Algorithm for Flagging High-Scatter Pixels on VIIRS

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Introduction

The Visible/Infrared Imager Radiometer Suite (VIIRS), built by Raytheon Space & Airborne Systems, measures radiance for 22 bands from wavelengths of 0.4 to 11 microns. It has a spatial resolution from 375 to 750 m at nadir and 750 to 1600 m at the edge of scan, which is 56 degrees off nadir. It is a cross-track scanning sensor & maintains high spatial resolution at edge of scan by varying the in-scan aggregation as a function of scan angle.[1, 2, 3] This complicates the computation of the scattering, however, because the algorithm requires a radiance field with a constant spatial resolution in each dimension.

Causes of Scattering in Optics

All optical systems that focus light must contend with scattering. Scattering is caused by various imperfections in the optics. However, because light is a wave, even with perfect optics it will diffract at the edges of apertures. Diffraction decreases rapidly as a function of angle off the optical axis of the system, but it is non-zero even up to 90 degrees off the optical axis. In addition to diffractive scattering, imperfections, roughness and scratches in the manufacturing of the reflective and refractive optical surfaces will cause scattering.[4] Contamination of the optical surfaces is another cause of scattering. This can be due to dust and other materials that come into contact with the surface of the optics. Raytheon and Northrop Grumman plan to minimize contamination of the optics using clean rooms and other techniques during the manufacture, testing and storage of VIIRS, but on-orbit contamination will accumulate over the life of the instrument, increasing the scattering. Raytheon has models to predict this increase in contamination and the resultant increase in scattering up to end-of-life of the instrument.

Purpose of Algorithm

Scattered light can contaminate pixels in the vicinity of bright objects in VIIRS scenes. Also, bright objects can loose light that is scattered out to darker areas. Areas that are uniform experience almost no scattering degradation because about as much light is being scattered into as out of a given pixel. Although the fraction of scattered light is low, for a sufficiently bright source close to a dim nearby pixel the scattered contribution can dominate the radiometric uncertainty. Several Environmental Data Record (EDR) specifications, including ocean color, and land surface albedo, have exclusion conditions in the NPOESS System Spec around bright pixels, and call for a flag to indicate when scattering is above an acceptable level. The algorithm identifies pixels that are likely to be contaminated by scattered light and produces the flags required by the EDR algorithms. The algorithm applies to all bands except Day/Night band (DNB). The output of this algorithm will be a 4-bit flag for each pixel in each band that characterizes the level of contamination of signal by scattered light.

Scattering Nomenclature

Scattering is referred to by different names by different groups among the NPOESS community:

- Optical Engineering
  - –Near Field Scattering (NFS);
  - –Point Source Transmittance (PST);
  - –Scattering Point Spread Function (PSF).
- Sensor Spec
  - –Near Field Response (NFR)
  - –Structured Scene Requirement
- EDR & NPOESS System Spec
  - –Bright Pixel Identification or Quality Flag
  - –Bright Pixel Exclusion requirement

Equations Used in Computing Scatter Fraction

What we want

$$\%\ \text{scattered light} = \frac{S_{scat}}{S_{meas}} * 100$$

Definitions

S_{true} = true scene

S_{meas} = measured scene including scattered light

P_{true} = true full PSF; ε_{true} = true scatter PSF

P_{meas} = measured PSF; ε_{meas} = measured scatter PSF

δ = Dirac Delta Function

$$\delta(i,j) = \begin{cases} 1 & \text{if } i = i_{center}\ \&\ j = j_{center} \\ 0 & \text{otherwise} \end{cases}$$

i = in - track sample index

j = in - scan sample index

Scattering is a Convolution

$$S_{meas} = P_{true} * S_{true}$$

Scattering as perturbation on PSF

$$P_{meas} = \delta + \varepsilon_{meas}$$

$$P_{true} = \delta + \varepsilon_{true}$$

Normalization Conditions

$$\sum_i \sum_j P(i,j) = 1$$

$$\sum_i \sum_j e(i,j) = 0$$

Change in Radiance caused by Scattering

$$S_{scat} = S_{meas} - S_{true} = P_{true} * S_{true} - \delta * S_{true} = (P_{true} - \delta) * S_{true} = \varepsilon_{true} * S_{true}$$

