Predicted Performance of the VIIRS Cloud Mask Algorithm

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Introduction

Abstract:
Recent changes in the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program have resulted in a broader range of stringent requirements on automated cloud mask analyses to be derived from data collected by the Visible/Infrared Imagery/Radiometer Suite (VIIRS). These requirements are based on a review of users needs for NPOESS cloud products along with the need to retrieve these cloud data products in an operational environment. As a result, four performance indicators are now used to evaluate analyses created with the VIIRS Cloud Mask (VCM) algorithm. They include a probability of correct typing (PCT), leakage rate, defined as the probability a pixel is classified as cloud-free when a cloud is present, false alarm rate defined as the probability a pixel is classified as cloudy when no cloud is present, and the capability to discriminate between clouds and heavy aerosols. Extensive system-level testing of the VCM algorithm has recently been completed at Northrop Grumman Space Technology (NGST) and the on-orbit performance of the VCM algorithm can now be predicted. The results of this testing is the topic of this paper. The predicted performance is based upon analyses of globally distributed datasets of MODIS granules, compared to manually-generated cloud analyses, as well as testing with global synthetic datasets. The results show that the wide range of NPOESS and user requirements can be satisfied with the single VIIRS cloud mask algorithm. A summary is also presented of the few actions that remain open as NPOESS team prepares for the first VIIRS launch on NASA's NPOESS Preparatory Project (NPP) mission

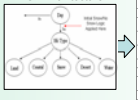
VCM Requirements:
The VCM algorithm was designed to form the beginning of the processing chain for other VIIRS data products. Results from the VCM algorithm will be used to produce 22 EDRs including: seven cloud products (gridded field of cloud optical thickness and effective particle size; cloud top pressure, height, and temperature; cloud base height; and cloud cover/layers at a near constant 6-km resolution), three ocean products (sea surface temperature, ocean color, and net heat flux), five land products (surface temperature, normalized difference vegetation index and enhance vegetation index, albedo, soil moisture, and surface type), three snow/ice products (a sub-pixel snow mask, ice surface temperature, and ice age), and three atmospheric aerosol products (optical thickness, particle size parameter, and suspended matter). VIIRS imagery is a separate EDR product. VCM requirements under non-degraded, daytime conditions are listed in Table 1.

Paragraph	Subject Binary Cloud Map	Specified Value
4D.4.2-14	l. Horizontal Cell Size	0.8 km @ Nadir
4D.4.2-15	m. Binary Map Horizontal Reporting Interval	Binary Map HCS
4D.4.2-16	n. Binary Map Measurement Range	Cloudy/Not Cloudy
	o. Binary Map Probability of Correct Typing	
4D.4.2-17b	1. Ocean, Day, COT > 1.0	94%
4D.4.2-17d	2. Day, Land, COT > 1	90%
4D.4.2-17e	3. Ocean, Night, COT > 1	85%
	p. Cloud Leakage Rate	
4D.4.2-17i	1. Ocean, Day, COT > 1.0, no Sun Glint	1%
4D.4.2-17p	2. Land, Day, COT > 1.0	3%
4D.4.2-17q	3. Land, Ocean, Night, COT > 1.0	5%
	q. False Alarm Rate	
4D.4.2-17l	1. Ocean, Day, COT > 1.0	5%
4D.4.2-17m	2. Land, Day, ToC NDVI < 0.2 or ToC NDVI > 0.4, or Desert, COT > 1.0	7%
4D.4.2-17r	3. Land, Ocean, Night, COT > 1.0	8%
4D.4.2-17n	r. Differentiate heavy aerosols from clouds, Day (0 ≤ OD < 2), dust/sand, smoke, volcanic ash.	85% (TBR)

