Detecting Light Outages After Severe Storms Using the S-NPP/VIIRS Day/Night Band Radiances

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***Abstract*—Power outages after a major storm affect the lives of millions of people and cause massive light outages. The launch of the Suomi National Polar-orbiting Partnership satellite with the Visible Infrared Imaging Radiometer Suite (VIIRS) significantly enhances our capability to monitor and detect light outages with the well-calibrated day/night band (DNB) and to use light loss signatures as indication of regional power outages. This study explores the use of the DNB in quantifying light outages due to the derecho storm in the Washington DC metropolitan area in June 2012 and Hurricane Sandy at the end of October 2012 on the East Coast of U.S. The results show that the DNB data are very useful in detecting power outages by quantifying light loss, but it also has some challenges due to clouds, lunar illumination, and straylight effect. Comparison of light outage and recovery trend determined from DNB data with power company survey shows reasonable agreement, demonstrating the usefulness of DNB in independently verifying and complementing the statistics from power companies.**

***Index Terms*—Day/night band (DNB), derecho, Hurricane Sandy, light/power outage detection, nighttime remote sensing, Suomi National Polar-orbiting Partnership (S-NPP) Visible Infrared Imaging Radiometer Suite (VIIRS).**

I. Introduction

THE day/night band (DNB) of the Visible Infrared Imaging Radiometer Suite (VIIRS) [1] onboard the Suomi National Polar-orbiting Partnership (S-NPP) satellite launched in October 2011 represents a major advancement in nighttime imaging capabilities because it surpassed its predecessor Operational Line Scanner (OLS) on the Defense Meteorological Satellite Program (DMSP) in radiometric accuracy, spatial resolution, and geometric quality [2]. Satellite sensors such as OLS on DMSP have been acquiring day/night images since the early 1970s for the detection of moon-lit cloud with other applications such as military surveillance, estimating power consumption, and providing weather and climate related data (e.g., in [3] and [4]). Elvidge *et al.* [5] developed schemes to produce stable lights (percent frequency of light detection) and coarse radiance resolution (64-level gray) global composites of nighttime light products from DMSP-OLS observations. The nighttime light database is available through the National Geophysical Data Center and has been widely used. However, it has a number of limitations such as lack of accurate calibration, coarse radiometric resolution, low spatial resolution, saturation, and, to some extent, geometric distortion, all of which have been overcome by the DNB on VIIRS.

The DNB is a *de facto* radiometer because it uses an onboard solar diffuser calibration system to generate the radiances for Earth observations, compared to the OLS which is an imager and has no onboard calibration for visible channels. The dynamic gain selection and fine radiometric quantization of DNB ensure fine radiometric resolution in its measurement. The advanced DNB capabilities ensure the accuracy of the observed radiances for its use in nighttime remote sensing imagery for various civilian applications including quantifying the massive light outages that occur due to regional power outages during natural disasters such as hurricanes.

Several previous studies of light outages using DMSP/OLS data are available (e.g., [3]). However, they are limited by the instrument capabilities [6], partly due to the lack of onboard calibration for visible channels preventing accurate quantitative radiance analysis. Also, the OLS often saturates in urban areas where bright lights are found [7]. This study explores the use of the DNB radiances observed during two major storm events to detect light outages and to demonstrate the capabilities of the DNB over the OLS. One is the derecho storm over Washington DC in June 2012, and the other is Hurricane Sandy in the East Coast in October 2012. DNB radiance data were collected before, during, and after the storm and then analyzed to quantitatively evaluate the radiance changes during the storm as an indication of regional power outages. The effect of lunar illumination is estimated using a lunar model [8] and then subtracted before the comparison. This letter first briefly introduces the methodology of the study, and then, the onboard calibration is discussed to illustrate the radiometric accuracy. The data sets are introduced, and the results of the analysis are presented. Limitations and challenges in our analysis are also discussed.

