

New VIIRS DNB stray light correction method

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ABSTRACT

The Day/Night Band (DNB) broadband (500-900nm) imager is one of the sensors in the Visible Infrared Imaging Radiometer Suite (VIIRS) on-board the Suomi National Polar-orbiting Partnership (SNPP) and the NOAA-20 satellites, which are polar-orbiting and fly at about 830km above the surface of the Earth. Depending on the satellite location and the sensor viewing geometry, for a short period just before (or after) the satellite enters into (or emerges from) the shadow of the Earth, unwanted stray light, seemingly caused by the reflection of solar beam on the slightly exposed inner side of the leading (or trailing) nadir door, can enter the instrument and impose noticeable impacts to a narrow portion of DNB satellite images in every orbit. The impacted images can be modified to look normal, and the current DNB stray light correction algorithm empirically assigns corrections. There is also an alternative approach using image-processing techniques. Both methods rely mainly on the stray light impacted measurements. To simplify the approach and for better correction results, the new method presented in this paper incorporates the observed asymptotic nature of measurements surrounding the stray light impacted region by fitting to the drop off in sun light from day to night. The new method can be applied to the raw measurements in real-time, and it can help to advance our understanding of this special type of DNB stray light that happens over the polar regions.

Keywords: VIIRS, DNB, stray light, correction

1. INTRODUCTION

To enable an improved understanding of the Earth as an integrated system, NASA's Earth Observing System (EOS) is a coordinated series of polar-orbiting and low inclination satellites for long-term well calibrated global observations [1]. The Joint Polar Satellite System (JPSS), a civilian successor of the Suomi National Polar-orbiting Partnership (SNPP) [2], is a new generation polar-orbiting operational environmental satellite system. Currently the SNPP and the JPSS-1 (now NOAA-20) satellites circle the Earth from pole-to-pole and cross the equator about 14 times daily providing full global coverage twice a day. One of the instruments onboard these satellites is the Visible Infrared Imaging Radiometer Suite (VIIRS) [3]. The VIIRS is designed to provide moderate-resolution, radiometrically accurate images of the globe. It is a wide-swath (~3000km) scanning radiometer with fourteen reflective solar bands, seven thermal emissive bands, and one day and night band (DNB) that is capable of capturing low light images during the nighttime [4]. The DNB covers a spectral range of 500-900nm, consist of three gain stages to span a large signal range from daytime to nighttime, and has a spatial resolution of 375m at the nadir view. This paper will describe the DNB stray light phenomenon, its impact to satellite images, and stray light correction methods, including a new, physical model method.

2. DNB STRAY LIGHT

The sources and magnitudes of stray light vary as a satellite travels around the Earth. Due to the viewing geometry, unwanted sunlight can enter the instrument to contaminate the signal. Figure 1 illustrates four typical situations for a sun synchronous orbit.

1. During the daytime: The sunlight is from behind the instrument while it points at the surface of the Earth; therefore, the source of stray light is mainly the Earth disk. This situation has been simulated in the pre-launch

test to ensure that the magnitude of stray light is within the design specifications of the instrument (e.g., less than 1% of the typical measurement) [5]. This situation is not considered in this paper.

2. Over the North Pole region: As the satellite travels from daytime towards night, because its orbit is about 830km above the Earth surface, there will be a short period when the surface directly beneath the satellite has entered nighttime while the satellite is still illuminated by the sun. In this situation the sunlight hits the trailing side of the instrument, and the leading side of the nadir door becomes increasingly exposed to the sun, resulting in gradually elevated stray light. An impacted NOAA-20 (N20) image in the northern hemisphere is shown in the upper panel in Figure 2. The profiles of three cross sections along the track direction are also plotted. They are from near the left edge, around the center, and at the right edge of the image. The stray light mostly remained within an order of magnitude above the measurement noise level, except in N20 where close to the end of scan the stray light increased exponentially and reached three orders of magnitude higher than the noise.
3. During the nighttime: Light from stars can enter the instrument, for example through the space view, causing stray light. This type of stray light is not considered in this paper.
4. Over the South Pole region: Similar to that in the northern hemisphere, there will be stray light after the satellite emerges from the shadow of the Earth, which may be caused by the exposure of the trailing side of the nadir door to the sun. In addition, the leading side of the instrument with the solar diffuser port that provides the reference irradiance using the solar illumination for sensor calibration is facing the sun, adding more stray light. An impacted N20 image in the southern hemisphere is shown in the lower panel of Figure 2. Three cross sections are also included. In this example the peak value of stray light along the right edge of the image is about twice as large compared to that in the northern hemisphere.