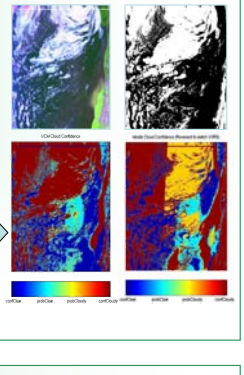
Overview of the VCM Algorithm

Overview of Cloud Confidence Logic:
The VCM algorithm has its heritage in several cloud mask algorithms, including the CLAVR, SERCAA, and APOLLO algorithms; but it design most strongly follows the architecture of the MODIS algorithm (Ackerman et al., 2002). The probability that a pixel is cloudy is based upon the proximity of results for a given cloud test to the threshold that separates cloudy from non-cloudy conditions coupled with the results from all tests used under the given geophysical conditions, as illustrated in Figure 1 and Table 2. The VCM algorithm produces a pixel-level cloud confidence that includes (1) confidently cloudy, (2) probably cloudy, (3) probably clear, and (4) confidently clear.

VCM Architecture



Cloud Tests	Water	Land	Desert	Coast	Snow
1. MODIS 250 m Reflectance Test	×	×	×	×	×
2. MODIS 11 μm (10.76 – 11.01 μm) Emissive Test	×	×	×	×	×
Difference (IR1)					
3. MIT (11.0 μm) Emissive Temperature (IR1) Test	×				
4. MODIS 1.38 μm Reflectance Test	×			×	
5. Visible/Infrared (VIS/IR) Ratio Test (0.65 μm/1.61 μm)	×				
6. MODIS 11/12 (8.55/10.76 μm) BTD Test	×	×	×	×	×
7. MODIS 11/12 (8.55/10.76 μm) BTD Test	(if ice was present) ×	×	(if Lat > 45° or < -45°) ×	(if ice was present) ×	×
8. MODIS 11/12 (8.55/10.76 μm) BTD Test	×	× (if Lat > 45° or < -45°) ×	(if Lat > 45° or < -45°) ×	×	(if Lat > 45° or < -45°) ×
9. MODIS 0.672 μm Reflectance Test	×			×	
10. MODIS 0.672 μm Reflectance Test	×	×			
11. MIT (0.65 μm) Reflectance Test	×				
12. MIT (0.65 μm) Reflectance Test			×		
13. MODIS 1.38 μm Spatial Test	×				
14. MODIS 0.672 μm Reflectance Test	×				



While based upon the architecture of the MODIS cloud mask algorithm, the VCM algorithm has been modified substantially to more fully exploit the unique data collected by the VIIRS sensor (Hutchison et al., Int'l J. Rem. Sens. 2005). For example, the VCM algorithm now exploits bands not previously used in automated cloud classification algorithms such as the ocean-color bands (Hutchison and Jackson, Geophy. Res. Ltrs. 2003; Hutchison and Cracknell, 2005) which are dual-gain in the VIIRS design to avoid saturation in cloudy atmospheres, as may occur with MODIS sensor data. In addition, the VCM algorithm includes (1) new cloud top phase logic, based upon the procedures described by Pavolonis and Heidinger (JTECH, 2004), (2) a top-of-canopy (TOC) normalized-difference-vegetation-index (NDVI) database to aid in cloud detection over diverse land surfaces, and (3) uses spatial tests with imagery resolution (375-m) bands that are nested inside radiometry resolution (750-m) bands to detect cloud edges that can impact sea surface temperature (SST) analyses.

Results from the VCM have been quantitatively compared against manually-generated cloud masks to assess VCM performance as shown in Figure 2. These comparisons have also been extended to include results from the MODIS cloud mask algorithm, Collection 4 which were available at the onset of chain testing. (See NGST document D44199).

Initial Performance (PCT, Leakage Rate, and False Alarm Rate)

Leakage, false alarms, and probability of correct typing (PCT) are the terms used in the NPOESS System Specification (Table 1) to assess VCM performance. The goal for the VCM is to minimize the leakage rate, which affects land and ocean surface products, minimize the false alarm rate, which impacts all cloud and aerosol products, and maximize PCT. The performance definitions are:

(a) Leakage: the number of pixels classified to be cloud-free in the automated cloud mask but found to contain clouds in the truth data. Leakage rate is the ratio of number of confidently clear pixels in the VCM that are cloudy in the manually-generated cloud mask to the total number of pixels in surface types shown in Figure 1.

