A Geometry-Based Approach to Identifying Cloud Shadows in the VIIRS Cloud Mask Algorithm for NPOESS

Keith D. Hutchison*, Robert L. Mahoney*, Eric Vermote#, Thomas Kopp^, John M. Jackson*, Alain Sei*, and Barbara Iisager*
*** Northrop Grumman Space Technology, Redondo Beach, CA; & # University of Maryland; ^The Aerospace Corporation**

Abstract

A geometry-based approach is presented to identify cloud shadows using an automated cloud classification algorithm developed for the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program. These new procedures exploit both the cloud confidence and cloud phase intermediate products generated by the Visible/Infrared Imager/Radiometer Suite (VIIRS) cloud mask (VCM) algorithm. The procedures have been tested and found to accurately detect cloud shadows in global datasets collected by NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) sensor and are applied over both land and ocean background conditions. These new procedures represent a marked departure from those used in the heritage MODIS cloud mask algorithm which utilizes spectral signatures in an attempt to identify cloud shadows. However, they more closely follow those developed to identify cloud shadows in the MODIS Surface Reflectance (MOD09) data product. Significant differences were necessary in the implementation of the MOD09 procedures to meet NPOESS latency requirements in the VCM algorithm. In this presentation, the geometry-based approach used to predict cloud shadows is presented, differences are highlighted between the heritage MOD09 algorithm and new VIIRS cloud shadow algorithm, and results are shown for both these algorithms plus cloud shadows generated by the spectral-based approach. The comparisons show that the geometry-based procedures produce cloud shadows far superior to those predicted with the spectral procedures. In addition, the new VCM procedures predict cloud shadows that agree well with those found in the MOD09 product while significantly reducing the execution time as required to meet the operational time constraints of the NPOESS system.

Introduction

Undetected cloud shadows can severely impact many of the VIIRS products, which are also referred to as environmental data records (EDRs), including the aerosol, land, and snow/ice EDRs. For example, the MODIS aerosol algorithms, used to create the MOD04 product, nominally examines 400, 500-m pixels to retrieve aerosol optical thickness (AOT) at a spatial resolution of 10-km over land and includes sophisticated schemes, e.g. the "dark-pixel" correction (Remer et al., 2006), to reduce the possible effects of cloud shadows which have been shown to produce with MODIS data much lower than expected AOT values compared to ground-based observations (Hutchison et al., 2008). On the other hand, the VIIRS intermediate AOT product is generated for each cloud-free, nominal 800-m pixel and the product can be severely degraded if shadows are not accurately identified because the path radiance will be much lower than assumed by the retrieval algorithm. Furthermore, the need to accurately detect cloud shadows is important to the generation of a variety of land products created from a variety of remote-sensing platforms including AVHRR, LandSat, and MODIS (Huete et al., 2002; Liang et al., 2002; Simpson and Stitt, 1998). Therefore, it is critically important that cloud shadows be accurately identified in the automated cloud screening algorithms such as the VCM.

During the initial testing of the VCM algorithm, it was found that the heritage, spectral-based cloud shadow approach seldom detected shadows that were evident in MODIS imagery, since no unique spectral characteristics exist that describe cloud shadows over complex global, cloud-free surfaces. Similarly, the approach often predicted false shadows, i.e. shadows not associated with any clouds. As a result, a new approach to identify cloud shadows was sought and the geometry-based approach, used to create the MODIS Surface Reflectance (MOD09) product, was identified as the primary candidate. However, preliminary testing with the MOD09 algorithm raised concerns about the lengthy processing time required to identify shadows with this approach. As a result, the MOD09 cloud shadow algorithm was significantly modified for use in the VCM to meet the stringent latency requirements of the operational NPOESS system. In this poster, shadows for water and ice clouds are presented for a number of algorithms, including the geometry-based cloud shadow approach used in the latest version of the VCM and MOD09 algorithms along with those found with the spectral-based cloud shadow algorithms used in the older version of the VCM and the current MODIS Collection 5 (MOD35) MODIS cloud mask (MCM) algorithms.

Spectral Approach to Cloud Shadow Detection

Spectral tests have been employed by the MCM (Ackerman et al., 2006; 2002; 1997) and original VCM (Reed, 2002) algorithms to identify cloud shadows, while noting that a geometric approach requires too much CPU to run operationally.

Figure 1 shows results produced by these spectral-based cloud shadow tests applied to a MODIS Terra granule collected over the western US on October 30, 2003 at 1835 UTC. (The granule ID is MOD.2003.299.1835.)