Although only a small percentage of satellite images are impacted by the special type of stray light over the polar regions, they should be corrected.

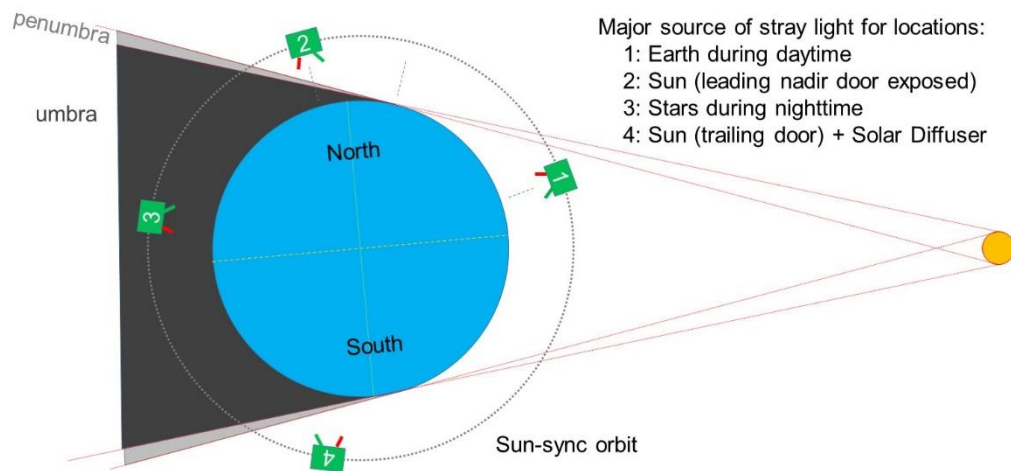


Figure 1. An illustration of sun synchronous orbit and major sources of DNB stray light. Four situations are highlighted. Notice that at position 4 the leading side of VIIRS with a window for the solar diffuser for calibration is exposed to the sunbeam, causes additional stray light.

3. DNB STRAY LIGHT CORRECTION METHODS

Because the stray light is lumped into total measurements, its exact magnitude is unknown; however, depending on assumptions about how the data should be partitioned, there are different ways to make the stray light impacted images look normal. Three methods with different tradeoffs are described in this section, and the corrected images are shown in Figure 3, where the upper and the lower panel is for the northern and the southern hemisphere, respectively.

