Introducing the Suomi-NPP VIIRS Aerosol Products

The Visible Infrared Imaging Radiometer Suite (VIIRS, launched on the Suomi-NPP (S-NPP) satellite on October 28, 2011, offers a new set of satellite-derived aerosol products. Because VIIRS wavelength bands are similar to MODIS's, VIIRS aerosol algorithms are based on the MODIS heritage. The VIIRS aerosol over ocean algorithm follows from the MODIS Dark Target heritage (MOD04). The VIIRS aerosol over land algorithm does NOT follow from the MODIS Dark Target heritage, but instead follows from the MODIS over land atmospheric correction heritage (MOD09). There is currently no Deep Blue algorithm applied operationally to VIIRS data.

Table 1. MODIS and VIIRS Instrument and Aerosol Product Specifications

	Aqua MODIS	S-NPP VIIRS
Orbit altitude	705 km	824 km
Equator crossing time	13:30 Local Time	13:30 Local Time
Granule size	5 minutes	86 seconds
Swath width	2330 km	3000 km
Sensor bands used for aerosol retrieval (additional wavelength reported for VIIRS)	0.411, 0.466, 0.554, 0.646, 0.856, 1.242, 1.629, 2.114 μm	0.412, 0.445, 0.488, (0.550), 0.555, 0.672, 0.746, 0.865, 1.24, 1.61, 2.25 μm
Pixel size, nadir	0.5 km	0. 75 km
Pixel size, edge of scan	2 km	1.2 km
Bow-tie effects	Yes	No
Product resolution, nadir	10 km	6 km (AOT and Angstrom exponent) 0.75 km (Suspended matter)
Product resolution, edge	40 km	10 km (AOT and Angstrom exponent) 1.2 km (Suspended matter)
Products, land	AOD (1 primary wavelength)	AOT (1 primary wavelength), Suspended matter
Products, ocean	AOD (7 wavelengths), Size (fine mode fraction)	AOT (11 wavelengths), Angstrom exponent, Suspended matter
Global gridded product	Level 3 daily, 8-day, monthly mean	None

VIIRS aerosol products include aerosol optical thickness (AOT), Angstrom exponent and suspended matter. AOT is available at the 11 wavelengths listed in Table 1, although at this time the recommendation is to restrict use of over land AOT to only 0.550 μm. Angstrom exponent over ocean is calculated for the wavelength pair 0.865 and 1.61 μm, which differs from the similar product from MODIS. Angstrom exponent over land is calculated for the wavelength pair 0.488 and 0.672 μm. At this time, the recommendation is to not use the over land Angstrom exponent. Suspended matter is an aerosol type classification that does

not have a counterpart in the MODIS heritage. It is a separate product, available at sensor pixel resolution and identifies dust, non-dust (likely smoke) and volcanic ash events.

AOT Products for Air Quality Applications

AOT is a measure of the scattering and absorption of visible light by particles in a vertical column of the atmosphere. It is analogous to Aerosol Optical Depth (AOD) from MODIS. AOT is related to particulate matter (e.g., $PM_{2.5}$) concentrations in the atmosphere; higher values of AOT correspond to higher concentrations of particles. AOT is a unitless measurement and is represented on a color-coded scale ranging from 0 to 1 in VIIRS imagery. Clouds block AOT retrievals, so there are no AOT data for cloud-covered areas. AOT is useful for identifying and tracking areas of high particulate concentrations that correspond to an air quality event, such as a wildfire, dust storm, or haze episode.

There are two AOT products available from VIIRS: the Intermediate Product (IP) and Environmental Data Record (EDR).

Intermediate Product Aerosol Optical Thickness – IP AOT

The VIIRS IP AOT is a cloud-free pixel level retrieval with ~750 m resolution. It comes with four different quality flags: **high, degraded, excluded,** and **not produced**. The conditions that determine these quality flags are shown Table 2, taken from Jackson et al., JGR, 2013.

