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Land and cryosphere products from Suomi NPP VIIRS: Overview and status

Christopher O. Justice,[1,2] Miguel O. Román,[2,3] Ivan Csiszar,[4] Eric F. Vermote,[3] Robert E. Wolfe,[3] Simon J. Hook,[5] Mark Friedl,[6] Zhuosen Wang,[7,8] Crystal B. Schaaf,[7,8] Tomoaki Miura,[9] Mark Tschudi,[10] George Riggs,[11,12] Dorothy K. Hall,[12] Alexei I. Lyapustin,[13] Sadashiva Devadiga,[3,14] Carol Davidson,[3,14] and Edward J. Masuoka[3]

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[1] The Visible Infrared Imaging Radiometer Suite (VIIRS) instrument was launched in October 2011 as part of the Suomi National Polar-Orbiting Partnership (S-NPP). The VIIRS instrument was designed to improve upon the capabilities of the operational Advanced Very High Resolution Radiometer and provide observation continuity with NASA's Earth Observing System's Moderate Resolution Imaging Spectroradiometer (MODIS). Since the VIIRS first-light images were received in November 2011, NASA- and NOAA-funded scientists have been working to evaluate the instrument performance and generate land and cryosphere products to meet the needs of the NOAA operational users and the NASA science community. NOAA's focus has been on refining a suite of operational products known as Environmental Data Records (EDRs), which were developed according to project specifications under the National Polar-Orbiting Environmental Satellite System. The NASA S-NPP Science Team has focused on evaluating the EDRs for science use, developing and testing additional products to meet science data needs, and providing MODIS data product continuity. This paper presents to-date findings of the NASA Science Team's evaluation of the VIIRS land and cryosphere EDRs, specifically Surface Reflectance, Land Surface Temperature, Surface Albedo, Vegetation Indices, Surface Type, Active Fires, Snow Cover, Ice Surface Temperature, and Sea Ice Characterization. The study concludes that, for MODIS data product continuity and earth system science, an enhanced suite of land and cryosphere products and associated data system capabilities are needed beyond the EDRs currently available from the VIIRS.

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1. The S-NPP Mission and the VIIRS Instrument for Land Remote Sensing

[2] The Visible Infrared Imaging Radiometer Suite (VIIRS) instrument was launched in October 2011 as part of the NPOESS (National Polar-orbiting Environmental Satellite System) Preparatory Project (NPP), subsequently renamed the Suomi National Polar-orbiting Partnership (S-NPP) in January 2012. S-NPP was planned as a bridging mission intended to provide observation continuity with NASA's Earth Observing System (EOS) and the operational VIIRS

[1]Department of Geographical Sciences, University of Maryland, College Park, Maryland, USA.
[2]These authors contributed equally to this work.
[3]Terrestrial Information Systems Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[4]NOAA Center for Satellite Applications and Research, College Park, Maryland, USA.
[5]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

Corresponding author: C. O. Justice, Department of Geographical Sciences, University of Maryland, College Park, MD 20782, USA. (justice@hermes.geog.umd.edu)
M. O. Román, Terrestrial Information Systems Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. (miguel.o.roman@nasa.gov)

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[6]Department of Earth and Environment, Boston University, Boston, Massachusetts, USA.
[7]Department of Environmental, Earth and Ocean Sciences, University of Massachusetts, Boston, Massachusetts, USA.
[8]Center for Remote Sensing Department of Earth and Environment, Boston University, Boston, Massachusetts, USA.
[9]Department of Natural Resources and Environmental Management, University of Hawaii at Manoa, Honolulu, Hawaii, USA.
[10]Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado, USA.
[11]Science Systems & Applications, Inc., NASA Goddard Space Flight Center, Lanham, Maryland, USA.
[12]Cryospheric Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[13]Climate and Radiation Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[14]Sigma Space Corporation, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