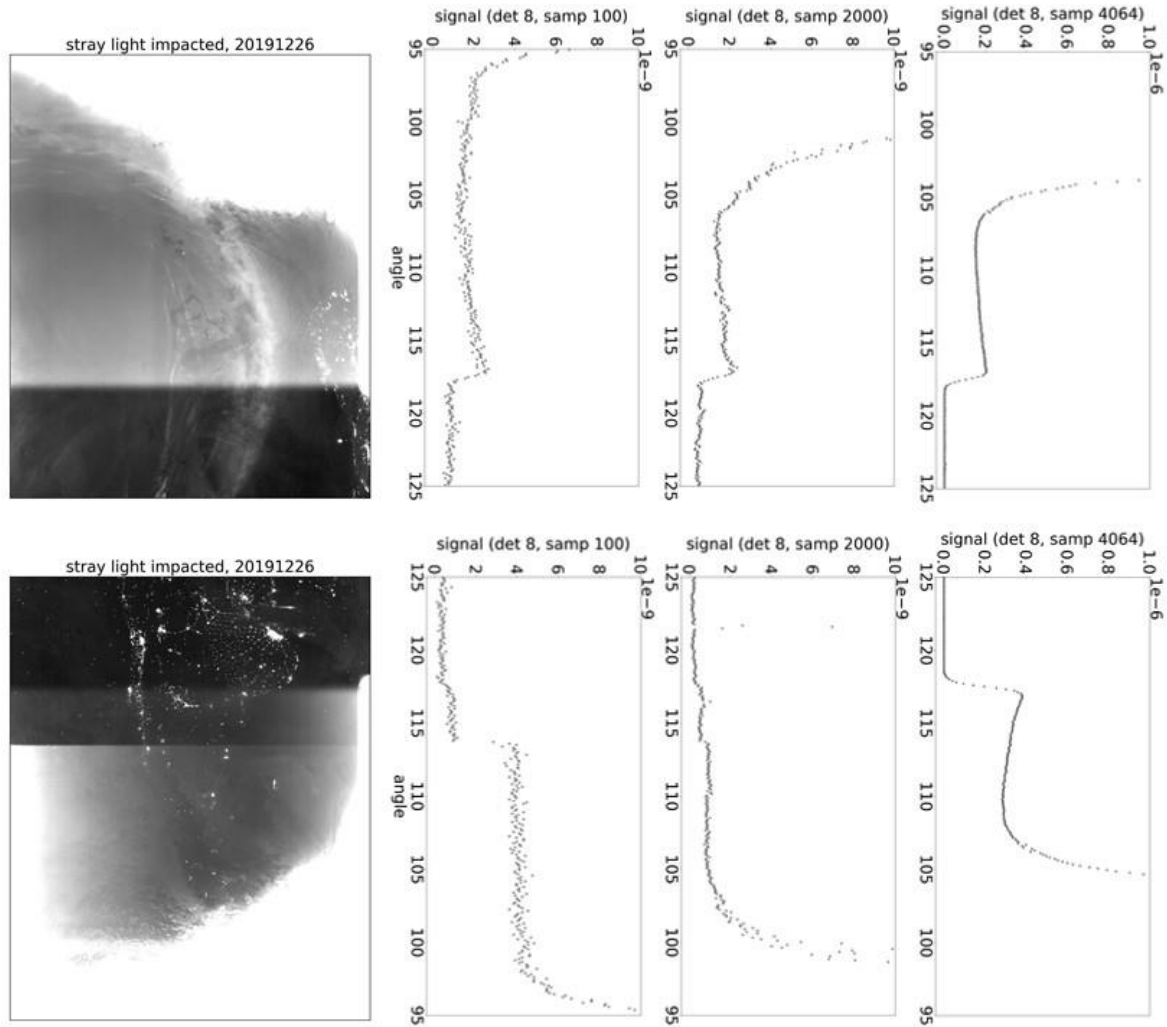


Figure 2. Examples of stray light impacted N20 DNB images from the northern (upper panel) and the southern (lower panel) hemispheres. The values shown range between -1×10^{-10} and $3 \times 10^{-9} \text{ Wm}^{-2}\text{sr}^{-1}$ (about a thousandth of the upper limit of the high gain signal). The measurement resolution is about $1.5 \times 10^{-10} \text{ Wm}^{-2}\text{sr}^{-1}$. In both images the track direction is from top to bottom, and the scan direction is from left to right. The plots in each panel at the right are cross sections of sample numbers 100 (left), 2000 (middle), and 4064 (right, i.e., the last sample, or the right edge of the image), respectively.