The "**IP High**" tab on IDEA shows IP AOT for cloud-free pixels containing high quality AOT overlaid on RGB imagery. Comparisons of VIIRS IP High AOT imagery to corresponding MODIS imagery indicate that VIIRS has AOT missing in some locations where MODIS shows retrievals. The data gaps are due to the VIIRS aerosol algorithm flagging these retrievals as degraded due the surface being dominated by soil, aerosols perceived as cirrus cloud, etc. The "**IP High***" tab shows pixels with IP AOT that is **high** quality plus pixels for which IP AOT is **degraded** due to a cirrus flag or the surface being dominated by soil. The "**IP High & Degraded**" tab shows pixels with IP AOT that is **high** plus **degraded** due to any of the conditions that are listed in Table 2. For *quantitative* applications, users should use **IP High** imagery and for *qualitative* applications, users should use **IP High*** imagery.

Environmental Data Record Aerosol Optical Depth – EDR AOT

The EDR AOT product (~6 km resolution) is aggregated from IP AOT retrievals in a 8 × 8 pixel box (Figure 1). The EDR AOT product has three levels of quality flags: **high, medium,** and **low**. These flags are determined based on the number of IP AOT pixels with a particular quality flag that fall inside or outside of a threshold number. For example, EDR AOT has a **high** quality flag if the number of aggregated IP pixels is greater than 16 (out of a possible 64) and all of those pixels are IP **High**. In the aggregation process, the top 40% and bottom 20% of IP AOT pixels are discarded to avoid cloud leakage/shadows.

Key Aspects of the VIIRS Aerosol Imagery

When comparing **"IP High"** and **"EDR High"** AOT imagery for the same day and location, a user will notice that the coverage is not the same in the two images. It may appear that the

"IP High" AOT has less spatial coverage than corresponding **"EDR High"** AOT. This difference in apparent coverage is due primarily to the difference in spatial resolution of the two products. There are also situations when retrievals are present in the **"IP High"** AOT, but **"EDR High"** AOT is not available in the same location. This is because the number of pixels with **"IP High"** AOT is less than 16, a requirement for EDR AOT to have a **high** quality flag. Furthermore, sometimes when a user toggles between **"IP High"** and **"EDR High,"** the pixels may appear to shift. This is because the latitude/longitude used for the center of the IP pixels and EDR pixels is different.

Table 2. VIIRS Aerosol Algorithm Data Screening Criteria

Condition	Pixel Quality Level			Applies to:		Detected by:	
	Degraded	Excluded	Not Produced	Land	Ocean	VCM	Internal Tests
Out of Spec Range		X		X	X		X
Coastal or Inland Water			X			X	
Cloud Contamination			X	X	X	X	X
Cloud Adjacency	X			X	X		X
Cirrus	X			X	X	X	X
Invalid SDR data			X	X	X		X
Sun Glint			X	X	X	X	X
Cloud Shadow	X			X	X	X	
Snow/Ice			X	X	X	X	X
Fire			X	X		X	X
Soil Dominated	X			X			X
Bright Surface			X	X			X
Turbid Water			X		X		X
Ephemeral Water			X	X			X
65° ≤ SolZA < 80°	X			X	X		X
SolZA ≥ 80°			X	X	X		X
Large Retrieval Residual	X			X	X		X

