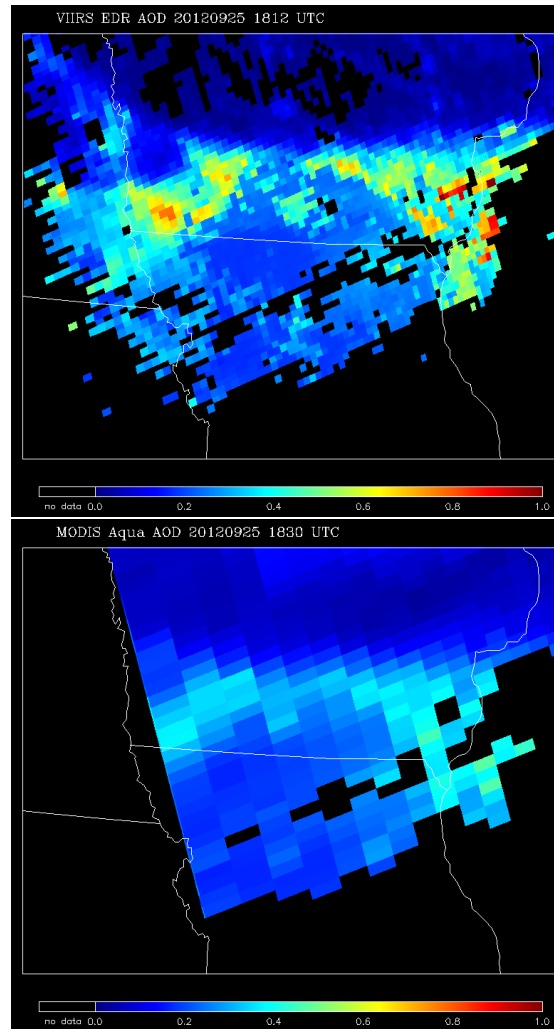
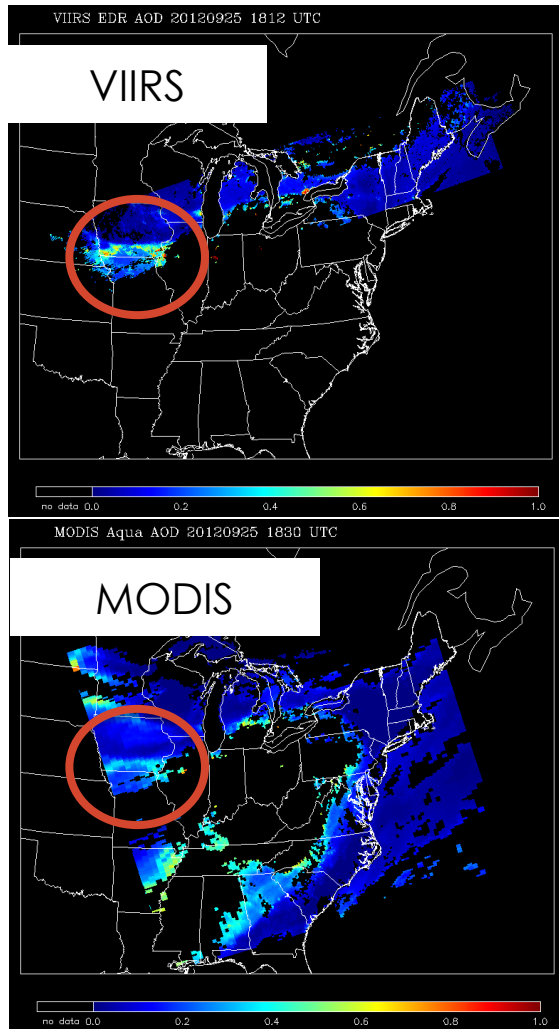
MODIS (Aqua)
Nov 24, 2011



Aqua MODIS True Color Image EOP1 MY009
S20: Surface Reflectance Band 1-2
Sensor Acquisition Date: 2011-11-24
Collection: S05
Image created on 2011-11-29 09:36 UTC