(b) False alarms: the number of pixels classified to be cloudy in the automated cloud mask product but are cloud-free in the truth data.

(c) PCT: the sum of probably of confidently clear pixels in the VCM that are clear in the truth data plus probably or confidently cloudy pixels in the VCM that are cloudy in the truth data divided by the total number of pixels in each surface type.

(d) The VCM also must identify and flag heavy aerosols that were initially given a cloud confidence of confidently cloudy.

Manual cloud analyses were created for the 14-MODIS granules shown in Table 3 and initial VCM performance was established in 2006 during system-level testing. While known deficiencies existed in the VCM algorithm (e.g. heavy aerosols were detected as clouds, some VCM cloud tests could not be applied with MODIS data), these initial results showed consistently higher performance across the stressing, global conditions than was found in heritage algorithms.

Chain Test Scene	Granules ID	Leakage Rate (percent)	False Alarm Rate (percent)	PCT (percent)
#1	2002.032.1750	0.3	7.0	89.4
#2	2002.001.0340	0.1	13.6	81.8
#3	2003.194.0905	2.1	3.3	89.1
#4	2002.001.0435	2.2	0.1	89.7
#5	2003.299.1835	0.1	9.5	88.3
#6	2001.213.1210	1.0	8.3	84.9
#7	2001.196.1755	1.2	10.6	85.7
#8	2002.032.2210	1.0	0.6	97.5
#9	2001.152.1600	1.4	3.8	85.8
#10	2001.213.1220	0.2	2.1	88.8
#11	2002.118.0215	0.0	10.9	85.0
#12	2002.032.1745	0.1	13.7	82.2
#13	2002.032.0220	1.7	5.2	87.6
#14	2003.299.1040	0.1	5.7	88.7

Specifying Cloud Top Phase

Cloud top phase is crucial for the analysis of a series of additional cloud products that contain different processing logic for ice clouds compared to water clouds, e.g. cloud optical properties and cloud top parameters. Thus, the VCM produces a pixel-level cloud phase analysis.

Initially the approach used to generate the VCM cloud phase was based upon MODIS heritage algorithms (Strabala et al., 1994; Menzel et al., 2006; See MODIS Cloud Top Properties ATBD). However, a new technique that identifies overlap conditions, i.e. occurrence of ice clouds over water clouds in a single VIIRS pixel, was developed through the NPOESS IPO (Pavolonis and Heidinger, JTECH 2004). This logic has been integrated into the VCM algorithm. The VCM which now produces seven cloud phase classifications including water, thin cirrus, opaque cirrus, mixed phase, and overlap, along with clear, partly cloudy, and not executed. Figure 3 demonstrates the accuracy of this cloud phase algorithm.

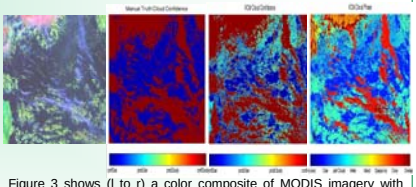
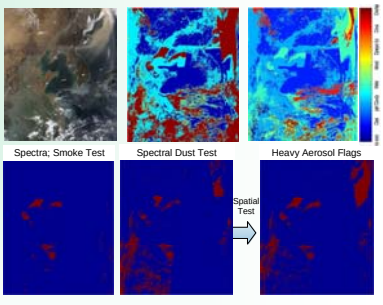


Figure 3 shows (l to r) a color composite of MODIS imagery with water clouds displayed in yellow, thin cirrus blue, and opaque cirrus pink. The manually-generated cloud mask for this scene (#10 in Table 3) is shown next, followed by the VCM analysis, with a PCT of 88.8%, which is slightly less than the requirement for a mixed land/ocean scene shown in Table 1. Finally, is shown the cloud phase analysis, which is seen to accurately depict most clouds fields, based upon qualitative comparisons with the MODIS imagery.