VCM: VIIRS Cloud Mask; SolZA: Solar Zenith Angle; SDR: Sensor Data Record

From Jackson et al., JGR, 2013

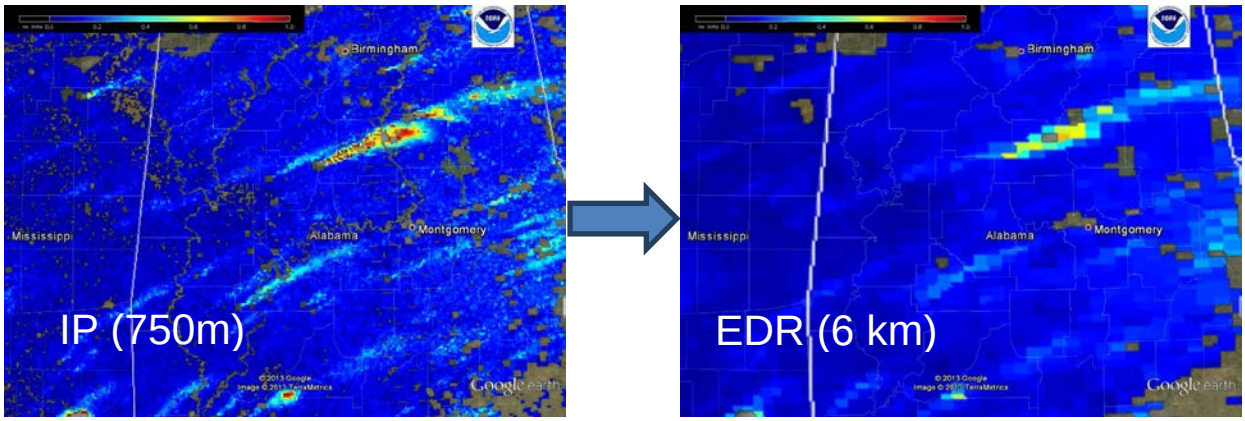

Figure 1. An example of IP AOT (left) and its corresponding EDR AOT (right)

Smoke/Dust Mask

The smoke/dust mask is a qualitative smoke/dust aerosol index that provides information on the identification of dust plumes and plume transport. Users can access the smoke/dust mask on IDEA by clicking the "Toggle Smoke/Dust Mask" button. The smoke/dust mask tab comes up when IP AOT tab is clicked because both dust/smoke mask and IP products are at pixel level. The smoke/dust mask comes with two quality flags: **confidently smoke/dust** and **probably smoke/dust**. The dust mask is a new research product that was first developed for MODIS and is now being applied to VIIRS (Ciren and Kondragunta, JGR, 2014).

The dust mask algorithm relies on two indices: Dust Aerosol Index (DAI) and the Non-Dust Aerosol Index (NDAI), which help identify and discriminate dust from non-dust (e.g., smoke) aerosols. Equations for these two indices are:

$$DAI = -100 \times \left[\log_{10}\left(\frac{R_{412\,nm}}{R_{445\,nm}}\right) - \log_{10}\left(\frac{R'_{412\,nm}}{R'_{445nm}}\right)\right] \qquad (1)$$

$$NDAI = -10 \times \left[\log_{10}\left(\frac{R_{412\,nm}}{R_{2.25\mu m}}\right)\right] \qquad (2)$$

In equations 1 and 2, R represents reflectivity at a particular wavelength and R' represents reflectivity from Rayleigh scattering. The spectral dependence of surface reflectance, dust absorption, and Rayleigh scattering allows the use of top of the atmosphere reflectance measurements at multiple wavelengths to separate dust from non-dust. The DAI threshold values were determined based on analysis of DAI and NDAI values from VIIRS data over different geographic regions and time periods. Based on this analysis, we identified a threshold value of 11.5 and 0 for DAI and NDAI, respectively, for pixels over land. There is a small overlap of non-dust aerosols with dust aerosols, which results in some falsely identified non-dust aerosols as dust aerosols. Threshold values for DAI and NDAI are 4 and -10, respectively, for pixels over water. For pixels that clear the threshold test, a

confidently dust quality flag is assigned if the surface is not determined to be bright (e.g., desert). If the surface is determined to be bright, then the pixel is assigned a **probably dust** quality flag. This discrimination is done to avoid misidentifying bright surfaces as airborne dust. Both over land and water, the cirrus flags from the VIIRS cloud mask is applied to eliminate any pixel contaminated by cirrus and any pixel with R_{412nm}>=0.5 is considered as cloudy as well. Residual clouds are further discriminated from aerosols using a spatial variability test of R_{865nm} over water, and spatial variability test of R_{412nm} over land. As example, the flowchart for dust detection over land is given in the figure 2.