SNPP VIIRS Advantages

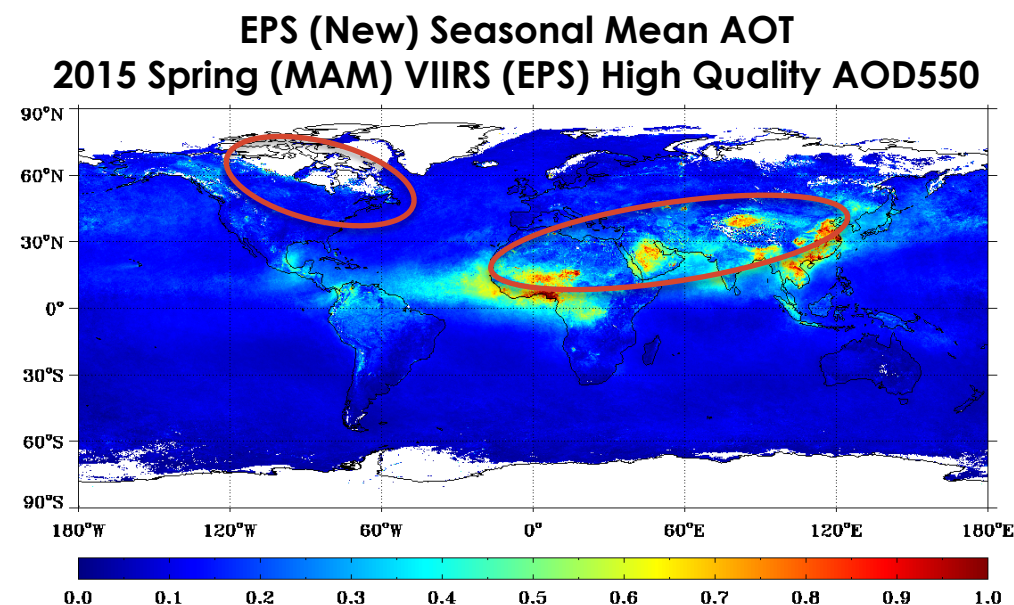
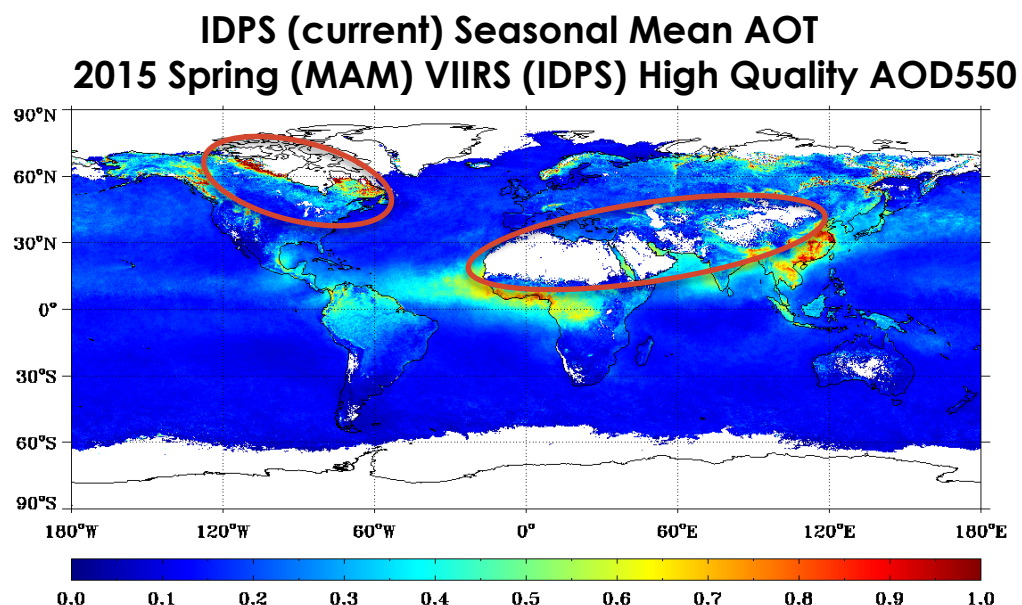