instruments to be flown on the first Joint Polar-Orbiting Satellite System (JPSS-1) in 2017. The VIIRS instrument is intended to improve upon the operational Advanced Very High Resolution Radiometer (AVHRR) and provide continuity with the EOS Moderate Resolution Imaging Spectroradiometer (MODIS). Since the VIIRS first-light images were received in November 2011, NASA and NOAA scientists have been working to evaluate the instrument on-orbit performance and generate land and cryosphere products to meet the needs of the NOAA operational user community and NASA science. NOAA's focus has been on refining and validating a suite of operational products known as Environmental Data Records (EDRs), developed by Northrop Grumman and Raytheon according to project specifications. The NASA NPP Science Team has focused on evaluating the EDRs for science use and developing and testing additional or improved VIIRS products to meet outstanding science data needs and provide MODIS data continuity. The S-NPP has had a dynamic and complex history with roles and responsibilities changing between federal agencies and private contractors. With the emphasis of the program on meeting operational user needs, the bulk of the resources and effort to generate land and cryosphere products from S-NPP have been focused on the contractor-developed EDRs [*Justice et al*., 2011].

[3] The primary target audience for the NOAA EDRs is the traditional NOAA operational users, such as the National Weather Service and the Air Force Weather Agency. Data from the VIIRS are being used to generate land and cryosphere EDRs (hereby termed EDRs or "VIIRS products") for use in a number of operational applications, ranging from real-time weather operations to forecast model input and environmental monitoring applications. The VIIRS products are currently being processed in NOAA's near-real-time Interface Data Processing Segment (IDPS), which receives raw instrument data and telemetry from the ground stations supporting the S-NPP mission. The IDPS converts the Raw Data Records, generated by sensors on S-NPP, into calibrated geolocated measurements called Sensor Data Records (SDRs) and then into geophysical parameters or Environmental Data Records (EDRs). In addition to SDRs and EDRs, the IDPS produces Intermediate Products (IPs) and Application-Related Products (ARPs). Application-Related Products (ARPs) are a subcategory of EDRs and are subject to the same latency requirements. Intermediate Products (IPs) are produced as an interim step in the EDR processing and (for the S-NPP mission) are stored for long-term archiving. These products are archived and distributed by NOAA's Comprehensive Large Array-Data Stewardship System (CLASS).

[4] The standard VIIRS IDPS-generated products (EDRs, ARPs, and IPs) are only produced in swath-based Level 2 format. Thus, only information from a single orbit is used, and available "per-pixel" information from overlapping swaths is not used. In contrast, the MODIS land products are stored using the Level 2 Grid (L2G) approach, which provides users with the original observations and their subpixel geolocation information. The rationale behind the L2G approach was to select the observations least affected by off-nadir viewing observations while maximizing coverage within a cell of the gridded projection. This improves the efficiency of processing and reprocessing of L2G and higher-level gridded products.

[5] Early versions of the VIIRS Land EDRs have been available since "first light" to allow data users to gain familiarity with data formats and parameters. In the first 12 months of on-orbit operations, three major baseline releases (termed IDPS Mx5.3, Mx6.2, and Mx6.3) were installed to deliver product fixes and look-up table updates. However, the products have undergone limited "Beta" testing and in some cases contain significant errors. Further detailed evaluation is needed to determine their suitability for quantitative scientific studies [*Román et al*., 2012]. As the VIIRS on-orbit performance has stabilized and ground-truth campaigns and data examination exercises are generating results, the NOAA JPSS Land Product Algorithm Development and Cal/Val team and the NASA S-NPP VIIRS Land discipline team are working toward bringing EDRs to "provisional" status by the end of 2013.

2. VIIRS Land EDR Evaluation and Status

[6] As with the MODIS products, the VIIRS Land EDRs can be grouped into four general product categories: (1) radiation budget variables, i.e., the Surface Reflectance (corrected for effects of the atmosphere), Land Surface Temperature (LST), and Surface Albedo; (2) ecosystem variables, i.e., Vegetation Indices (VI); (3) land-cover characteristics, i.e., Surface Type (ST) and the location of Active Fires; and (4) cryospheric products, i.e., Snow Cover, Ice Surface Temperature (IST) and Sea Ice Characterization (SIC). A number of these products, including the Surface Reflectance, have their heritage in the MODIS product algorithms, and in some cases early versions of the MODIS code were used by the contractor in the VIIRS product algorithm development. The Land Group of NASA's S-NPP Science Team is evaluating the suitability of the VIIRS Land algorithms in terms of their ability to fulfill NASA's science needs. It should be noted that data from the VIIRS Land Product Evaluation and Analysis Tool Element's (Land PEATE) archive sets (AS) 3001 (products generated by the Land PEATE using the IDPS software) and AS 3002 (products generated by the Land PEATE using NASA Land Science Team adjusted versions of the IDPS software) were used in the evaluation of the VIIRS EDRs (cf. section 3 for a description of the Land PEATE). The improvements performed as part of AS 3002 included algorithm improvements, bug fixes, and look-up table updates. In most cases, these adjustments were implemented months before they transitioned into operational production in the IDPS (AS 3001).