II. Methodology

A. DNB Onboard Calibration and Radiance Accuracy

The VIIRS/DNB utilizes a backside-illuminated charge coupled device (CCD) focal plane array for sensing of radiances spanning seven orders of magnitude in one panchromatic (0.5–0.9 μm) solar reflective band. The primary objective of the DNB is to provide imagery of clouds and other Earth features over illumination levels ranging from full sunlight to quarter moon. In order to cover this extremely broad measurement range, the DNB employs four imaging arrays that comprise

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three gain stages: the low-gain stage (LGS), the medium-gain stage (MGS), and the high-gain stage (HGS). A gain selection algorithm is implemented onboard, which determines which stage's output should be used for each pixel. More details about the algorithm can be found in [9]. The spatial resolution of the DNB is ~750 m across the entire swath. This is achieved by performing on-chip aggregation of the CCD detector elements that comprise pixels, which results in 32 aggregation zones through each half of the instrument swath on either side of nadir.

The final product generated from a DNB raw data record is the radiance sensor data record, and it requires accurate knowledge of the dark offsets and gain coefficients for each DNB stage. These are stored in lookup tables that are used during ground processing. The LGS gain values are determined by solar diffuser data (aka the onboard calibration). The MGS and HGS cannot be calibrated directly using solar diffuser data because these gain stages saturate at solar diffuser illumination levels. Since the three gain stages have sufficient overlaps, the MGS and HGS values are determined by multiplying the LGS gains by the MGS/LGS and HGS/LGS gain ratios, respectively. The overall accuracy of the calibrated DNB radiances is estimated to be comparable to that of the other reflective solar bands on VIIRS, which is on the order of 2%. However, achieving this accuracy requires rigorous calibration/validation which is currently ongoing.

B. Quantifying Night Light Radiances and Cloud Clearing

The nighttime scene is scanned sequentially such that each scene is imaged by all three gains on DNB. On a pixel-by-pixel basis, the most appropriate of the three stages is selected to be transmitted to Earth, ensuring that DNB will not be saturated by bright city lights. The signals of DNB are digitized using 14 bits for the HGS and 13 bits for the MGS and LGS. The fine quantization of HGS enhances the appearance of terrestrial light emissions, including faint city lights. By applying gain coefficients and offsets, raw data are converted into radiometric units, i.e., in watts per square centimeter per steradian.

To quantify the extent and evolution of regional power outage, the light loss is estimated by analyzing radiance changes at region of interest (ROI) as a time series. It is difficult to accurately quantify the radiance change if the region is covered by clouds. In this study, we only select events and sites with cloud-free DNB observations. Cloud detection and screening is performed using the VIIRS cloud mask (VCM) product. The VCM product for the period of interest is of beta data quality, although the data quality appears to be reasonable as stated in the beta release. For each DNB pixel, cloud mask data provide information such as the probability of cloud contamination, type of cloud, and information about cloud shadow. A strict criterion with highest level of confidence flag was used to identify and exclude the cloud-contaminated pixels. The performance of VCM was compared with the long wave thermal infrared images for consistency. It was found that, even though the VCM product that we used was of beta quality as of early May 2012, it was good enough for screening out the land pixels contaminated with cloud.

In selecting observations, attention needs to be paid to terminator straylight effect on the instrument due to solar illumination when the satellite passes through the day–night terminator. This effect is more significant for the northern hemisphere region during summer solstice. During the derecho storm over Washington DC in June 2012, straylight effect on radiance is estimated to be about $3.23 \pm 0.46\ 10^{-9}\ \mathrm{W/(cm^2 - sr)}$. For the Hurricane Sandy event, the straylight effect is of no concern since the solar zenith angles for the ROIs were $> 140^\circ$ at the S-NPP spacecraft. Straylight effect removal or correction for DNB is still ongoing. The data that we presented in this letter during the derecho storm contain straylight. The resulting uncertainty incurred for light outage estimation in the Washington DC region is discussed in Section III-C.

C. Lunar Radiance Removal

In the past, for OLS applications such as assembling stable lights and radiance-calibrated global composites of nighttime light products [5], periods with low-lunar-illumination conditions are often selected to eliminate the effect from moonlights. However, to monitor the light outage and recovery at ROI, it is important to include all useful observations, and some might be added with strong lunar illuminations. The resulting DNB nighttime imagery is a composition of light emission from human settlements and reflected moonlight from Earth's surface. The amount of moonlight illuminating Earth's surface depends on the lunar phase (ranging from a new to full moon) and lunar elevation in the sky. We use a top-of-atmosphere (TOA) spectral lunar irradiance model (MT2009) developed by Miller and Turner [8] to quantify the effects of lunar radiation on DNB observation. The model uses solar source observations and lunar spectral albedo data, and accounts for the time-varying Sun/Earth/Moon geometry and lunar phase. It produces 1-nm resolution irradiance spectra over the interval [0.3, 1.2 μm] for any given lunar phase. The model has been benchmarked against lunar observations from SeaWiFs and MODIS-Aqua satellites, and the ROLO [10] lunar irradiance model. In general, the uncertainty in lunar irradiance as modeled by MT2009 is expected to be ~7%–12% in the spectral band of DNB.