A false-color image of the region of interest is enlarged in Panel 1A. Large shadows are apparent near clouds located at Points A, B, and C. Panels 1B and 1C show shadows predicted with the spectral tests.

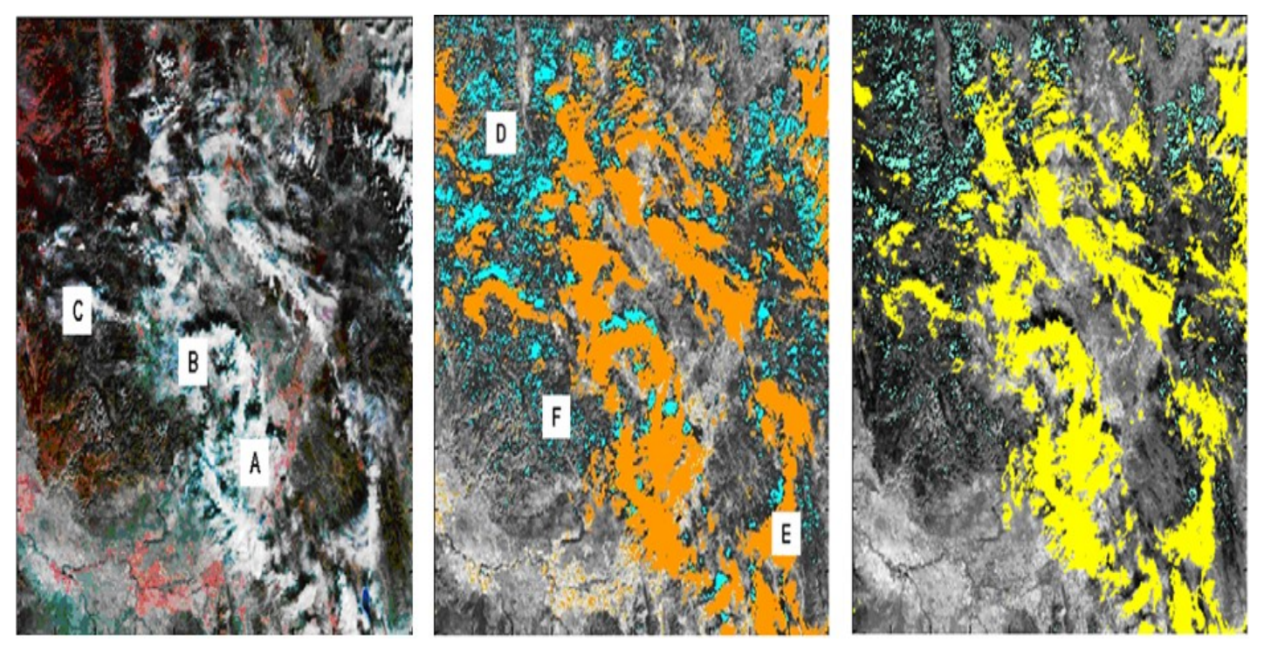

Figure 1 (a) (b) (c)

Cloud shadows predicted by the spectral tests with this case study represent the best produced in 40+ MODIS granules analyzed during the course of these investigations. In most cases, the spectral-based tests failed to detect correctly any cloud shadows.

Results

Shadows from Water Cloud

Figure 3 shows results of the geometry-based cloud shadows for the scene containing water clouds in Figure 1. Panel 3A shows results from the VCM algorithm while Panel 3B shows the data contained in MOD09 product. Clouds in the MOD09 product are displayed in yellow while those from the VCM algorithm appear as orange. Shadows appear turquoise for both products.