Distinguishing between Clouds and Aerosols (using the Aerosol Flag)

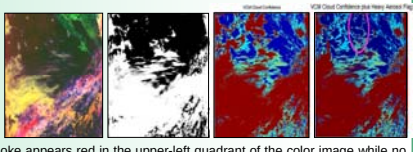
VCM heritage algorithms have been shown to misclassify aerosols as clouds when their optical depths exceed about 0.6 (Brennan et al., IEEE Trans. Geo. Rem. Sens., 2005). Therefore, new procedures were developed at NGST to identify pixels that contain heavy aerosols that were misclassified as clouds in an earlier stage of the VCM algorithm logic (Hutchison et al., JTECH in press). The new VCM logic employs unique spectral tests (using the dual-gain, 412-nm VIIRS band) to detect candidates that might contain dust, smoke, and pollution over ocean areas. It also uses the cloud phase analyses over land to identify additional heavy aerosol candidates. Spatial tests, based upon the VIIRS I1 imagery band (0.65-μm), are then used to segregate these candidates into water clouds and heavy aerosols. Finally, pixels containing volcanic ash are identified using a modification to the test developed by Prata et al., (1989). The procedures are demonstrated through the analysis of complex scene shown in Figure 4, which MODIS granule 2002.091.0240 and not in Table 3.



The top panels in Figure 4 show (l to r) a true-color image of dense airborne dust extending across the Yellow Sea into the Sea of Japan while pollution is evident in the lower-left quadrant of the scene. Most of these aerosol regions are called confidently cloudy and water clouds in the VCM analyses found in the next two panels. In the lower panels, first spectral tests for smoke and dust are shown. These results are then combined with water clouds results from the phase analysis over land before the spatial test is applied. The heavy aerosol flags in the lower right agree well with the pollutants seen in the imagery.

Intermediate Performance of the VCM

The initial performance shown in Table 3 has been updated to include the new procedures that differentiate between clouds and heavy aerosols. To assess quantitatively the performance of these new procedures, a pixel is counted as probably clear in the VCM binary cloud mask if it is classified as confidently cloudy and the heavy aerosol is true. However, the VCM cloud confidence results remain unchanged.



Quantitative results are shown for Scene 14 in Table 3. Smoke appears red in the upper-left quadrant of the color image while no aerosols are indicated in the manual cloud analyses in the next image. Before the heavy aerosol tests were execute, the VCM classifies all the smoke as confidently cloudy. After the tests were executed, as discussed in Figure 3, the heavy aerosols flags and cloud confidences were combined (and for visualization the cloud confidences were changed) as shown in the far right. The accurate identification of heavy aerosols improved the PCT from 88.7% to 91.6%. Most misclassification occur over the Baja Peninsula where the M5 Reflectance test has misclassified a cloud-free region as cloudy. Similar results were found in Scene 6 where PCT increased from 84.9 to 87.0 %. No heavy aerosols exist in the other scenes listed in Table 3.

VCM Final Performance after Future Enhancements

While the VCM is approaching NPP-launch readiness, several problems were identified during system-testing and remain to be resolved. Once corrected, the VCM is expected to meet system requirements as shown in Table 1. The deficiencies include:

- Non-functioning cloud shadow logic: The VCM does not accurately identify cloud shadows and there is no heritage cloud mask logic suitable for this task. NGST has evaluated new logic developed for the MODIS Collection 5 Aerosol Module which shows promise but it was found unsuited for integration into the VCM at this time. Further improvement is desirable.
- Correction to VCM thresholds: Several thresholds used in VCM cloud tests are based upon heritage cloud masks and must be altered to realize the full potential of the VCM, e.g. thresholds for the M5 Reflectance test are based upon AVHRR data.