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NASA's Black Marble nighttime lights product suite

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ABSTRACT

NASA's Black Marble nighttime lights product suite (VNP46) is available at 500 m resolution since January 2012 with data from the Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band (DNB) onboard the Suomi National Polar-orbiting Platform (SNPP). The retrieval algorithm, developed and implemented for routine global processing at NASA's Land Science Investigator-led Processing System (SIPS), utilizes all high-quality, cloud-free, atmospheric-, terrain-, vegetation-, snow-, lunar-, and stray light-corrected radiances to estimate daily nighttime lights (NTL) and other intrinsic surface optical properties. Key algorithm enhancements include: (1) lunar irradiance modeling to resolve non-linear changes in phase and libration; (2) vector radiative transfer and lunar bidirectional surface anisotropic reflectance modeling to correct for atmospheric and BRDF effects; (3) geometric-optical and canopy radiative transfer modeling to account for seasonal variations in NTL; and (4) temporal gap-filling to reduce persistent data gaps. Extensive benchmark tests at representative spatial and temporal scales were conducted on the VNP46 time series record to characterize the uncertainties stemming from upstream data sources. Initial validation results are presented together with example case studies illustrating the scientific utility of the products. This includes an evaluation of temporal patterns of NTL dynamics associated with urbanization, socioeconomic variability, cultural characteristics, and displaced populations affected by conflict. Current and planned activities under the Group on Earth Observations (GEO) Human Planet Initiative

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are aimed at evaluating the products at different geographic locations and time periods representing the full range of retrieval conditions.

1. Introduction

The Day/Night Band (DNB) sensors of the Visible Infrared Imaging Radiometer Suite (VIIRS), on board the Suomi-National Polar-orbiting Partnership (S-NPP) and Joint Polar Satellite System (JPSS) satellite platforms, provide global daily measurements of nocturnal visible and near-infrared (NIR) light that are suitable for earth system science and applications studies. Since the launch of the S-NPP satellite in 2011, multiple studies have used the VIIRS DNB as primary data source covering a wide range of topics. These include: (1) feature extraction techniques, based on manual or semi-automated interpretation of the underlying VIIRS DNB radiances, to detect severe weather impacts to urban infrastructure (Cao et al., 2013; Cole et al., 2017; Mann et al., 2016; Molthan and Jedlovec, 2013); (2) detection of sub-pixel scale features, *e.g.*, fires (Polivka et al., 2016), shipping vessels (Asanuma et al., 2016; Elvidge et al., 2015; Straka et al., 2015), lightning flashes (Bankert et al., 2011), surface oil slicks (Hu et al., 2015), and gas flares (Elvidge et al., 2015; Liu et al., 2017, 2017); and (3) techniques for monitoring nighttime atmospheric optical properties, including clouds (Minnis et al., 2016; Walther et al., 2013), aerosols (Johnson et al., 2013; McHardy et al., 2015), particulate matter (Wang et al., 2016), and gravity waves in the upper atmosphere *via* nightglow (Miller et al., 2015).

As with early research that utilized the Defense Meteorological Satellite Program's Operational Line Scanner (DMSP/OLS) (Huang et al., 2014), recent studies using the VIIRS DNB have employed statistical analyses and correlation discovery methods to confirm established empirical relationships with a wide range of human-linked patterns and processes. These include socioeconomic variables (Chen and Nordhaus, 2015; Chen et al., 2015; Levin and Zhang, 2017; Li et al., 2013; Ma et al., 2014; Shi et al., 2014; Yu et al., 2015), as well as changes driven by urban built-up expansion (Guo et al., 2015; Sharma et al., 2016; Shi et al., 2014), energy use (Coscieme et al., 2014; Román and Stokes, 2015), and carbon emissions (Oda et al., 2017; Ou et al., 2015).

In order to make timely and quantitative use of nighttime lights (NTL), one must first quantify the subset of variations that are correlated to human-linked patterns and processes from those that are not. This requirement is especially true for products derived from the VIIRS DNB, given its ultra-sensitivity in low-lit conditions, and the resulting influence of extraneous light emission sources on the NTL time series record. Such artifacts can lead to discrepancies, *e.g.*, when using moon-free NTL composites as proxies to regional-scale socioeconomic features (Bickenbach et al., 2016; Chen and Nordhaus, 2015). To resolve retrieval uncertainties and measurement errors, the quality assurance of NTL products also needs to be emphasized, *e.g.*, by encouraging usage of quality flags that indicate the reliability of individual pixel values, or if retrievals are possibly affected by extraneous artifacts. More broadly, a meta-analysis of 132 research articles revealed the need to better trace the quality and provenance of NTL products as one of the most pressing areas of focus for future studies (Huang et al., 2014).