To compute the lunar radiance L_m as observed by the DNB sensor, we use

$$L_m = \frac{E_m}{\pi} \rho \cos(\theta_m) \tag{1}$$

where θ_m is the lunar zenith angle. E_m is the downwelling TOA sensor response function-weighted lunar irradiance derived from the MT2009 model, i.e., $E_m = (\int_{\lambda_1}^{\lambda_2} I_{MT}(\lambda) SRF(\lambda) d\lambda / \int_{\lambda_1}^{\lambda_2} SRF(\lambda) d\lambda)$, where $I_{MT}(\lambda)$ is the lunar irradiance spectra calculated from MT2009 model and $SRF(\lambda)$ is the spectral response function of the DNB sensor. In (1), ρ is the band-averaged TOA reflectance at the ROI and is estimated using the TOA reflectance data derived from the daytime observations of the ROI by visible (M4, M5, and M7) channels of VIIRS.

III. Event Analysis and Results

Two major light outage events are investigated in this letter. One is during the derecho storm that occurred in Mid-Atlantic and Midwestern U.S. at the end of June 2012, and the other

one is during Hurricane Sandy that occurred in Mid-Atlantic and Northeastern U.S. at the end of October 2012. During a major storm or hurricane, light outage may occur sporadically in different local areas. In our analysis, for each location, a ROI of fixed size is selected. DNB data are collected for these ROIs to include a few days of data before and after the event of interest. These data are first screened to ensure that clear sky DNB images are used. After performing cloud clearing and lunar radiance removal, the mean of the DNB radiances of all ROIs was computed. Time series of nighttime radiances is assembled to detect the light outage and recovery at these ROIs.

A. June 2012 Mid-Atlantic and Midwestern U.S. Derecho Event

The June 2012 Mid-Atlantic and Midwestern U.S. derecho was a powerful and long-lasting wind storm that blew from the Midwest U.S. to the Atlantic Ocean, travelling roughly 600 miles in about 10 h, and it was one of the most destructive and deadly fast-moving severe thunderstorm complexes in North American history. The June 2012 derecho struck the Mid-Atlantic area with wind gusts in excess of 110 km/h. The progressive derecho tracked across a large section of the Midwestern U.S. and across the central Appalachians into the Mid-Atlantic states on the afternoon and evening of June 29, 2012, and into the early morning of June 30, 2012. Damage was widespread and extensive along the entire path of the derecho. Extensive property damages were found for these areas, and power outages were extensive, with about 4.22 million customers losing power in the affected regions according to the Department of Energy (DOE) report on June 2012 derecho [11]. It led to the largest nonhurricane power outage in history for the region.

Fig. 1(a) shows VIIRS DNB nighttime images of U.S. East Coast on days from June 27 to July 05. The light loss in the Washington DC region (to the left of the red label "DC" on the image) during the event and its recovery can be identified by comparing images recorded before June 28, on June 30 and July 1 (during the light outage), and on July 5 (recovery). To quantify the extent and evolution of light outage in the Washington DC metropolitan area, three ROIs were selected for analysis: DC metro area (geographic latitude $= 38.899°$, longitude $= -77.036°$), Rockville ($39.083°, -77.149°$) in MD, and Dulles airport area ($38.994°, -77.450°$) in VA. The derived time series of radiance with lunar radiance correction at these ROIs are shown in Fig. 1(b). The lunar radiance contribution is also plotted at the bottom of Fig. 1(b). During the period of interest, the lunar phase changes from around waxing crescent on June 24 to full moon on July 3 and to waning gibbous on July 6. From June 24 to June 30, the moon is below the horizon, with no radiance contribution at the time of NPP's overpass. After June 30, the lunar radiance contribution to the total observed radiance by DNB at ROIs can be $\sim$10% or more, indicating the importance of lunar radiance removal in our analysis.