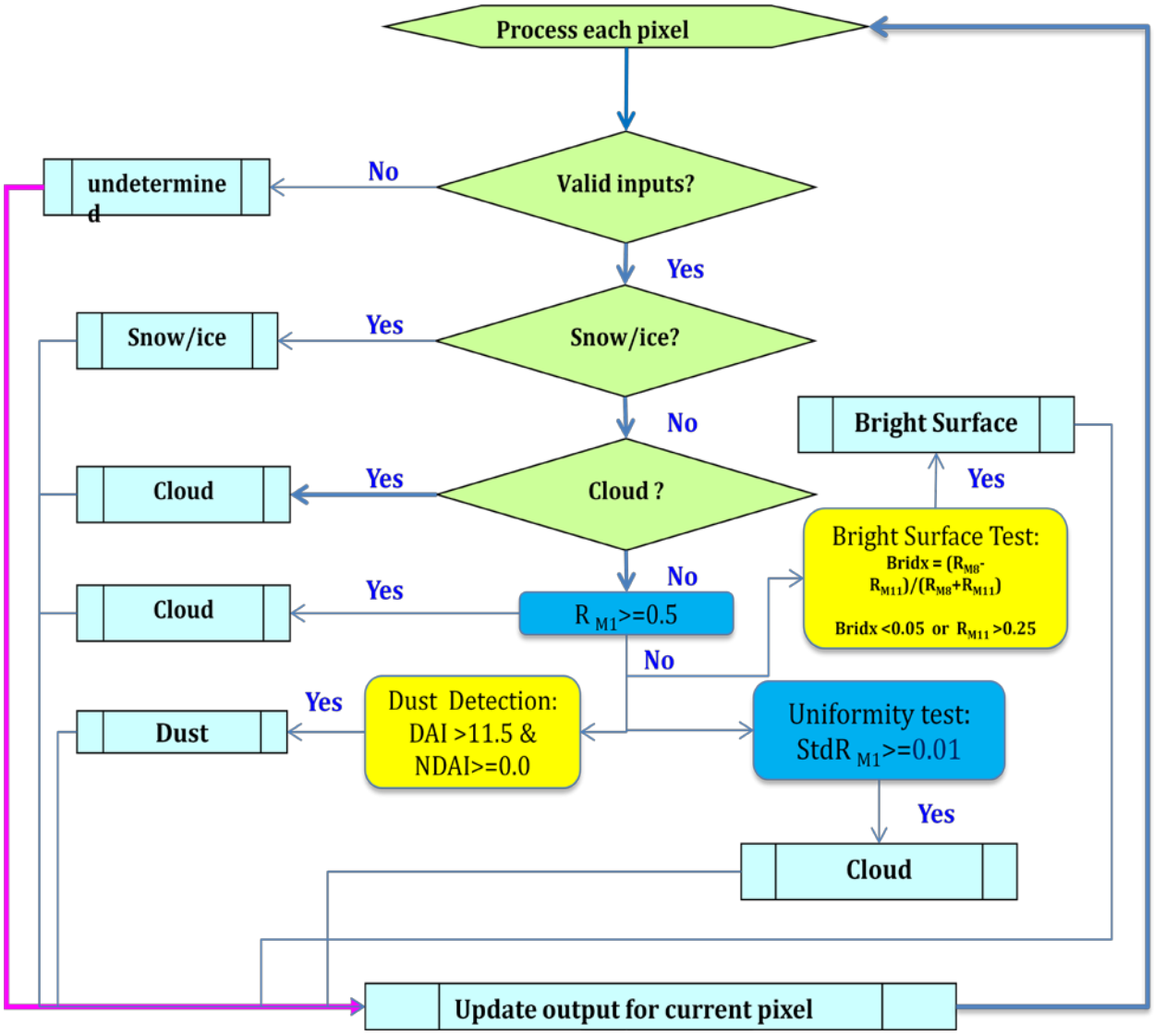

Figure 2. Flowchart of dust detection over land.

For smoke mask algorithm, it relies also on the two indices given in equation (1) and (2). However, it works on the pixels which are not picked up as dust but might contain other absorbing aerosols including smoke. The same cloud screening processes as dust detection are applied with the following threshold tests used for DAI and NDAI.