3.1. Binning and threshold method

The current DNB stray light correction method in the NASA's Land Science Investigator-led Processing System (SIPS) for the SNPP and the N20 VIIRS is an empirical approach [6-8], which uses measurements on a new moon day to develop a look up table (LUT) for stray light correction. Major steps of the algorithm are:

- Select data from multiple orbits to form an image composite for robust statistics. The selected solar zenith angle (SZA) range is 95° - 125° , where an angle less than 90° is in daytime, and greater than 90° is in nighttime on the surface of Earth. For example, the dimensions of the image composite may be 10800×4064 , with 10800 scans of 4064 samples.
- Bin the image composite into blocks to facilitate calculations. For example, divide the 4064 samples in each scan into 127 bins with 32 samples in each bin, and group every 15 scans.
- Sort data in each block and assign the lowest 20% to represent the impact of stray light.

- Interpolate the assigned values from blocks to each pixel and smooth the results.
- Assign the beginning of stray light, treat the penumbra separately, and pick nightglow.
- $corrected = measured - impacted + nightglow$.

The binning and threshold method is effective but has its limitations; especially the empirically assigned binning and the 20% threshold. In addition, the bright stripes around the SZA 100° cannot be corrected by assigning a beginning of the stray light. The corrected images are shown in the left column in Figure 3. Some residual effects, such as the sudden change across the penumbra and the stripping across samples, are related to the cross-scan and cross-sample smoothing applied in the method. There is a significant artifact near the end of scan, i.e., the right side of the corrected image, where the stray light increases exponentially in N20.