Side Courtesy: Shobha Kondragunta



New Aerosol Optical Thickness Algorithm

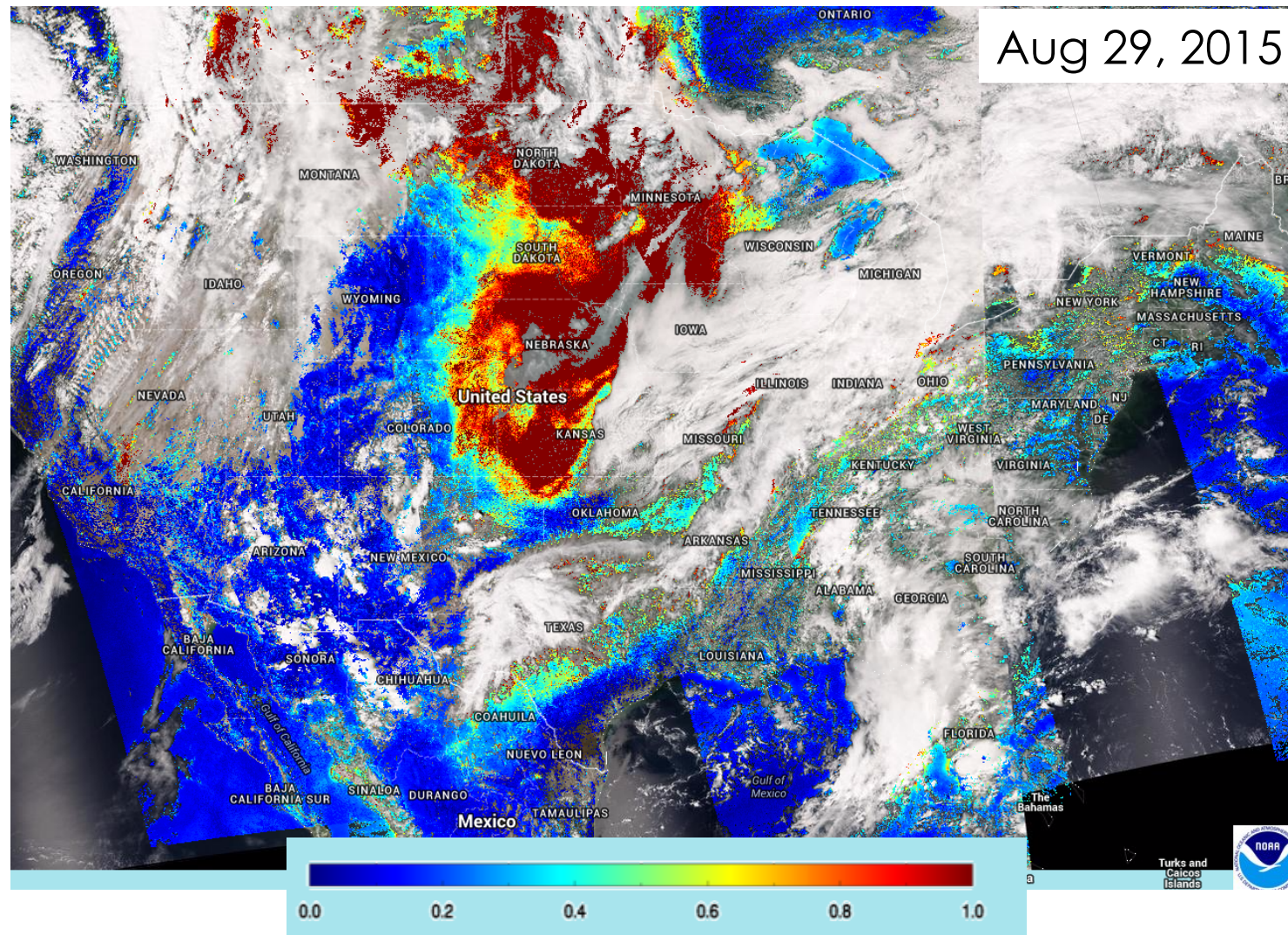
- **New Enterprise Processing System (EPS)** expected to become operational July 2017: replaces current *Interface Data Processing Segment (IDPS)* algorithm
 - Retrieval over bright land, extended reporting range [-0.05-5.0], extensive internal test
- Separate algorithms for land and water



Zhang et al. (2016), An enhanced VIIRS aerosol optical thickness (AOT) retrieval algorithm over land using a global surface reflectance ratio database, *J. Geophys. Res. Atmos.*, 121, 10,717–10,738. Slide Courtesy: Shobha Kondragunta