Water: thin smoke:

DAI ≥ 4.0 and NDAI ≤ -10.0 and $R_{410} < 0.1$

Water: thick smoke:

DAI ≥ 9.0 and NDAI ≤ -4.0

Land: thin smoke

DAI ≥ 5.0 and NDAI ≤ -2.0

Land: thick smoke:

DAI ≥ 9.0 and NDAI ≤ -2.0 and $0.2 < R_{410} < 0.4$

For pixels which are identified as smoke, DAI values are used as smoke aerosol index for the purpose of showing the intensity. As an example, the flowchart of smoke detection over land is given in figure 3.

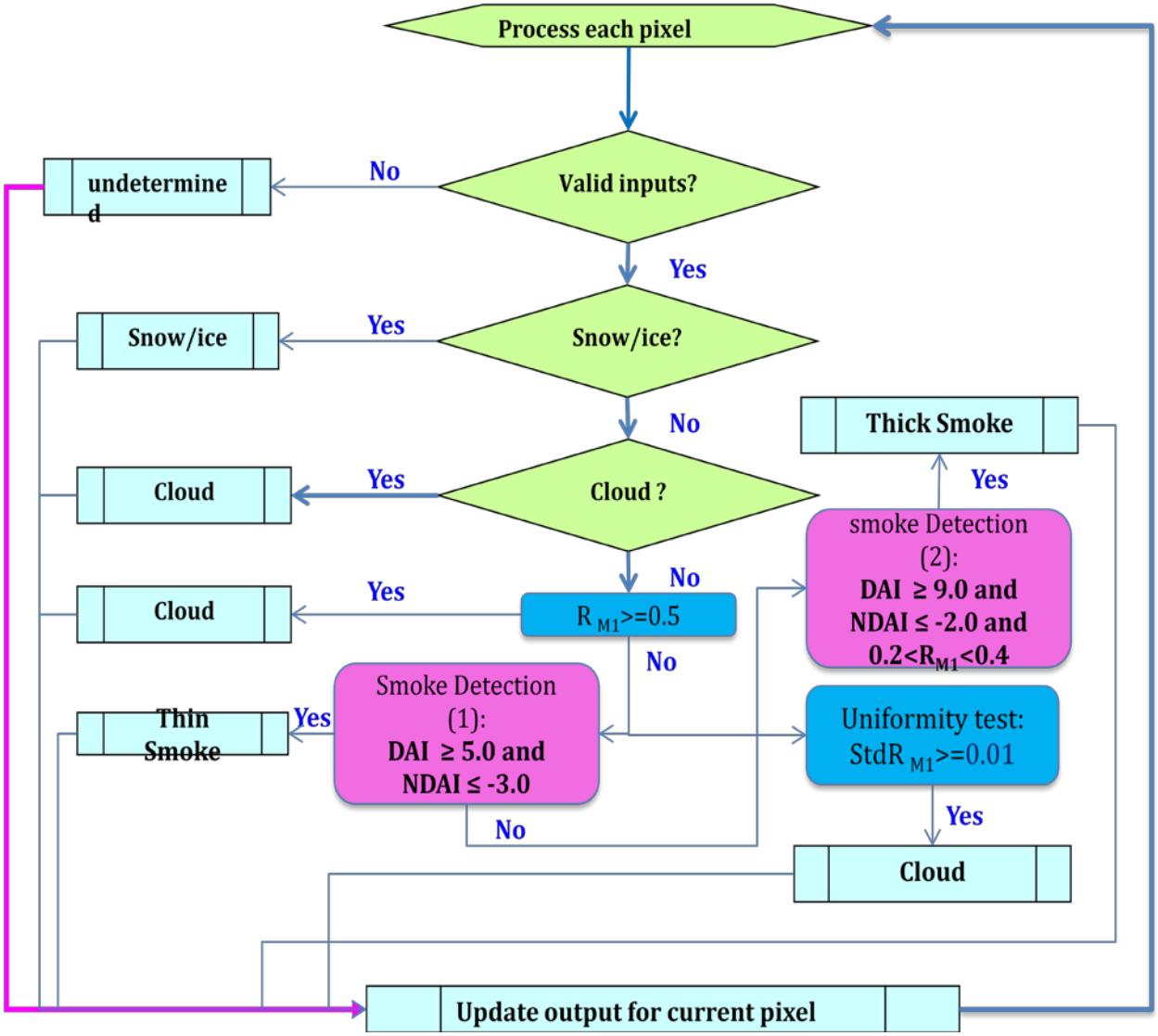

Figure 3. Flowchart of smoke detection over land.