Significant radiance reduction at all ROIs on June 30 can be clearly identified from Fig. 1(b). To quantify the extent of light outage, we define light outage percentage as $LO_{\mathrm{DNB}}(\mathrm{ROI}) = (L_n - L_s/L_n)$, where L_n is the radiance observed by DNB at

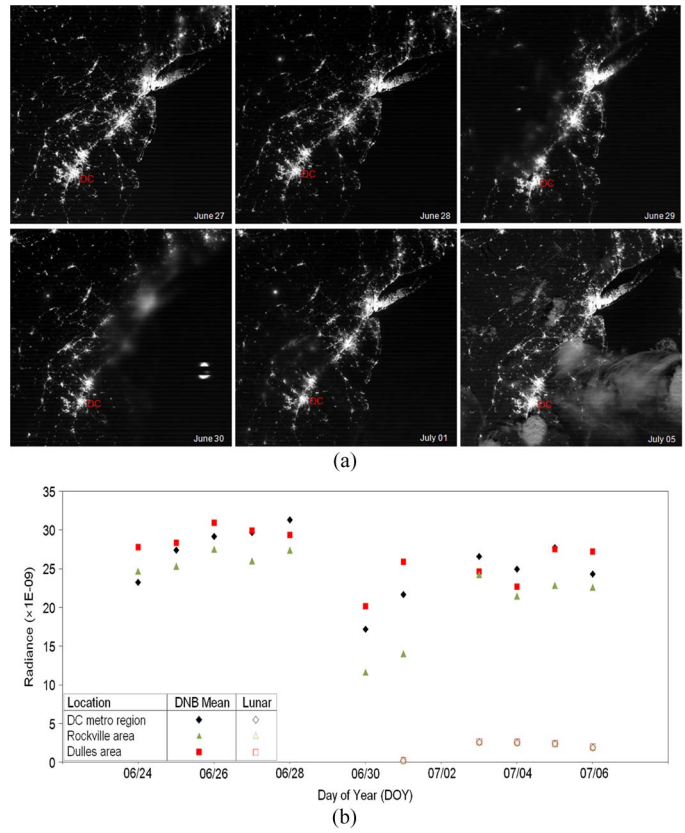

Fig. 1. (a) VIIRS DNB images showing nighttime Washington DC metropolitan region (marked with red "DC") from June 27 to July 05, 2012. (b) Time series of corrected mean DNB radiance and corresponding lunar radiance corrections (in watts per square centimeter per steradian) at selected ROIs (DC metro area size: 40 km × 40 km; Rockville and Dulles area size: 10 km × 10 km) during the derecho.

ROI during normal days and L_s is the DNB radiance after the storm day. In this event, L_n is calculated as the five-day average of daily mean radiance before June 28. The corresponding estimated light outage percentage is $LO_{\mathrm{DNB}}(\text{DC metro area}) = 38.9 \pm 7.4\%$, $LO_{\mathrm{DNB}}(\text{Rockville}) = 55.4 \pm 2.2\%$, and $LO_{\mathrm{DNB}}(\text{Dulles area}) = 31.22 \pm 1.3\%$, respectively. For comparison, it was reported that there were 68 thousand ($\sim$26.3%) customers losing power in the Washington DC metro area [11], 238 thousand ($\sim$67.5%) customers lost power in Montgomery county of MD where Rockville is located, and $\sim$31.5% customers lost power in VA where Dulles area is located [11]. The overall agreement between LO_{DNB} and power company survey is reasonable, and both show that Rockville area has the highest power outage percentage. In particular, LO_{DNB} is in good agreement with power company survey for Dulles area and differs by $\sim$12% for DC and Rockville area. The difference might be mainly due to the fact that power company survey on customers with power loss may not be linearly correlated with the regional nighttime light intensity. For example, the DC metro area may have shut down the power during nights immediately after the storm even though the power is back, which explains the resulting higher LO_{DNB} than that inferred from the power company survey. Nevertheless, the reasonable agreement validates the usage of DNB observation as complementing measures to quantify and monitor power outages after severe storms.