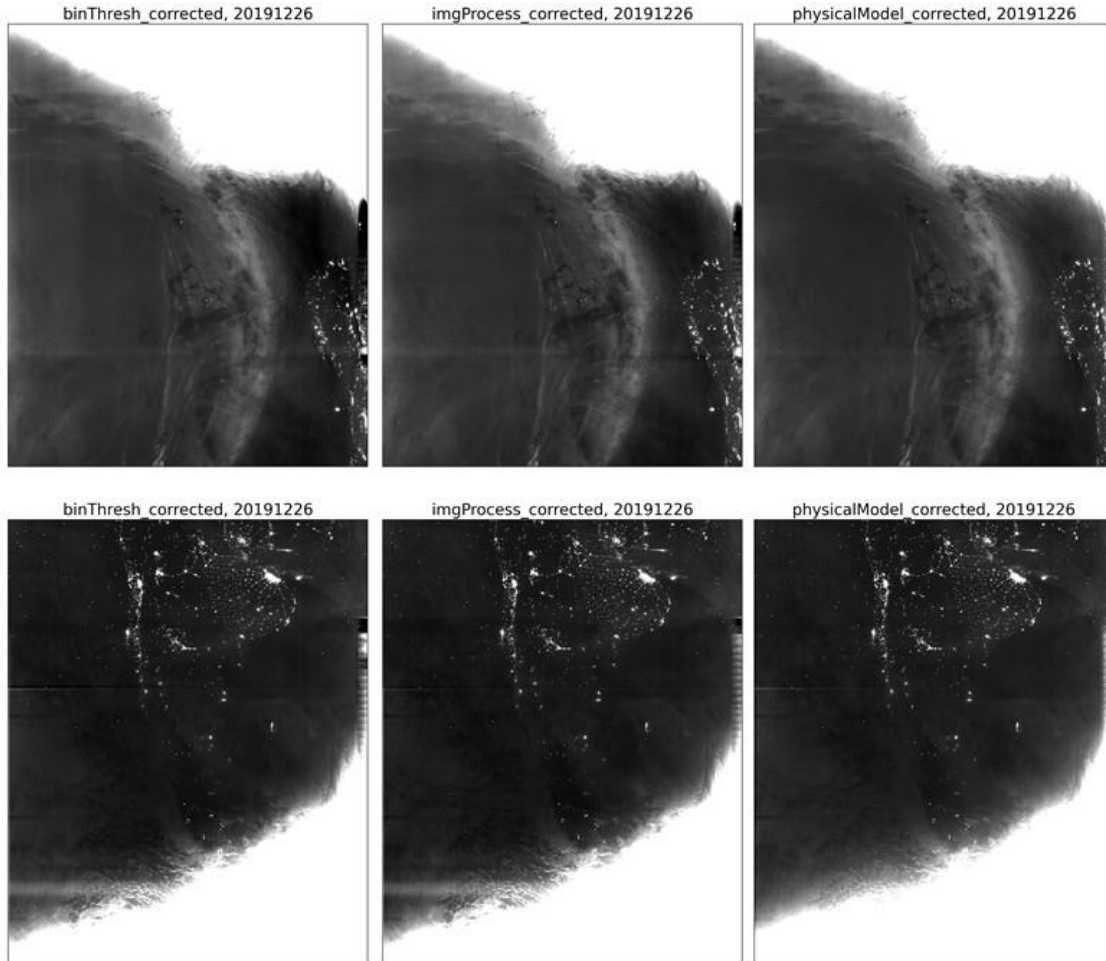


Figure 3. Sample results of the DNB stray light corrections for the raw N20 images shown in Figure 2, using the bin-and-threshold method (left), the image-processing method (middle), and the physical-model method (right). The upper/lower panel is from the northern/southern hemisphere. Notice that the first two methods cannot correct the bright stripes around SZA 100°.

3.2. Image processing method

Modified from the binning and threshold method to take advantage of existing image processing techniques, the complex steps of binning, threshold, interpolation, and smoothing are replaced by a moving median. Similar to the previous method, after the stray light impact is subtracted from the measurements, a fixed nightglow is added, and the beginning of stray light is assigned empirically.

The corrected images are shown in the middle column in Figure 3 for comparisons. The image processing method is more straightforward, and the moving average can retain more details of an image than binning, although binning may reduce the amount of computations. The quality of the results depends on how the calculations are tuned.