Convolving the PSF with Measured Scene is actually a double convolution (once by nature, once by algorithm)

$$S_{double\text{-}conv} = P_{meas} * S_{meas} = (\delta + \varepsilon_{meas}) * (\delta + \varepsilon_{true}) * S_{true} = (\delta * \delta + \varepsilon_{meas} * \varepsilon_{true} + \varepsilon_{meas} + \varepsilon_{true}) * S_{true}$$

Some Algebra

$$S_{scat} = S_{double\text{-}conv} - S_{meas} = P_{meas} * S_{meas} - \delta * S_{meas} = (\delta + \varepsilon_{meas} - \delta) * S_{meas} = \varepsilon_{meas} * S_{meas} = \varepsilon_{meas} * (\delta + \varepsilon_{true}) * S_{true}$$

gives

$$S_{scat} = S_{scat} + (\varepsilon_{meas} - \varepsilon_{true} + \varepsilon_{meas} * \varepsilon_{true}) * S$$

therefore, if

$$\varepsilon_{true} \cong \varepsilon_{meas} \quad \& \quad \varepsilon_{true} * \varepsilon_{meas} * S \cong 0$$

then

$$S_{scat} \cong S_{scat}^{-}$$

so

$$\%\ \text{scattered light} = \frac{S_{scat}}{S_{meas}} * 100 \cong \frac{S_{scat}}{S_{meas}} * 100 \cong \frac{\varepsilon_{meas} * S_{meas}}{S_{meas}} * 100$$

Approximations

As long as the measured Near Field Response (NFR) is a good estimate of the true NFR, and NFR is a small contribution to the whole PSF, then the difference between the doubly convolved scene and the measured scene is a good estimate of the scattering given in the equations here. In addition to the requirement that the measured scattering distribution be close to the real one and much smaller than 100%, there is another requirement here. Very close to a bright object, where the % scattered light is close to or greater than 100%, the exact value will become very uncertain. However, though the exact value is unknown, it is certain that the scattering is very large, and what is not known is exactly how large. Since we choose the highest threshold of 10% for the flags, anything above this is flagged as >10% scattered light, so it will not matter whether it is, say 20% or 40%. Either way, it is much too large of an error to provide a meaningful Environmental Data Record (EDR) product.

Raytheon measures the NFR before delivery of the instrument. Until such measurements become available for the flight unit, the in-track and cross-track NFR contribution to the PSF will be based on a fit to a Harvey-Shack (H-S) BRDF model. Test measurements will be translated from the H-S BRDF into ε_{meas}, using the angular separations in the BRDF to describe the scattering to adjacent samples in the in-track and in-scan direction.

Even if the scattering was perfectly measured before launch, the true scattering function is expected to differ from this, especially over the life of VIIRS as optical surfaces degrade with time, and SBRS has models to estimate this impact. So that our flags are conservatively pessimistic, we will use the end-of-life (EOL) estimates over the entire mission.

Definitions of 4-bit Flags

Once scattering has been computed, a set of thresholds are applied to determine a 4-bit flag which is the output of the program:

Binary	Number	Condition
0000	0	0.0 - 0.01% scattered light
0001	1	0.01 - 0.02% scattered light
0010	2	0.02 - 0.05% scattered light
0011	3	0.05 – 0.1% scattered light
0100	4	0.1 – 0.2% scattered light
0101	5	0.2 – 0.5% scattered light
0110	6	0.5 - 1.0% scattered light
0111	7	1.0 - 2.0% scattered light
1000	8	2.0 – 5.0% scattered light
1001	9	5 – 10% scattered light
1010	10	> 10% scattered light
1111	15	calculation unreliable

Filling in the Gaps

The radiances calculated by the VIIRS calibration algorithm are, unfortunately, not a complete description of the radiance in the scene. Radiance beyond the edges of the scene is unknown, and some bands saturate in the bright parts of the scene. Much of the algorithm involves reconstructing the unmeasured radiances in the scene. The following rules are applied:

For Saturated pixels, use another proxy band as substitute. Reflective bands use solar spectrum scaling to multiply substitute band by before substituting. Emissive bands use black body temperature for scaling. If no suitable proxy band is found, then default radiance based on maximum reflectance or brightness temperature will be used.