Fig. 1(b) also shows that, on July 4, the observed DNB mean radiance recovered back to 88.5 ± 10.9%, 77.4 ± 4.3%, and 81.9 ± 4.8% of prestorm level for the DC metro, Rockville, and Dulles areas, respectively. According to the DOE report on June 2012 derecho [11], the power outage recovery took about five days around Washington DC metropolitan area, and on July 4, customers having electric power recovered in DC metro area and MD and VA states are ∼93%, ∼83%, and ∼84%, respectively, of all customers. DNB observations and *in situ* power company reports agree reasonably well on the outage recovery trend.

B. Hurricane Sandy

Hurricane Sandy was a Category 2 storm at its peak intensity and devastated portions of the Caribbean and the Mid-Atlantic and Northeastern U.S. during late October 2012. While it was a Category 1 storm off the coast of the Northeastern U.S., the storm carried winds spanning 1800 km as measured by diameter, and it became the largest Atlantic hurricane on record. On October 29, Sandy moved north-northwest and then ashore near Atlantic City, NJ, as a post-tropical cyclone with hurricane force winds. Hurricane Sandy caused particularly severe damage in NJ and NY. Its storm surge hits New York City on October 29, flooding streets, tunnels, and subway lines, and cutting power in and around the city. Preliminary estimates of losses due to damage and business interruption are over $65.6 billion, which would make it the second costliest Atlantic hurricane, only behind Hurricane Katrina. At least 253 people were killed along the path of the storm in seven countries.

Fig. 2(a) shows series of DNB images of the U.S. East Coast region during and after the Hurricane. These images show the development and extent of the storm cloud during the hurricane. Because of the masking by the cloud, most of the DNB data just before and after Hurricane Sandy cannot be used for radiance analysis. Only three cases (October 22, November 1, and November 16) with clear sky above New York City (NYC) and NJ (NJ) are selected for our light outage assessment. Two locations each in NYC and NJ are chosen in our analysis. The information on geographic locations and sizes of these selected ROIs are listed in Table I. During those three days of interest, there is no lunar illumination when the NPP satellite flew above those ROIs on October 22 and November 17. However, on November 1, it is nearly full moon, and the DNB radiance observed on November 1 needs to be corrected with lunar radiance removal. Fig. 2(b) shows the bar plot of corrected DNB radiances at four ROIs over three days. The light outage on November 1 can be clearly seen at all four sites. Comparing the observation at Middletown area and Manhattan area, the radiance values vary by two orders of magnitude, with Manhattan being much brighter. However, the light outage can be clearly identified at both sites, demonstrating the advantages of large dynamic range and fine quantization of the DNB.

Table I also lists the estimated light outage percentage LO_{DNB} which is calculated by taking the percent difference between data on November 1 and on October 22, 2012. The estimated LO_{DNB}'s at both Queens and Manhattan area in NYC are around 50% on November 1. According to DOE Hurricane Sandy Situation Report #8 [12], as of early November 1, over