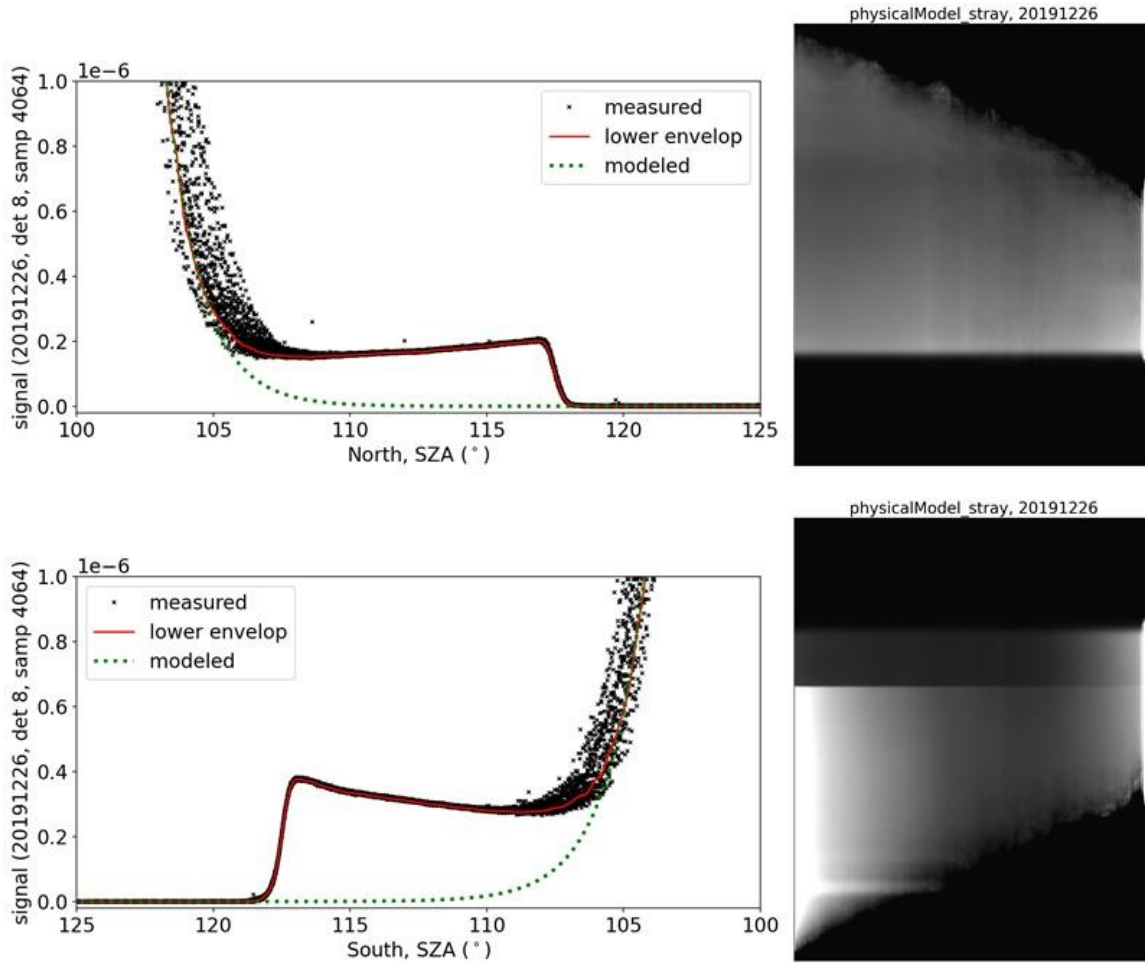


Figure 4. Left column: examples of signal (Wm⁻²sr⁻¹) versus SZA data from multiple orbits, for detector 8, sample 4064 (i.e., the right edge of the image). Right column: derived image of DNB stray light using the physical model method.

3.3. Physical model method

Intuitively, the measured signal should decrease asymptotically towards the nighttime in absence of stray light. In other words, if the drop off in sun light from day to night is modeled, then the stray light is the deviation of the measured from the modeled. The steps in the new method are:

- Select multiple orbits of data for better statistics; similar to the previous methods, except in a wider angle range (e.g., from 85° instead of 95°) to capture a big picture by utilizing information not only in the stray light impacted region, but also in the regions before and after the impact.
- For each sample, capture the smooth trend of the measurements using its lower envelope to avoid the observed surface features as much as possible.
- Fit the parts of envelope that are not impacted by the stray light with an exponential function.
- $corrected = measured - (envelope - fitted)$.

The fitted asymptotic exponential function is considered as the first order approximation to the natural drop off in sun light from day to night:

$$L - L_0 = a e^{-b(\theta - \theta_0)} \quad (1)$$

where θ is the SZA (e.g., $\theta_0 = 90^\circ$), and L is the measured irradiance (L_0 is for dark); a and b are the two fitting parameters. The algorithm shifts the measured values downward to align with the model, so the stray light is removed. In contrast to the previous methods, there is neither an explicit assignment of where the stray light begins, nor any assumption on nightglow. Notice that the artifacts at the end of scan are reduced by processing each sample individually, as seen in the right column in Figure 3, although the signal to noise ratio is dramatically reduced due to the large unwanted stray light.