The following tests are used to screen out or degrade quality of smoke/dust mask :

- **Bright pixel test (over land)**

Bright_Pixel_Index=$(R_{M8}-R_{M11})/(R_{M8}+ R_{M11})$

If Bright_Pixel_Index<0.05 or R_{M11}>0.25 then the pixel is considered as a bright pixel, then smoke/dust mask quality is degraded. M8 is 1.24 μm and M11 is 2.15 μm for VIIRS instrument.

- **Sun glint mask (over water)**

The SM Product algorithm is designed to generate internal sun glint mask based on VIIRS viewing and illuminating angles. The sun glint angle (η) is calculated as follows

$$\cos(\eta) = \cos(\theta_0) * \cos(\theta) + \sin(\theta_0) * \sin(\theta) * \cos(180 - \varphi)$$

θ_0 : *solar zenith angle*

θ : *satellite zenith angle*

φ : *relative azimuth angle*

Note that, φ is defined as the difference between solar azimuth angle and satellite azimuth angle. An area with calculated sun glint angle greater than zero and less than 40^o is defined as sun glint area. In sunglint area, dust mask is not produced, smoke mask quality is degraded.

- **Snow/ice test (over land)**

Before proceeding to any tests over land, it is important to identify pixels contaminated by snow/ice. As described earlier, VIIRS snow/ice product is the primary source, and if the primary source is unavailable, snow/ice mask from IMS is used as a second source. However, a further test is designed to catch any pixels that pass through but have snow/ice. The test is described as following:

if $BT_{M15<}$285k & $(R_{M7}- R_{M8})/ (R_{M7}+ R_{M8})>0.01$

then snow/ice indicated for this pixel, then both smoke and dust is not produced. Note that BT is brightness temperature. R is the reflectance. M7, M8, and M15 are VIIRS 865 nm, 1.24 μm, and 10.763 μm respectively.

- **Turbid and shadow water test (over water)**

The turbid and shadow water tests are from MODIS heritage and used in VIIRS AOT algorithm as well. The test is as follows: the observed reflectance at M3, M8, M10 and M11 are used to derive power law fit using least squares minimization. Expected reflectances at M4 (550 nm) based on the power law fit are computed. Since a Rayleigh plus aerosol scattering atmosphere is expected to have a path reflectance which is a power law in wavelength, the differences between the observed reflectances and the calculated reflectances in these bands approximately correspond to the water leaving reflectance introduced by sediments. For clear water, the differences are close to zero; while for turbid water the differences are all greater than 0.01. The specific criteria to trigger that the pixel is affected by turbid water are:

$R^{ob}_{M4} - R^{es}_{M4} > 0.015$ &
$R_{M3} < 0.25$ &
$R_{M11} < 0.15$

$R^{ob}$is the observed reflectance and R^{es} is the estimated refleance from the fitted power law relationship. For pixle which is identified as turbid and shallow water, both smoke and dust mask is not produced. M3 and M11 bands are 488 nm and 2.15 μm respectively.

- **NIR-NDVI test (over land)**

  NIR-NDVI test is applied to screen out some pixels containing white sand that are misidentified as thick smoke. The NIR-NDVI is defined as:

  $NIR\_NDVI = (R_{M8} - R_{M5}) / (R_{M5} + R_{M8})$

  If NIR-NDVI <0.05 and the pixel is identified as thick smoke, then the quality of smoke mask is degraded. M5 and M8 are VIIRS 672 nm and 1.24 μm respectively.

Documents

The VIIRS user's manual, readme file, latest version of Algorithm Theoretical Basis Document (ATBD), and other related documents on data formats etc. can be found through online at:
http://www.star.nesdis.noaa.gov/smcd/emb/viirs_aerosol/documents.php

Important Usage Recommendations

- For quantitative applications, only use products with a "high" quality flag.

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