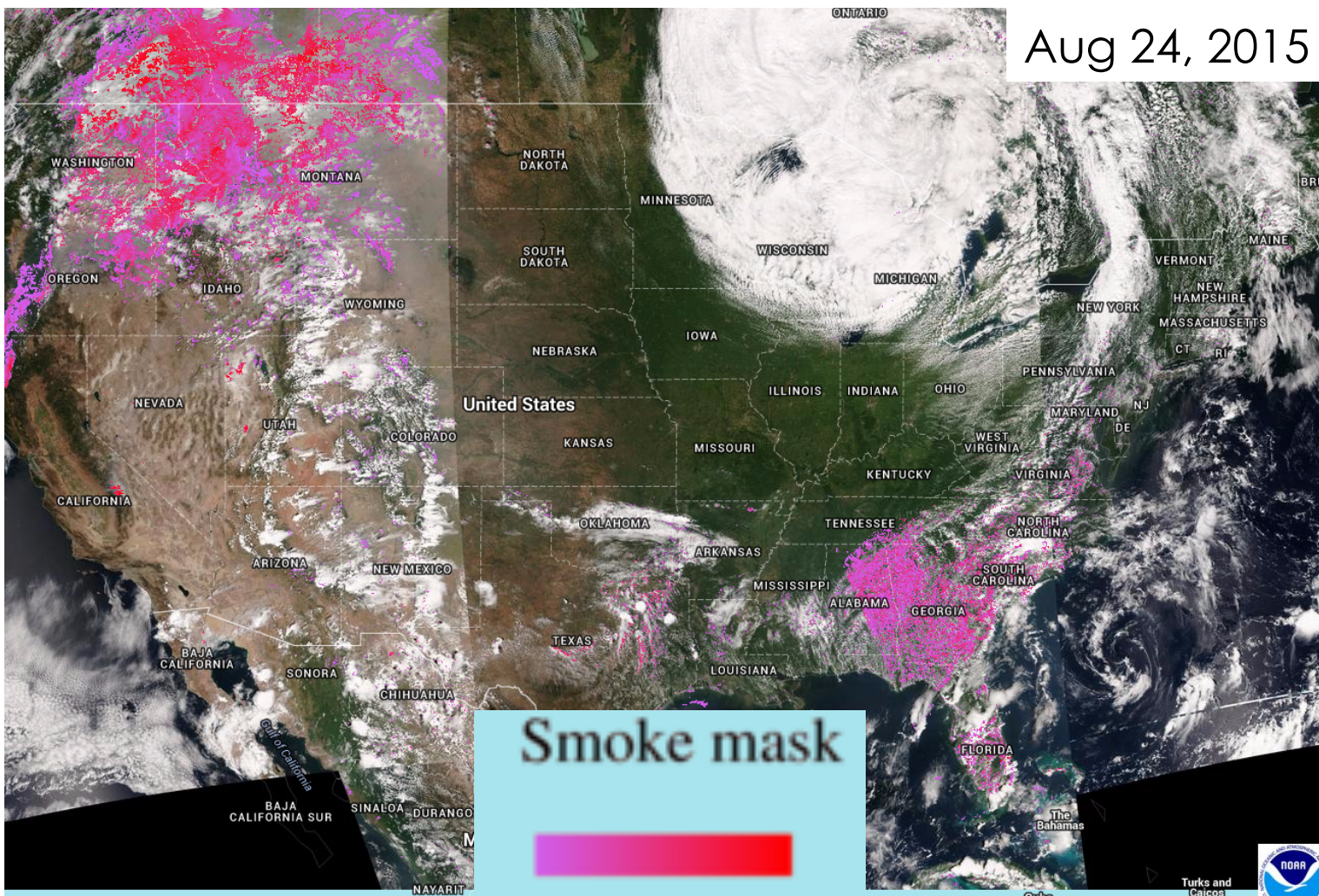
VIIRS AOD Retrieval Example



Slide Courtesy: Shobha Kondragunta



VIIRS Smoke Mask



- Smoke mask: qualitative indicator of smoke
- Derived using spectral and spatial threshold tests based on VIIRS measurements in visible and IR
- **Useful for identifying local and transported smoke plumes**
- Colored shades of pink
- Light pink: thin smoke
- Bright pink/magenta: thick smoke