2.1. Land Surface Temperature

[7] The VIIRS Land Surface Temperature (LST) EDR provides the skin temperature of the uppermost layer of the land surface (and larger inland waters) in swath format, equivalent to the MODIS Level 2 product. The EDR deviates from its MODIS counterpart in a few ways: (1) it has a functional dependency on previously generated surface type dependent coefficients; (2) it does not provide dynamic land emissivity per the current MODIS day-night product, MOD11B1 [*Wan and Li*, 1997], or MODIS temperature emissivity separation product, MOD21 [*Hulley et al*., 2010]; and (3) the fall-back two-band split-window algorithm (employed when cloud cover or strong atmospheric effects are detected) uses both thermal and middle-infrared bands. Surface emissivity is known to change under many circumstances, including rainfall in arid regions, phenological changes, and intrasurface type changes or fires. This variation is not fully

Table 1. JPSS Accuracy Requirements (Threshold and Objective as Listed in Version 2.7 of the JPSS Level 1 Requirements Supplement) and Estimated Performance Based on NASA VIIRS Science Team Evaluations To-Date[a]

EDR, IP, or ARP	Threshold	Objective	Estimate (Evaluation Scenario)
Land Surface Temperature[b]	1.4 K	0.8 K	~ 1.0 K (dense vegetation and water) > 2.5 K (semiarid, seasonally varying landscapes)
Surface Reflectance[c]	± (0.01 + 10%)	± (0.005 + 5%)	≤ 0.015 (dense vegetation and dark surfaces) > 0.015 (bright surfaces)
Surface Albedo	0.08	0.0125	> 0.078 (CEOS LPV sites and desert sites)
Vegetation Index (TOA NDVI)	0.05	0.03	< 0.030 (nadir view over Western Hemisphere versus MODIS Aqua)
Vegetation Index (TOC EVI)	0.05	N/S	< 0.030[d] (nadir view over Western Hemisphere versus MODIS Aqua)
Active Fires[e]	[1.0, 5,000 MW]	[1.0, 10,000 MW]	N/S
Surface Type[f]	70% PCT	80% PCT	~ 70% PCT (IGBP Classes 0 5, 10, 12 13, 15 16) < 70% PCT (IGBP Classes 6 9, 11, 14)
Snow Cover[g]	90% PCT	90% PCT	~ 90% PCT (midlatitude and high-latitude regions)
Ice Age	70% PCT[h]	90% PCT[h]	> 70% PCT[i] (polar regions, all seasons) < 70% PCT[h] (polar regions, all seasons)
Ice Concentration	N/S[j]	N/S	Good agreement versus MODIS sea ice extent (polar regions, all seasons)
Ice Surface Temperature	1.0 Kelvin[k]	N/S	< 0.2 K (versus MODIS IST) < 0.5 K (versus KT-19 observations, Ice Bridge cal/val campaign)

[a]Note that additional specifications typically apply to each product, such as revisit time, coverage, long-term stability and mapping, precision, and uncertainty; for brevity, these are not listed here. Further, each product has an associated set of exclusion conditions (e.g., high solar zenith angles) for which its specifications are relaxed. N/S = No value specified. PCT = Probability of correct typing.

[b]Results are based on IDPS MX6.2 build, after a look-up table update was implemented.

[c]Note that performance is dependent on both the spectral band and magnitude of the reflectance (e.g., increased surface brightness results in a multiplicative error of 5%).

[d]With EVI gain adjusted to 2.5.