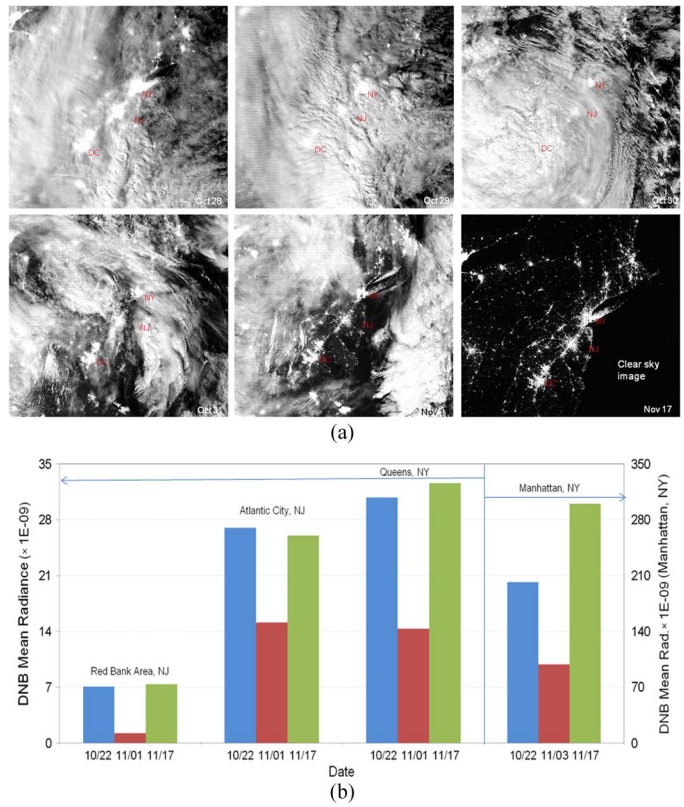

Fig. 2. (a) VIIRS DNB images of the East Coast region from October 28 to November 1 and November 17 with the locations of the Washington DC region, NJ state, and New York City marked as red labels DC, NJ, and NY, respectively. (b) Mean DNB radiance (in watts per square centimeter per steradian) over three days observed at different locations in NYC and NJ for assessing the light outage during Hurricane Sandy.

4.65 million customers remained without power in 15 states and the District of Columbia. The states with the most customers without power are NJ (1.813 million) and NY (1.583 million). Table I lists the estimated power outage percentage from power company surveys for comparison. LO_{DNB} and power company survey data agree reasonably well, indicating the usefulness of using DNB radiance observation to perform independent quantitative analysis on regional power outage.

C. Data Limitations and Challenges

To quantify the extent of light outage and the trend of recovery with DNB observations, multiday DNB data at ROIs need to be analyzed. The major limitation on using DNB is cloud masking since it is not possible to accurately quantify the light outage if the region is covered by clouds. Other uncertainties associated with using DNB radiance data can be due to variation in nighttime atmospheric conditions such as aerosols and water vapor content, uncertainty in lunar radiance estimation, variation in radiance because of slightly different observational time and geometry each day when the satellite overpasses the ROI, and day-to-day variations in human light usage habits. For a rough estimation of the overall contribution of these uncertainty factors, we analyze the five-day fluctuation of DNB radiance before June derecho. The day-to-day fluctuation at Rockville and Dulles areas is estimated to be ∼4%–5% and 11% for DC metro area before derecho. The relatively large uncertainty in DC radiance might be due to weekly variations

TABLE I
GEOGRAPHICAL AND LIGHT OUTAGE INFORMATION AT FOUR ROIS DURING HURRICANE SANDY

Location	ROI (Latitude, Longitude)	ROI area size	LO_{DNB}	Reported Power Outage
Middletown, NJ	(40.330°,-74.130°)	30 km × 30 km	82.3%	~77.6%[a]
Atlantic City, NJ	(39.377°,-74.428°)	15 km × 15 km	44.0%	~ 45%[b]
Queens, NY	(40.676°,-73.702°)	10 km × 10 km	53.4%	N/A
Manhattan, NY	(40.756°,-73.985°)	4 km × 4 km	51.1%	N/A

[a]Estimated from Jersey Central Power & Light report on power outage in Middletown, NJ area.
[b]Estimated from power outage report for New Jersey state by DOE Hurricane Sandy Situation Report [12].

in human light usage habits. The terminator straylight effect is also of concern for the Washington DC region during derecho. It is about 10%–15% of the DNB radiance data for ROIs and ∼1.5%–2.5% of day-to-day radiance variation. The resulting uncertainty in the light outage percentage that we determined can be up to ∼10%. It can be seen that the uncertainty percentage is much less than the typical light outage percentage (from ∼30% to ∼80%) that can be identified from DNB data during storms, which justifies using DNB radiance data to quantify light outage.

IV. CONCLUSION

In this letter, we have developed a scheme for analyzing DNB radiance data to derive multiday radiance changes at ROIs and to quantify the extent of light outage and its recovery during and after storms, as indication of regional power outages. Two power outage events are analyzed with multiday DNB data at various ROIs: 1) derecho storm in Washington DC metropolitan region and 2) Hurricane Sandy. Comparison between light outage and its recovery trend derived from DNB data and the power outage data from a local power company survey during the two events shows reasonable agreement. The study demonstrates that the DNB can be used to independently verify the light outage and the recovery trend, complementing the statistics from power companies. This facilitates future planning and policy making. It is expected that further refinements in the methodology will significantly reduce the uncertainties.

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