Slide Courtesy: Shobha Kondragunta



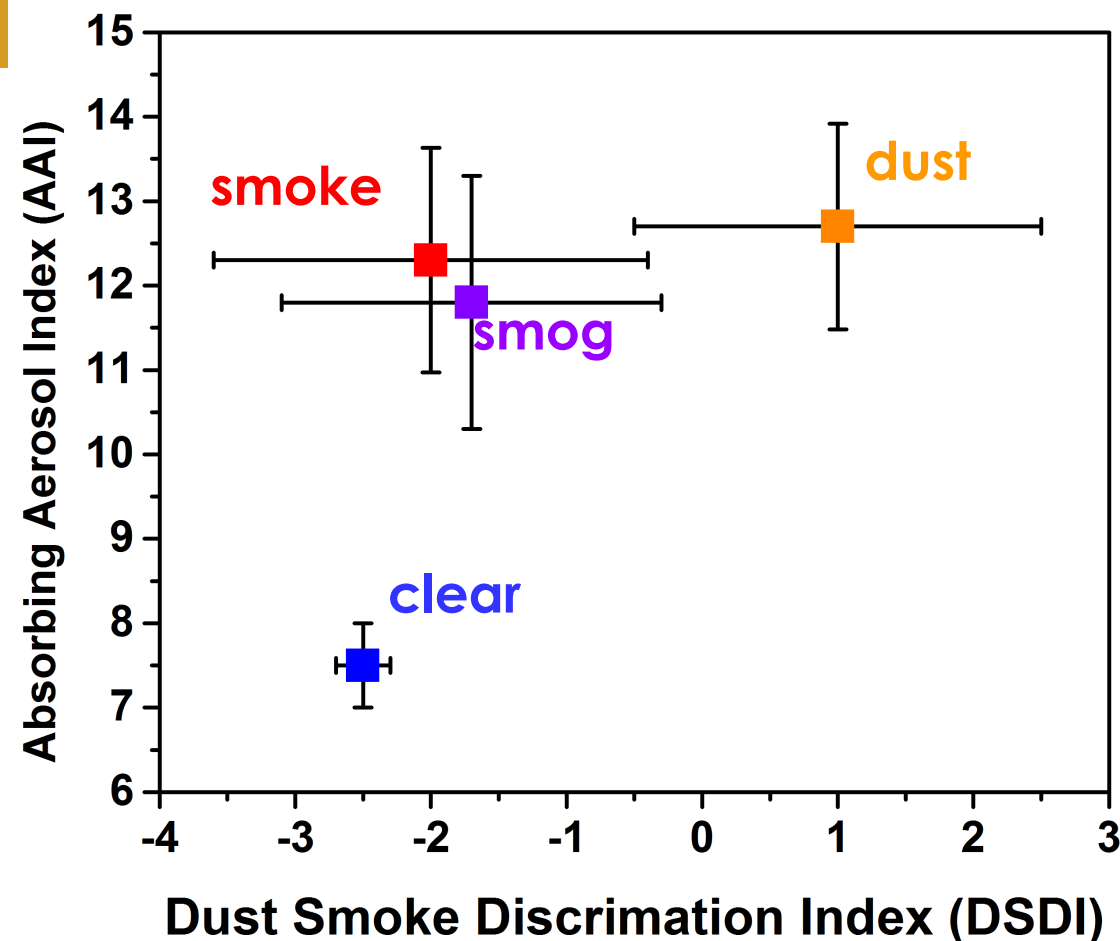
Overview of Aerosol Detection Algorithm

$$AAI = -100 [\log_{10}(R_{412}/R_{440}) - \log_{10}(R'_{412}/R'_{440})]$$

Input Reflectances

- Dust: 412, 440, 2250 nm
- Smoke: 412, 440, 2250 nm
- Spatial Variability Test: 412 nm
- Turbid Water Test: 488 nm, 1.24 μm , 1.61 μm , 2.25 μm
- Bright Pixel Test: 1.24 μm , 2.25 μm
- NDVI Test: 640 nm, 865 nm
- Snow Test: 865 nm, 1.24 μm

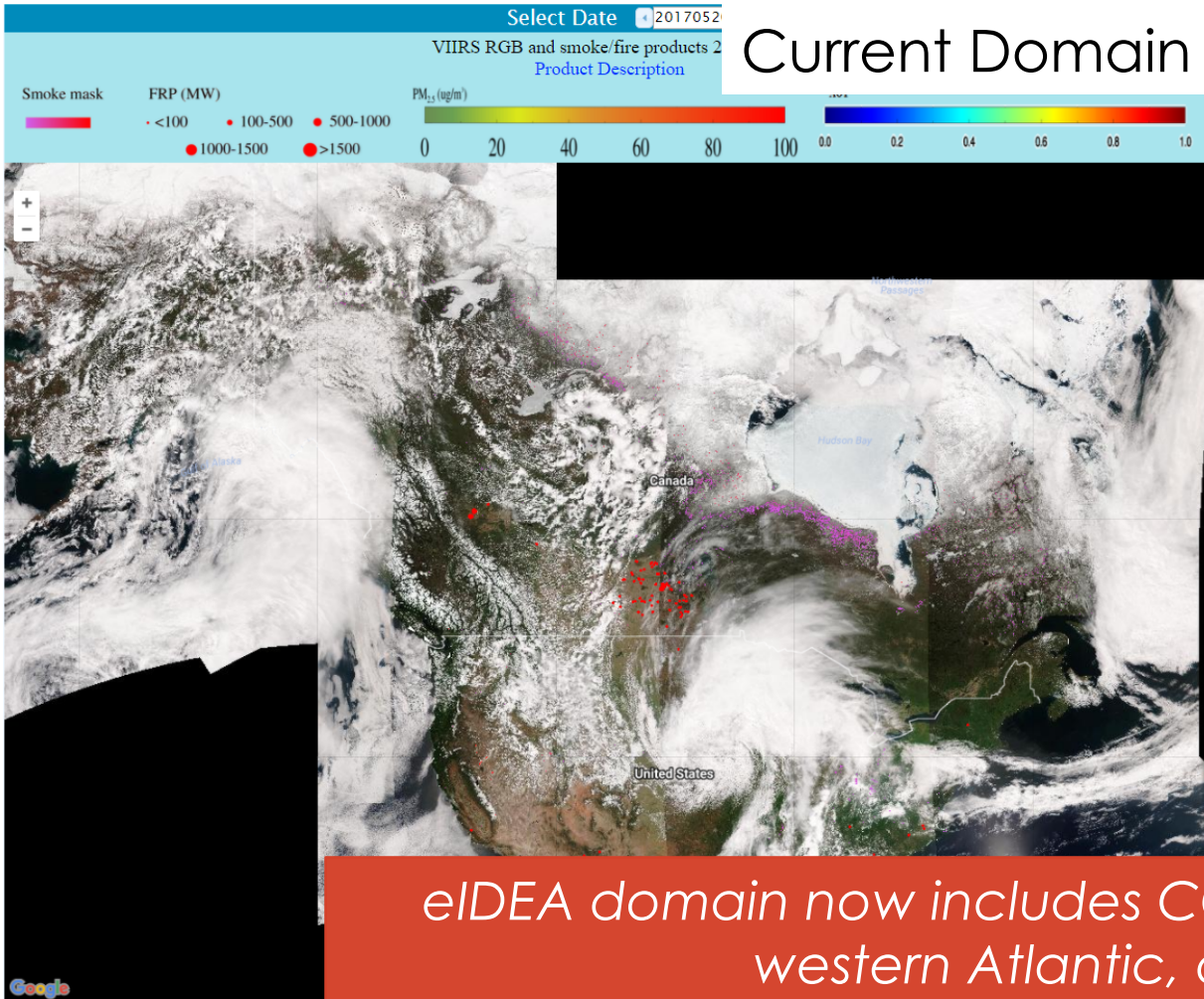
Slide Courtesy: Shobha Kondragunta



$$DSDI = -10 [\log_{10}(R_{412}/R_{2250})]$$



eIDEA Domain Recently Expanded



eIDEA domain now includes CONUS, Alaska, Canada, Mexico, western Atlantic, and eastern Pacific