[e]Fire Radiative Power (FRP) measurement range threshold requirement. The high end of the FRP measurement range threshold requirement (5000 MW) is based on current design capabilities (i.e., the present 634 K saturation specification for the VIIRS M13 Band) and the recommendation of the NOAA-NASA Land Science Team. Quantitative assessment of ARP product is pending on availability of quality reference data, primarily from airborne measurements.

[f]Seventeen-class IGBP classification.

[g]Applies only to snow/no-snow classification.

[h]Ice-free, new/young ice, all other ice.

[i]Ice/ice-free classification.

[j]VIIRS produces a sea ice concentration IP in clear sky conditions, which is provided as an input to the Ice Surface Temperature calculation.

[k]Uncertainty requirement for Ice Surface Temperature.

captured in the current IDPS version of the VIIRS product. Previous work has shown that for arid and semiarid regions, a better approach is to use an algorithm with dynamically varying emissivity, such as is used in the MOD11B1 or MOD21 products [*Hulley and Hook*, 2009]. For continuity, the generation of an emissivity product compatible with MODIS is desired, i.e., a merged product using both split-window and dynamic emissivity retrieval.

[8] The measurement accuracy (bias) and precision (1 sigma) specified for the VIIRS LST product are 1.4 and 0.5 K, respectively, which must be met when the VIIRS Cloud Mask indicates a high confidence of clear conditions (cf. Table 1). The dynamic range for the product extends from 213 to 343 K. The product is being generated over all land pixels except when conditions mentioned above are not met, as determined from the VIIRS Cloud Mask (VCM).

[9] Initial evaluation of the VIIRS Land Surface Temperature (LST) EDR (based on IDPS Mx6.2) was performed using three different approaches: (1) cross comparison with the Aqua MODIS LST product (MOD11) when the Aqua and S-NPP overpasses were within 30 min of each other; (2) absolute temperature validation using the Lake Tahoe and Salton Sea automated validation approach [*Hook et al*., 2007]; and (3) radiance-based (R-based) LST validation over a set of pseudo-invariant sites [*Wan and Li*, 2008]. The R-based method provides estimates of the true LST using a radiative closure simulation without the need for in situ measurements and requires input air temperature, relative humidity profiles, and emissivity data [*Hulley and Hook*, 2012].

[10] Figure 1 shows a plot of the validation results using MOD11, MOD21, and VIIRS for the Kelso Dunes pseudo-invariant field site using data from AS 3001 and AS 3002. Note that, at the time of this exercise, the baseline algorithm available at the IDPS (AS 3001) was the "fallback" split-window (land-cover-based approach) retrieval method. In contrast, the baseline algorithm available at the Land PEATE was the two-band, split-window algorithm.

[11] This case highlights the problem of using a static map for the emissivity coefficients seen with both the MOD11 and VIIRS products [*Hulley and Hook*, 2009]. In both cases the retrieved MOD11 and VIIRS LSTs are too low by 2–3 K (emissivity set too high), whereas the dynamic emissivity approach MOD21 gives the better answer. As a result, the VIIRS LST EDR retrieval does not meet the accuracy threshold requirement. In summary, while the VIIRS Land Surface Temperature EDR is shown to be good to 1 K over dense vegetation and water, users should beware of major deficiencies in the current IDPS algorithm, particularly over semiarid and seasonally varying regions, where large errors of several degrees kelvin have been found. Long-term validation is needed as well as additional comparisons with data from other instruments.