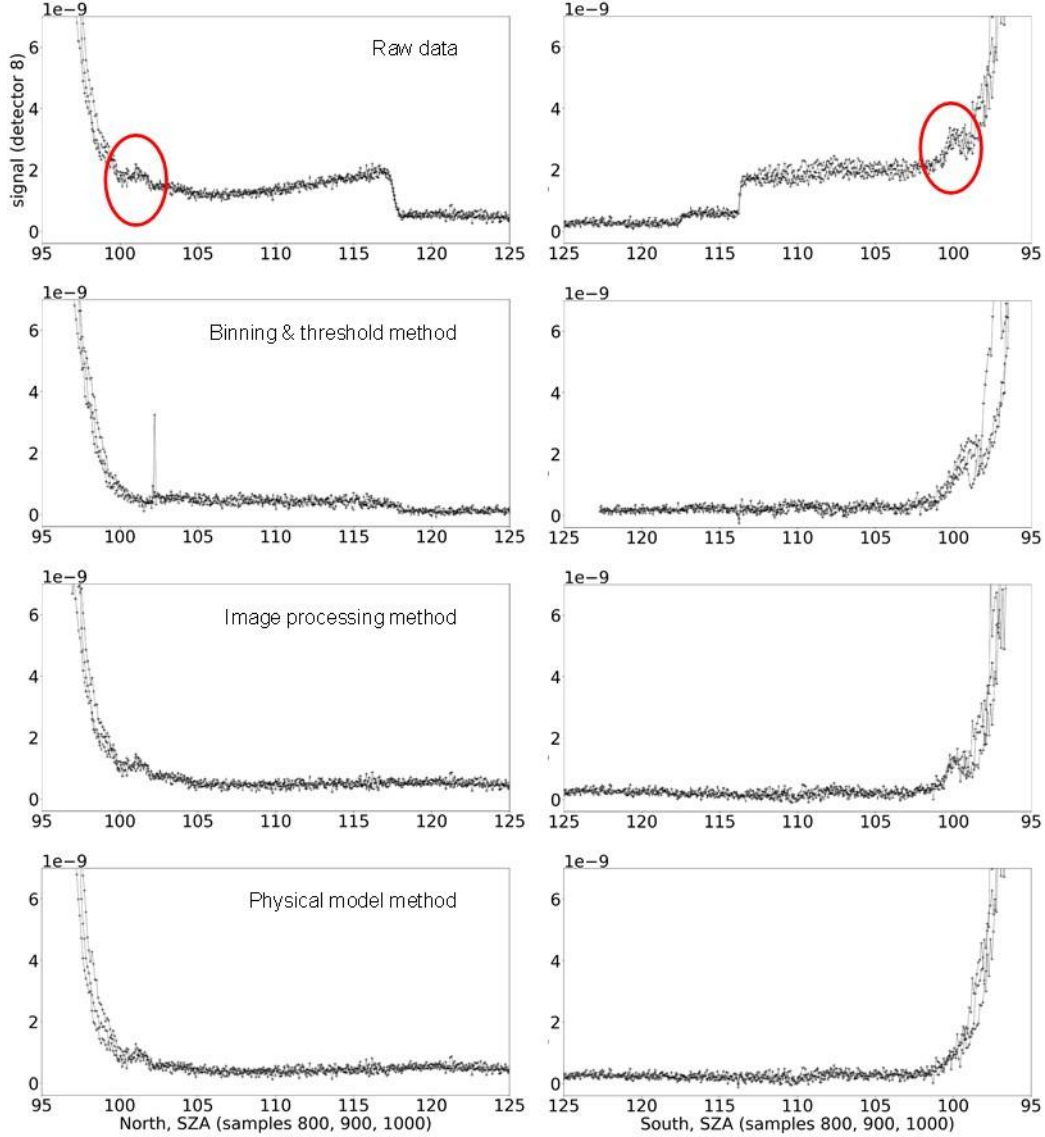


Figure 5. The bright stripe around SZA 100° before and after corrections. Left/right column: northern/southern hemisphere. Top panel: raw data, with the bright stripe part circled. Second panel from top: binning and threshold method, the spike seems to be an artifact. Third panel from top: image processing method. Bottom panel from top: physical model method. Signals along the track direction of three samples are plotted. The binning and threshold method is based on data between 95° and 125° in selected granules, while the others are from all scans between 85° and 125° , regardless of granule.

4. DISCUSSIONS

Following the steps of the physical model method, the algorithm is demonstrated in Figure 4. An example for one detector using data from all orbits in one day is shown for discussions. The sample at the end of scan is plotted, because the observed stray light impact is most severe.