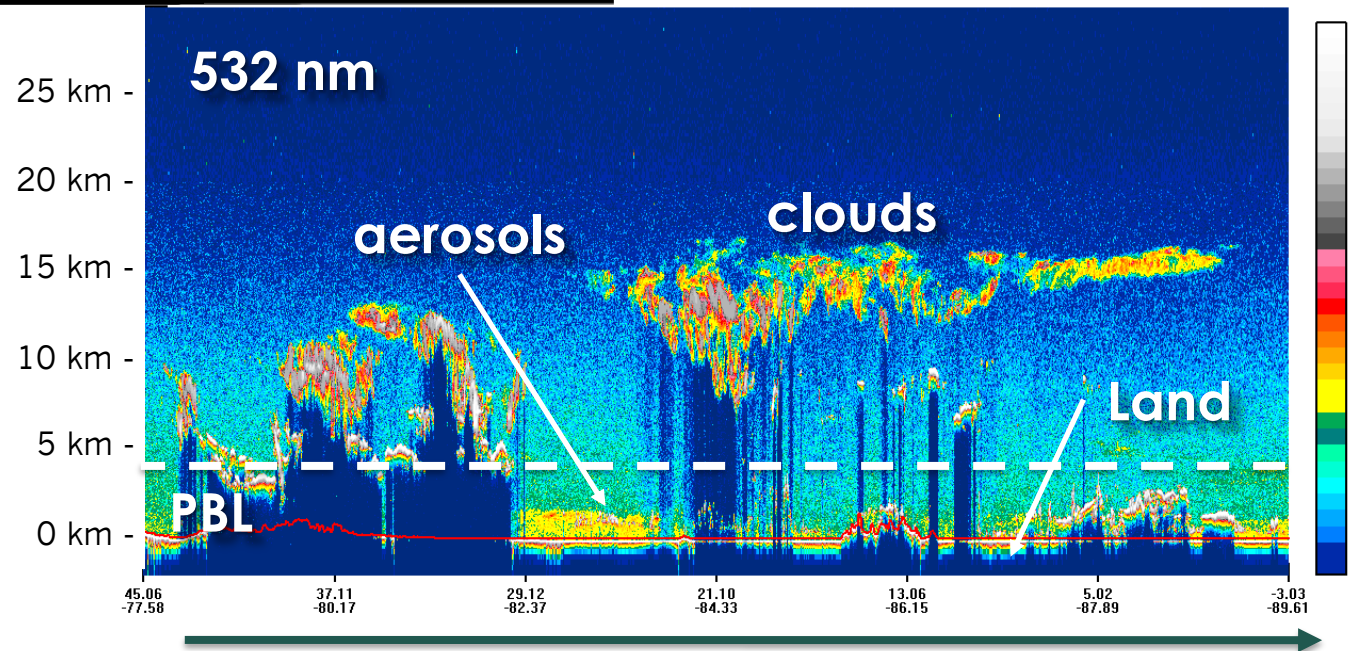
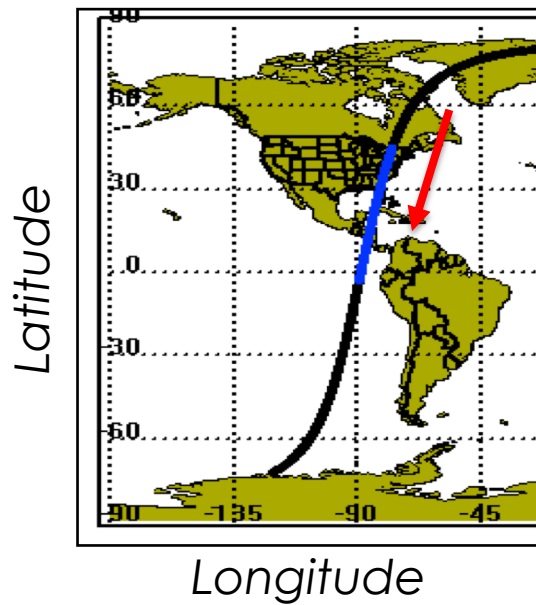
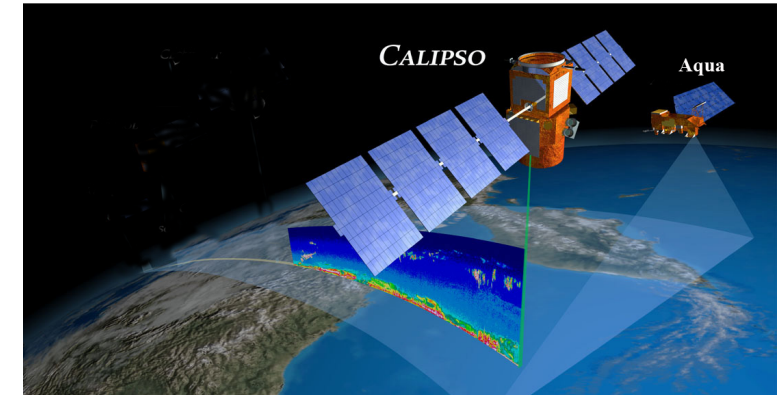
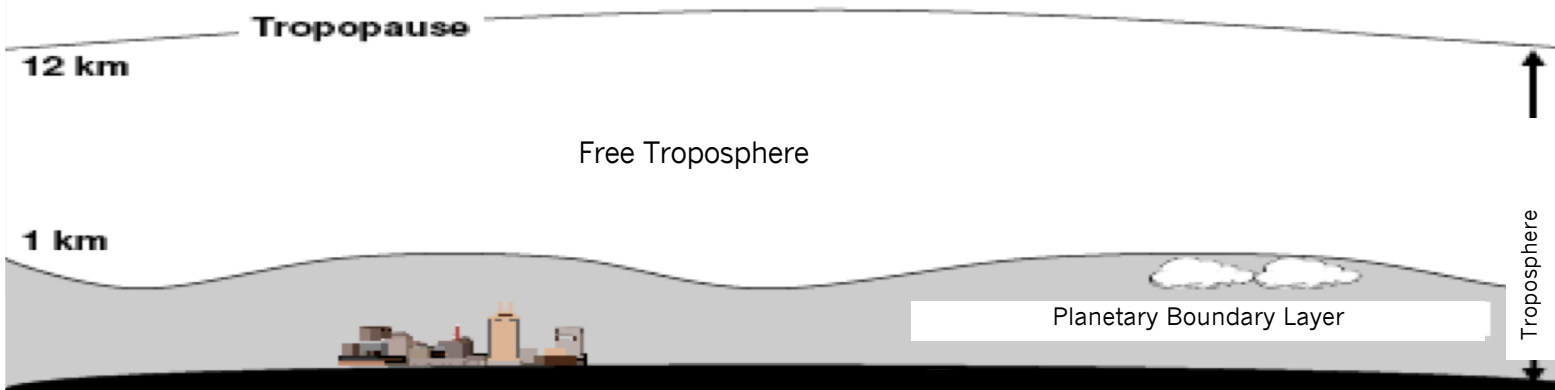
Slide Courtesy: Shobha Kondragunta