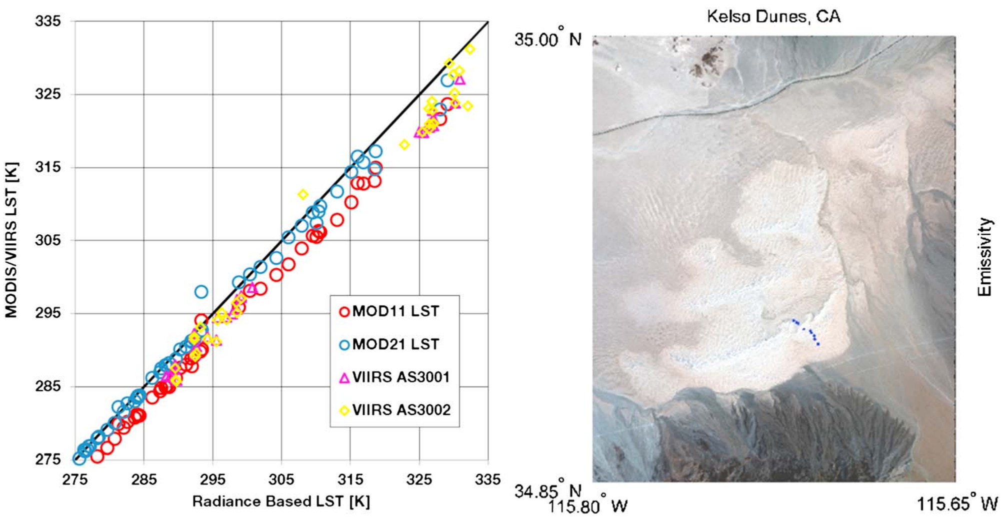

Figure 1. (left) Plot of MODIS/VIIRS LST at the Kelso Dunes, California, pseudo-invariant site (image on right) versus radiance-based LST.

2.2. Surface Reflectance

[12] Surface reflectance is one of the key products from VIIRS and, as with MODIS, is used in developing several higher-order land and cryosphere products, including Global Climate Modeling Grid (CMG) products (cf. Figure 2), which are used as input for modeling global trends. The VIIRS Surface Reflectance IP is based on the heritage MODIS Collection 5 product [*Vermote et al.*, 2002], which provides atmospherically corrected reflectances for the VIIRS bands M1, M2, M3, M4, M5, M7, M8, M10, and M11 for each moderate resolution pixel and for the VIIRS bands I1, I2, and I3 for each imagery resolution pixel. The quality and character of surface reflectance depend largely on the accuracy of the VCM and aerosol algorithms.

[13] A preliminary assessment of the VCM shows that the product correctly detects large, bright, and cold clouds and significantly underestimates small and low cumulus clouds. In part, this is a consequence of VCM being designed to satisfy all EDR algorithms and thus provide an average performance in terms of omission and commission errors, in contrast to the more conservative MODIS cloud mask. The leakage of small clouds creates large biases in the VIIRS Surface Reflectance IP, which are not currently captured by the quality flags.

[14] The quality of VIIRS aerosol retrievals is still being evaluated by the VIIRS Land and Aerosol cal/val teams, and a detailed picture has yet to emerge. At present, the VIIRS aerosol algorithm does not provide aerosol type (model) information, and its aerosol optical depth (AOD) product is of lower quality, often significantly, than that of MODIS. The deficiencies are most apparent over bright surfaces, where VIIRS often shows high AOD values when in fact it is clear. Over moderately bright and dark surfaces, VIIRS AOD rather unpredictably may show a substantial bias, which could stem from the adopted flexible selection of the aerosol model on a pixel basis [*H. Liu et al.*, Validation of Suomi-NPP VIIRS Aerosol Optical Thickness, submitted to *Journal of Geophysical Research: Atmospheres*, 2013].

[15] The VIIRS SDR, and particularly the associated calibration, is being closely monitored on a continuous basis by cross comparison of the VIIRS and MODIS Surface Reflectance product over instrumented field sites. At this early stage, we