For missing data, if the gap in radiance data is small, such as a single pixel, or a scan line of pixels, then the pixels will be estimated by interpolating the nearest neighbors. If the gap is large, then it will be filled in with proxy bands.

Around Scene edges, in the usual processing mode, there is always a granule before and after the current granule which should be used. In the case where the process is just starting up, the algorithm should create a guard region by reflecting the first or last granule in the processing chain so that the flags can be calculated. The alternative is to set the "calculation unreliable" flag until the 2nd or 3rd scan, if no data is available.

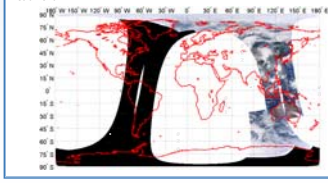
Edge of Scan, assume replication of the radiance to produce a guard band sufficient for the convolution.

Scan overlap (Bowtie) requires geolocation data to match the edges of a scan with the next scan and the previous scan. This produces a continuous radiance field across scans and across granules (groups of scans).

Creating VIIRS Radiances from NASA MODIS Data

Using a radiative transfer model is too slow to produce an entire orbit of simulated data. Therefore, to test the calibration algorithm and The High-Scatter Identification Algorithm with large amounts of data, MODIS data was resampled to match an NPOESS Preparatory Program (NPP) orbit. This resampled MODIS data was used as input to the sensor model. The figure below shows an orbit of proxy data projected as an earth scene. Here two orbits of data have been resampled into the VIIRS NPP orbit. Realistic spacecraft ephemeris and attitude data were generated for the NPP orbital plane for approximately 2 orbits (>3 hours), assuming perfect spacecraft attitude control (roll, pitch, yaw offsets set to zero). The sensor's scanning geometry was combined with spacecraft position and attitude information to produce geolocated sensor pixels and associated auxiliary data. TOA radiances were emulated for VIIRS using proxy Sensor Data Records (SDR) from MODIS on the Aqua platform. The sensor model then generated Earth-view, calibration, and engineering Raw Data Records (RDR) for the sensor using the Northrop Grumman sensor model, VIRRISM, consistent with the sensor's calibration software.[5] Test data is restricted to a limited number of sensor effects. Six 2-orbit cases have been produced, covering every other month of the year.

The modeled knowledge error was applied to the look-up tables and parameters used by the calibration algorithm. Since the SDR calibration algorithm is essentially the inverse of the sensor model, the residual radiometric errors mostly result from this knowledge error. The sensor model was used to produced raw sensor data containing counts for earth view, space view, OBC blackbody view, solar diffuser view, thermistors, DC restore voltage, scan encoder, along with simulated ephemeris data from the satellite. All this is the input to the SDR algorithm, and the algorithm was run, outputting radiances and geolocations.[6] These were compared with the original input files of truth radiances. Due to limits of dynamic range, some of the bands saturate in the modeled data just as they would on the actual VIIRS instrument.



Test Cases

1 Test Pattern Granule

3 daytime 48-Scan granules, MODIS Proxy, NPP Orbit

- MODIS Aqua data re-sampled to VIIRS resolution
- Over South Atlantic
- Parts of Argentina (Patagonia, are visible)
- Good mix of optically thick and optically thin clouds, clear ocean, coast & land

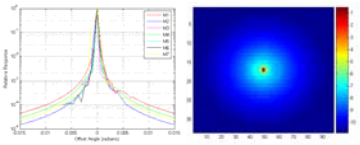
1 nighttime 48-Scan granules, MODIS Proxy, NPP Orbit

- Over Gulf of Mexico
- Parts of southern States are Included
- Good mix of optically thick and optically thin clouds, clear ocean, coast & land