Other Sensors

CALIPSO: Vertical Profiles



Source: Meloë Kacenenbogen



Satellite Aerosol Products

	MODIS	MISR	OMI	VIIRS
Strengths	<ul style="list-style-type: none"> • Coverage • Resolution • Calibration • Accuracy 	<ul style="list-style-type: none"> • Calibration • Accuracy • Particle Shape • Aerosol height for thick layer or plume 	<ul style="list-style-type: none"> • Indication of absorbing or scattering particles 	<ul style="list-style-type: none"> • Coverage • Resolution • Calibration • Smaller bow-tie effect
Weaknesses	<ul style="list-style-type: none"> • Bright surfaces • Ocean glint • Non-spherical particles 	<ul style="list-style-type: none"> • Coverage 	<ul style="list-style-type: none"> • Resolution • Cloud contamination 	<ul style="list-style-type: none"> • Bright surfaces* • Ocean glint
Main Products	<ul style="list-style-type: none"> • AOD • Ocean-5 wavelengths • Land-3 wavelengths • Fine Fraction (Ocean only) 	<ul style="list-style-type: none"> • AOD • 4 wavelengths • Spherical/Non-Spherical Ratio • Particle Size (3 bins) 	<ul style="list-style-type: none"> • AOD • AAOD • Aerosol Index 	<ul style="list-style-type: none"> • AOD • Aerosol Type
Product Resolution	<ul style="list-style-type: none"> • 10 km • 3 km 	<ul style="list-style-type: none"> • 17.6 km 	<ul style="list-style-type: none"> • 13 x 24 km 	<ul style="list-style-type: none"> • 0.75 km • 6 km
Global L3 Aggregates	<ul style="list-style-type: none"> • Daily • 8 day • 30 day 	<ul style="list-style-type: none"> • Monthly • 3 month • Annual 	<ul style="list-style-type: none"> • Daily • Monthly 	<ul style="list-style-type: none"> • Daily • Monthly



Available Satellites for Aerosol Monitoring

	Pros	Cons
MODIS	<ul style="list-style-type: none"> • High spatial resolution (0.25-1km) • Fine vs. coarse • Twice daily near-global coverage 	<ul style="list-style-type: none"> • No data under cloudy conditions • No vertical information • Larger uncertainties over bright targets
MISR	<ul style="list-style-type: none"> • Size/shape information • Higher accuracy • Multi-angle view 	<ul style="list-style-type: none"> • Limited swath width (360km) • Limited vertical information • No daily observations for air quality
OMI	<ul style="list-style-type: none"> • Daily near-global coverage • Absorbing aerosols • Precursor measurements (sulfate, NOx) • Available over bright targets 	<ul style="list-style-type: none"> • Lack of information on scattering aerosols • Coarse resolution to separate clouds • Larger uncertainties
POLDER	<ul style="list-style-type: none"> • Daily near-global coverage • Sensitive to small mode aerosols • Available over bright targets 	<ul style="list-style-type: none"> • No data under cloudy conditions • No vertical information • Larger uncertainties over bright targets
CALIPSO	<ul style="list-style-type: none"> • Vertical information available • Information on clouds 	<ul style="list-style-type: none"> • Narrow swath (almost point measurement) • Very limited global coverage • Larger uncertainties in retrieved data sets