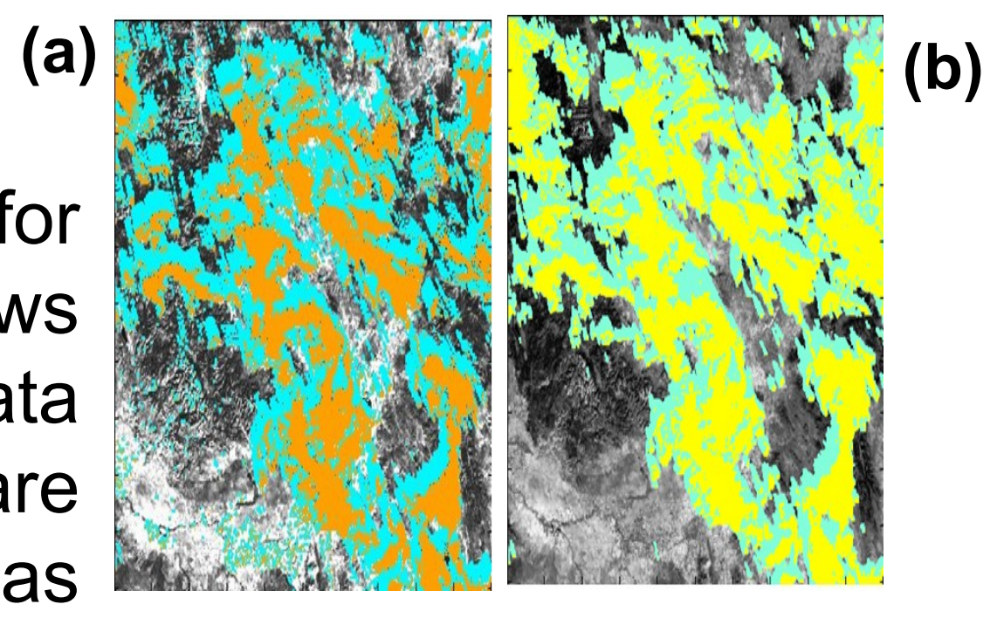

Figure 3

The NPOESS Geometry-Based Approach to Cloud Shadow Detection

The original geometry-based approach was developed by Dr. Eric Vermote for use in the MODIS Surface Reflectance (MOD09) product. A description of the geometry-based cloud shadow logic is shown in Figure 2. Differences between the MOD09 and VCM implementations of this cloud shadow logic are highlighted (bold and white text).

The shadow logic compiles statistics for 20x20 pixel "windows" which are the basic analysis regions. In the MOD09 product, this window "slides" one-row or one column at a time; however, in the VCM implementation, the window "hops" by groups of 20x20 pixels, i.e. no single pixel is examined more than once. Next, each pixel in the region is then examined to identify candidates that might cast a shadow within or outside these windows.