All Bands are tested

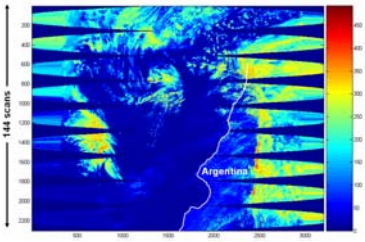
Scattering PSF

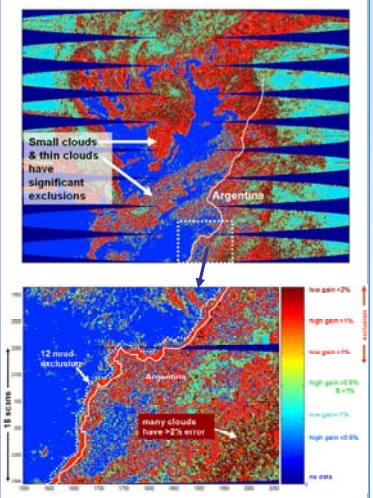
The Near field scattering response, represented here as a PSF, will be measured for the VIIRS flight unit, and input to the algorithm as a look-up table. The actual values have not yet been determined, but in order to test this algorithm a hypothetical PSF was produced. Cross-sections of the 2-dimensional PSF in the in-scan direction are shown in the left figure for the Vis/NIR bands. On the right is a 2-dimension plot of the PSF used for band M4, wavelength = 555 nm.



Results: South Atlantic & Argentina, Visible Band M4, λ=555 nm

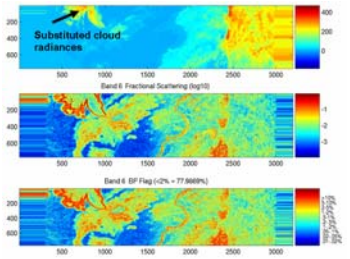
The 3 plots below show band M4 results. The first is the actual radiance, after substitutions. The second shows the flagged output. The third shows a detail of the flagged output. For this case 144 scans are shown. The scans are grouped into 16 scan bunches to demonstrate the importance of continuity in the convolution. The overlapping pixels are removed, so there are gaps between the bunches. The red regions show areas that would be excluded by the ocean color algorithm or a land algorithm. Note that there are significant exclusion areas, up to 12 milliradians around coasts and clouds. The area of exclusion is directly related to the area of the bright object.





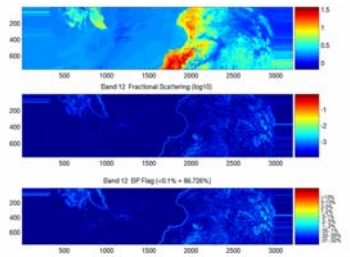
Results: South Atlantic & Argentina, Near IR Band M6, λ=746 nm

The 3 plots below show band M6 results. The first is the actual radiance, after substitutions. The second shows the computed fractional scatter. The third shows the 4-bit output code. Because M6 saturates for most bright clouds, it requires a substitution radiance. Note that the radiance after substitution does not appear to be saturated.



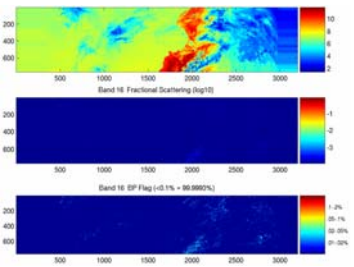
Results: South Atlantic & Argentina, Mid Wave IR Band M12, λ=3700 nm

The 3 plots below show band M12 results. The first is the actual radiance, after substitutions. The second shows the computed fractional scatter. The third shows the 4-bit output code. Note that for this emissive band the scattering is much weaker than for the reflective bands. Because this scene is daytime, it is a mix of reflected and emissive light.



Results: South Atlantic & Argentina, Long Wave IR Band M16, λ=12013 nm

The 3 plots below show band M16 results. The first is the actual radiance, after substitutions. The second shows the computed fractional scatter. The third shows the 4-bit output code. Note that for this long-wave IR (LWIR) emissive band the scattering is almost negligible. This is partly due to lower scattering, which is typical for longer wavelengths, but also because the scene has a lower contrast in a purely emissive band.



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4. John C. Stover, "Optical scatter: an overview", SPIE Digital Library, doi: 10.1117/12.50490
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6. Stephen Mills & Jodi Lamoureux, "Simulation and test of the VIIRS Sensor Data Record (SDR) algorithm for NPOESS Preparatory Project (NPP)", AMS 87th Annual Meeting, NPOESS/GOES-R Symposium Poster Session