VIIRS, GOES-R, HIMAWARI, GOCI, and many more



Satellite Limitations

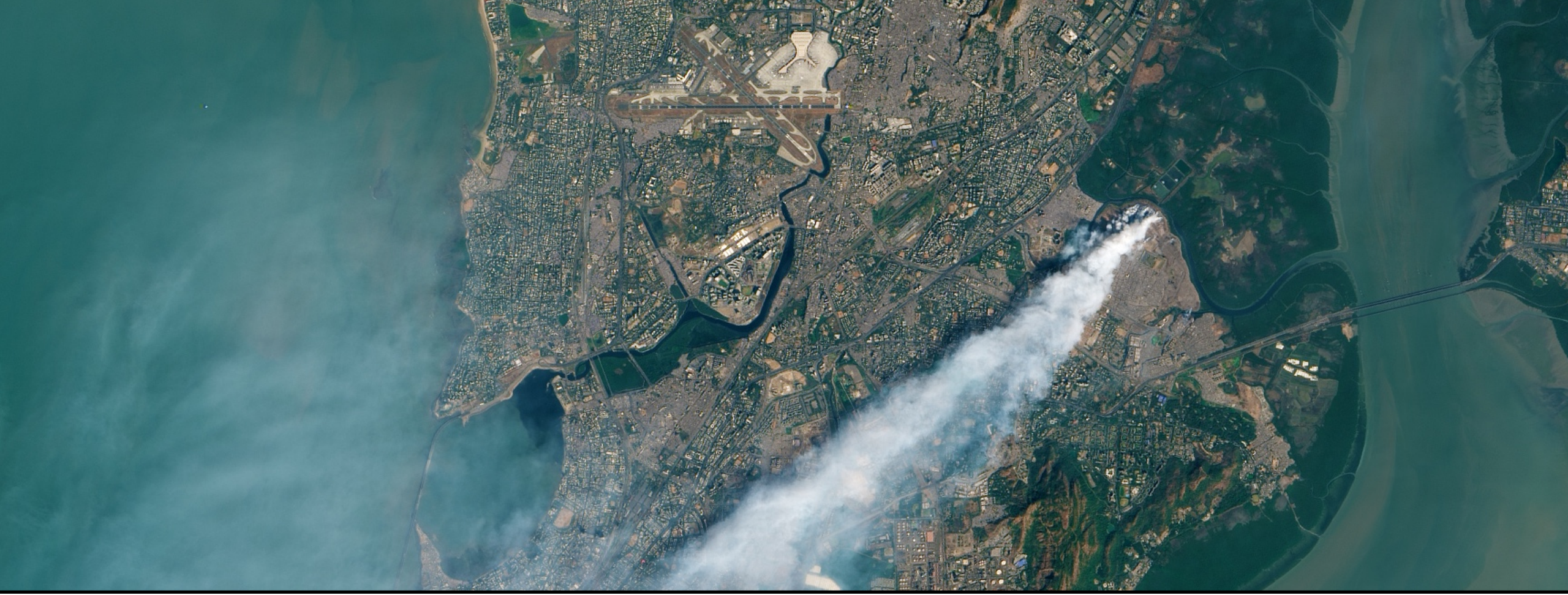
- **Optical measurements**
 - only available in day time
 - very limited in night time
- Only available under
 - cloud free conditions
 - Snow/Ice free conditions
- **Accuracy** - varies (AOD) – Depends on satellite/algorithm
 - Very good over dark vegetated surfaces
 - Moderate over urban surfaces- Algorithm dependent
 - Moderate to low over bright surface
 - Complex topography (i.e. mountains) – can be problematic
 - More uncertain for complex mixture of aerosols
- **Chemical Composition** - Very limited capabilities, only at research level
- **Temporal Coverage**
 - Usually once a day
 - But can use multiple satellite to get 2-3 a day
 - Geostationary will provide more frequent observations
- **Spatial Resolution**
 - 10 km (good)
 - 3 km (moderate)
 - 1 km, 0.75 km etc.



References & Links

- ARSET air quality page
 - <http://arset.gsfc.nasa.gov/airquality>
- NASA air quality
 - <http://airquality.gsfc.nasa.gov>
- MODIS Atmos
 - <http://modis-atmos.gsfc.nasa.gov/>
- MISR data
 - https://eosweb.larc.nasa.gov/PRODOCS/misr/Quality_Summaries/L2_AS_Products.html
- OMI data
 - <http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI>
- IDEA:
 - <http://www.star.nesdis.noaa.gov/smcd/spb/aq/>
- Smog blog:
 - <http://alg.umbc.edu/usaq/>





Questions & Discussion