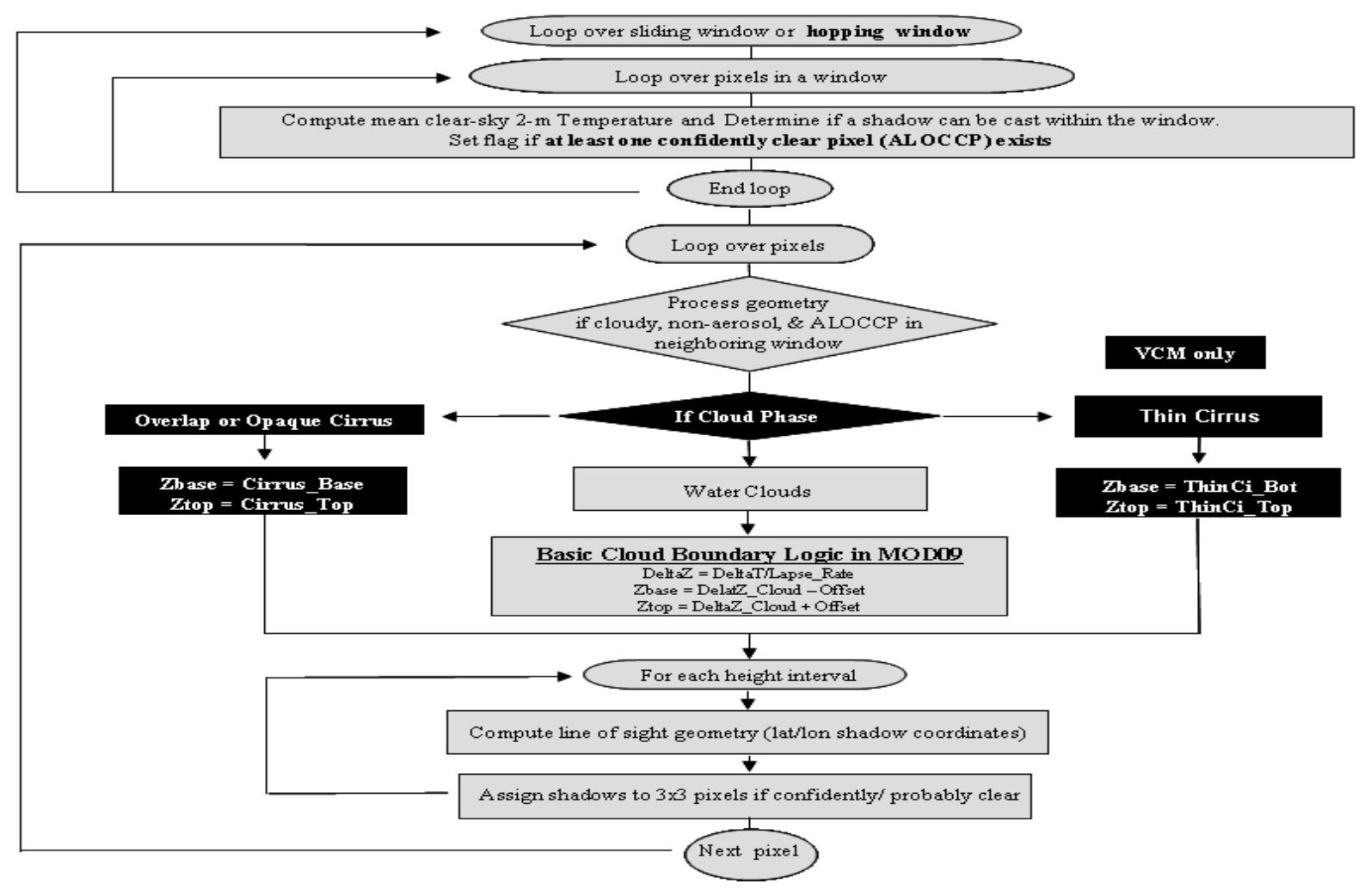

Figure 2

MOD09 approach: collects 11-mm and 6.7-mm brightness temperatures for each cloudy pixel to determine cloud boundaries. Cloud top temperatures (CTTs) are based on the 11-mm brightness temperature (BTs), corrected for water vapor attenuation above the cloud top using the 6.7-mm BTs. CTTs are converted to cloud top heights through comparisons against the mean 2-m NCEP surface air temperature, assuming a standard lapse rate, as shown in the box titled "Basic Cloud Boundary Logic in MOD09." **VCM approach:** Ice cloud boundaries are determined using the VCM cloud phase algorithm (Pavolonis and Heidinger, 2004) and shadows differ when the ice cloud phase is classified as opaque, thin, or overlap. Thick cirrus clouds, i.e. opaque cirrus and overlap cirrus, cast shadows larger than those found near thin cirrus. In addition, the maximum allowable cloud top heights of all cirrus clouds are varied linearly with latitude from a mean tropopause height of 16-km in tropical regions to 8-km in polar regions. Cloud boundaries for water clouds follows the logic used in the MOD09 approach.

Estimates of cloud boundaries in both approaches are then converted into geometric shadows using an algorithm that iterates over cloud boundaries to compute the line of sight cloud shadow geometry. **MOD09 approach:** each step of the iteration is constrained to a 0.5-km interval, which means 32-iterations per pixel may be required for a 16 km thick cloud to cast the shadow correctly onto the Earth's surface. **VCM implementation:** a maximum of four iterations is used to reduce latency.

Both implementations follow the same logic for the remaining steps of casting shadows onto the cloud-free Earth. Each cloudy pixel is projected onto a cloud-free pixel at the Earth's surface. No correction is made for terrain. If the cloud shadow logic projects onto a cloud-free pixel, the shadow fills all cloud-free pixels in a 3x3 neighborhood around this location. This process is repeated for each cloudy pixel.

Results

Shadows from Ice Cloud

Cloud shadows are shown for ice clouds shown in the MODIS scene contained in Figure 4, which covers the southwest USA and northern Mexico. These data were collected by MODIS Terra on February 1, 2002 at 1750 UTC (granule ID MOD.2002.032.1750).

Panel B of Figure 4 contains shadow results from the VCM algorithm using the spectral tests. (In this case, the actual VCM cloud mask is not shown separately since the spectral tests detected so few shadows.) Panels C and D in Figure 4 again show the VCM and MOD09 geometry-based cloud shadows. In this case, the VCM projects a slightly larger shadow that found in the MOD09 product. Upon close examination of the MOD09 product, it is seen that unmasked shadows in the imagery are evident around Points A and B in Panel D, while these edges of undetected shadows are not observed in VCM results shown in Panel C. It appears that using the cloud phase analyses in the VCM to specify the cloud top height of cirrus clouds can provide a more accurate cloud shadow when the clouds are not completely opaque. Smaller shadows in MOD09 product approach occur because the actual CTT is colder than the 11-µm brightness temperature, so the cloud top height is placed too low in the atmosphere.