Step 1: The scattered black dots in the plot mark the measured signals, which reveal the following:

- The impact of stray light remains consistent across orbits; therefore, a data composite from different orbits can be used in data processing for better statistics.
- In the northern hemisphere (upper panel in Figure 4), as the satellite travels towards the shadow of the Earth, the stray light increases gradually until reaches a peak before the penumbra. This provides useful information on the range and the onset of stray light. It is similar in the southern hemisphere (lower panel in Figure 4), although the pattern may be more complex due to that the solar diffuser is also illuminated by the sun.
- Only the low signal range in the DNB high gain (HG) measurements is impacted by this type of the DNB stray light; therefore, a correction can be applied directly to the measured digital number (DN). Potentially, this will eliminate the extra steps of calibrating the raw measurements first, then deriving a LUT for correction, and then applying the LUT to redo the calibration.

Step 2: The measurements are divided into three parts according to the degree of stray light impact:

- When the SZA is large enough (e.g., $> 118.5^\circ$), the satellite will be fully inside the shadow of the Earth, thus there is no stray light impact.
- The stray light impact is evident in the middle.
- The beginning of the stray light is unclear; nevertheless, it is reasonable to assume that the fraction of stray light diminishes towards the daytime, and the stray light impact should be negligible when the signal were significantly larger than the peak of the stray light (e.g., at least twice above the peak).

Step 3: Determine the trend of measurements across the SZA. In theory, the lower envelope of the selected data is unique, and the effect of the stray light appears to be an elevated lower envelope in the impacted region. By using the lower envelope, shown as the red curve in Figure 4, there is no need to assign any empirical threshold to these measurements.

Step 4: Fit the parts of the lower envelope that are not impacted by the stray light with the physical model described in Equation (1). The fitted parts consist of the dark part and the part with sufficiently large signals. The fitting result, which models the drop off in signal if there were no stray light, is shown as the green dashed curve in Figure 4. There is no need to explicitly hard code the beginning of the stray light because it begins whenever the measurement deviates from the fit. In addition, there is no need to assume a fixed nightglow across the SZA.

Step 5: The difference between the lower envelope and the fit is the impact of stray light for the sample. Combining the results of all samples from all detectors, the determined images of stray light are shown in the right column of Figure 4. For each hemisphere, subtracting the stray light image from the raw image shown in Figure 2 yields the corrected image shown in the right column in Figure 3.

In practice, an operational algorithm also includes some data conditioning steps. For example, the smoothness of the derived lower envelope is subjective and tunable, which may lead to the ring effect across a steep change of signal, resulting in an over correction followed by an under correction, especially at the start of illumination of the solar diffuser in samples close to the beginning of scans.

In addition, the drop off in sun light does not depend on detectors or samples, implying that the fitting parameter b in Equation (1) should remain a constant; however, there are many other influencing factors, such as that the samples away from nadir aim at the surface through slanted paths, adding atmospheric effects and so on; therefore, a cross-sample smoothing helps to reduce the inconsistency across samples. Similarly, the modeling results are sensitive to the dark signal,

i.e., the L_0 term in Equation (1), which may be affected by the observed surface light or the aurora at high altitude, and a cross-sample smoothing may reduce the unwanted influences.

After all, the influences of signals from the surface and the noises in measurements are unavoidable, and how to partition the signal to separate the stray light is subjective. Nevertheless, based on the observed change of signal in the polar regions, the new method is straightforward to follow, and it generates better results than the previous empirical methods. Figure 5 shows an example that the bright stripes around SZA 100° are handled poorly by empirically assigning the beginning of stray light, but there is no problem using the physical model method.

5. CONCLUSIONS

The DNB stray light correction is an image processing problem with straightforward solutions. The new method applies a physical model that fits the natural drop off in sun light from day to night, and captures the stray light in each sample as the difference between the smooth trend of measurements and the model. The new method can be applied to correct the DNB stray light in the raw data directly. It also provides more accurate corrections and helps to study different aspects of the DNB stray light, such as its temporal variations, and so on.

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