There is also a need to characterize uncertainties stemming from angular, diurnal, and seasonal variations in atmospheric and surface optical properties. This is crucial since, as we will present in this paper, NTL cannot be constrained directly from at-sensor top-of-atmosphere (TOA) radiances in part because of: (1) environmental factors, such as moon light, aerosols, and surface albedo whose reflectance contributes to the observed signal, and (2) errors stemming from seasonal variations and associated surface properties, which can significantly affect estimates of long-term trends. While it is generally neither desirable nor practical to delay the applied use of NTL products until they are proven to be error-free, or until known sources of error have been removed by product reprocessing, it is important to note that space agencies, coordinated by the Committee of Earth Observation Satellites (CEOS), place strong emphasis on product accuracy and performance. This information is needed by decision makers so they can trust the accuracy of the derived products, and by the science community, both to identify poorly performing products and opportunities for improvements, and to draw meaningful inferences from the long-term product records as they relate to trends in human settlements and urbanization.

There is increasing agreement in the growing body of literature concerning factors that govern the utilization of the VIIRS DNB for long-term analyses and applications. Recent studies have introduced a number of quantitative remote sensing techniques, including: (1) terrain-correction and trending of the VIIRS DNB geolocation (Wolfe et al., 2013); (2) establishing the calibration performance of the VIIRS DNB High Gain Stage (HGS), both in absolute terms and relative to future VIIRS flight units (Lee et al., 2015; Liao et al., 2013; Xiong et al., 2014; Zhang et al., 2016); (3) determining the effective spatial resolution and the impacts of spatial sampling on the VIIRS instrument and higher-level (Level 3) gridded products (Campagnolo et al., 2016; Pahlevan et al., 2017); (4) predicting the DNB's geometric characteristics (*i.e.*, time-varying Sun/Earth/Moon geometry, moon-illuminated fraction, phase, and albedo) (Miller et al., 2012a, 2012b); (5) estimating the highly variable TOA lunar spectral irradiance (Miller and Turner, 2009); (6) correcting for surface Bidirectional Reflectance Distribution Function (BRDF) effects caused by varying illumination conditions – namely moonlight and reflected airglow from the Earth's upper atmosphere (Cao et al., 2013; Cao and Bai, 2014; Román and Stokes, 2015; Zeng et al., 2018); and (7) assessing seasonal biases caused by sensor-specific stray light (Lee et al., 2015; Liao et al., 2013; Mills and Miller, 2016), as well as other biogeophysical processes, such as vegetation (Levin, 2017; Levin and Zhang, 2017) and snow cover (Bennett and Smith, 2017).

Despite this progress, substantial gaps remain in the quantification and documentation of uncertainty for NTL data and products. Such information is required by space agencies, such as the CEOS Working Group on Calibration and Validation (CEOS-WGCV). This development is particularly relevant if these products are to be used to establish global metrics and indicators for achieving a myriad of goals identified under the United Nations Agenda 2030 for Sustainable Development (Griggs et al., 2015). These sustainable development goals (SDGs) include: (1) addressing the needs of conflict-affected populations (SDG-1); (2) quantifying the effectiveness of local electrification projects in the developing world (SDG-7); (3) building resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation (SDG-9); and (4) ensuring that cities and human settlements are inclusive, safe, resilient, and sustainable (SDG-11).

While the current Joint Polar Satellite System (JPSS) requirements establish performance metrics for the VIIRS DNB calibration and sensor characteristics, the current DNB-associated key performance requirements are tied strictly to nighttime imagery for short-term operational weather applications at high latitudes (Hillger et al., 2013). Whereas these formalized performance metrics correspond to the “Threshold” requirements of Table 1, the “Breakthrough” and “Goal” values point to 1–2 orders of magnitude improvement in sensitivity and spatial resolution. Here, “Threshold” is defined as the minimum requirement to be met to ensure that NTL time series data are useful, and is based on the current JPSS on-orbit performance requirements for the VIIRS DNB's High Gain Stage (HGS) calibration (Liao et al., 2013). The “Goal”