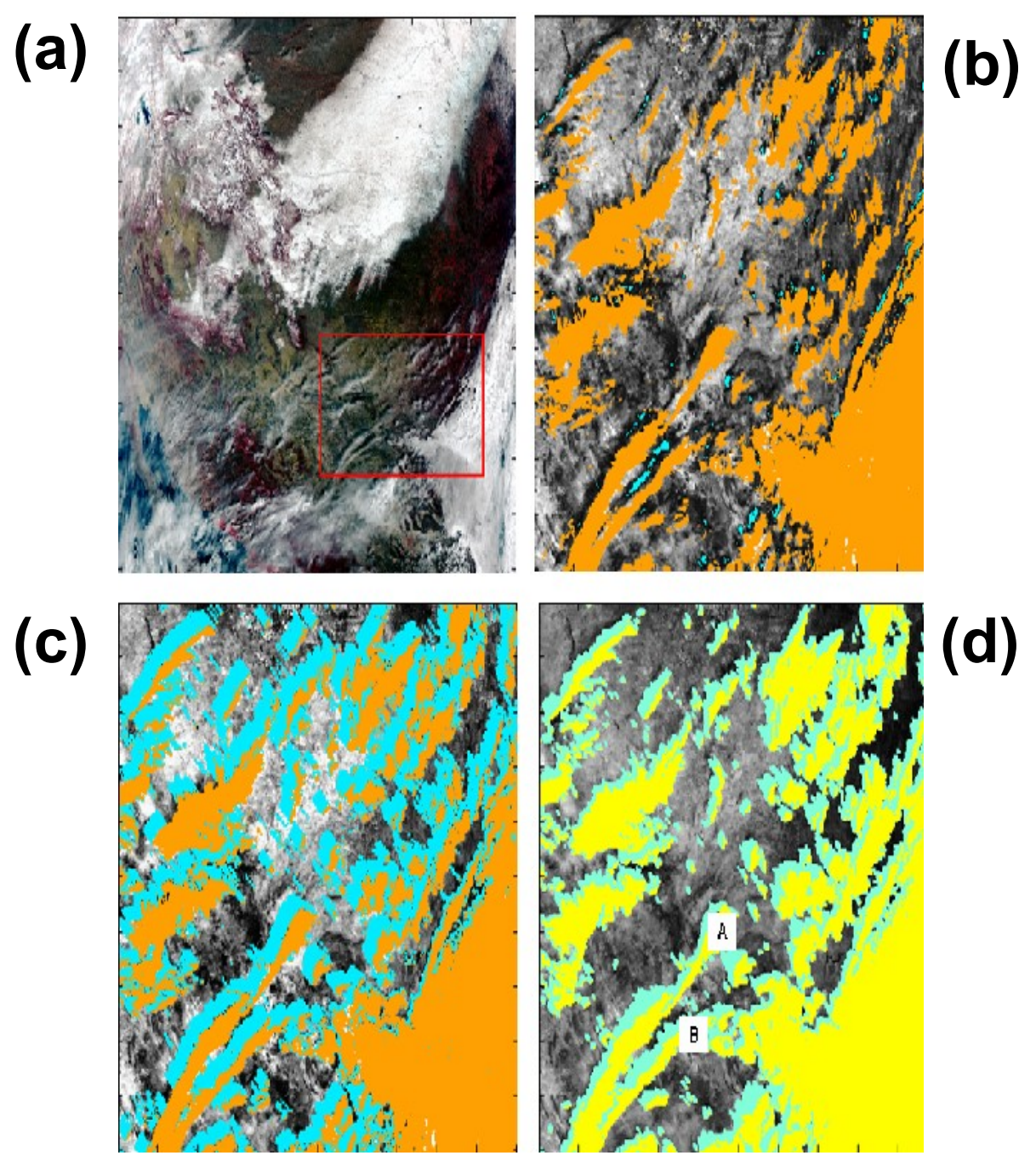

Figure 4

Conclusions

A geometry-based approach has been implemented to identify cloud shadows in the VCM algorithm for NPOESS. The procedures closely follow those used in the MOD09 algorithm. The new VCM cloud shadow procedures exploit both the cloud confidence and cloud phase intermediate products to better classify cloud tops associated with cirrus clouds. Results show that the geometry-based approach used to predict cloud shadows are far superior to those procedures that predict shadows with the spectral tests. In addition, procedures used in the new VCM implementation significantly reduced execution time of the MOD09 approach. The analyses of about 40 MODIS showed the core-time on an IBM computer, running AIX operating system was about 22-seconds per granule. Replacing the spectral test with a direct implementation of the MOD09 algorithm increased this core time to about 200-seconds, while running the VCM with the VCM implementation required about 45 seconds.