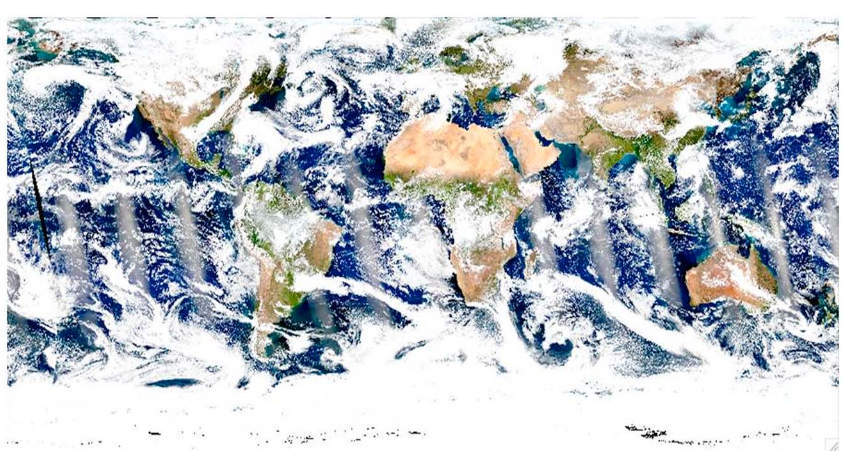

Figure 2. VIIRS Level 3 Global 0.05 Degree Global Climate Modeling Grid (CMG) Surface Reflectance Intermediate Product (Land PEATE-adjusted version of the Surface Reflectance IP IDPS algorithm) for 26 October 2012.

Table 2. Average Surface Reflectance and Bias of VIIRS Surface Reflectance IP for Selected Sites[a]

	M2 (436 454 nm)		M4 (545 565 nm)		M5 (662 682 nm)		M7 (846 885 nm)	
Site Name	Reflectance	Bias	Reflectance	Bias	Reflectance	Bias	Reflectance	Bias
Sites that have a relatively good performance with biases								
UCSB	0.042	0.007	0.070	0.006	0.084	0.005	0.230	0.005
Cuiaba-Miranda	0.033	0.004	0.069	0.000	0.084	0.002	0.254	0.006
Ispra	0.029	0.013	0.055	0.009	0.045	0.006	0.297	0.006
Evora	0.058	0.004	0.106	0.005	0.157	0.007	0.300	0.009
Konza	0.039	0.004	0.077	0.006	0.084	0.007	0.302	0.014
Alta Floresta	0.036	0.003	0.078	0.005	0.094	0.003	0.321	0.008
Bondville	0.027	0.010	0.059	0.004	0.052	0.005	0.348	0.012
Lille	0.042	0.015	0.081	0.011	0.074	0.009	0.355	0.001
Sites that have a marginal performance								
Table Mountain	0.082	0.017	0.123	0.014	0.156	0.011	0.250	0.008
Railroad Valley	0.123	0.018	0.183	0.015	0.229	0.014	0.273	0.010
Goddard Space Flight Center	0.038	0.026	0.063	0.018	0.053	0.019	0.295	0.008
Hamburg	0.032	0.012	0.071	0.011	0.060	0.010	0.345	0.007
Sites of poor performance								
Beijing	0.058	0.032	0.086	0.022	0.086	0.022	0.255	0.009
XiangHe	0.039	0.019	0.072	0.017	0.062	0.011	0.326	0.007
Dakar	0.079	0.028	0.132	0.037	0.147	0.028	0.328	0.086
Banizoumbou	0.066	0.021	0.174	0.005	0.298	0.029	0.467	0.049

[a]The analysis covered the period of January October 2012 based on 50 × 50 km^2 subsets of VIIRS data gridded to 0.750 km resolution over the AERONET sites. The full analysis includes Accuracy or bias, Precision, and Total Uncertainty (APU) for different levels of surface brightness in each target area. Results here provide a cumulative evaluation for the average reflectance level.

can confirm that the VIIRS SDR is suitable for generating Surface Reflectance IP; however, continuous monitoring is necessary, and in the absence of any reprocessing, data generated prior to the VIIRS SDR provisional status (March 2013) might not be suitable for the Surface Reflectance IP.

[16] An evaluation of the VIIRS Surface Reflectance IP was performed based on accuracy assessments over several Aerosol Robotic Network (AERONET)-based Surface Reflectance Validation Network sites [*Wang et al.*, 2009]. Results are summarized in Table 2. The data are organized to indicate an average performance level over regions with relatively low cloudiness, good AERONET record (without gaps in the measurements), and high retrieval statistics. The top part of Table 2 indicates sites that have a relatively good performance with biases across all spectral bands below 0.015. These study sites are characterized by an abundance of vegetation and relatively dark surfaces, with the exception of the University of California, Santa Barbara (UCSB) site. The middle part of Table 2 indicates sites that have a marginal performance, and the bottom part of Table 2 indicates sites of poor performance. Of these, the high biases for the Beijing and XiangHe are due to the high aerosol levels, and Dakar and Banizoumbou have bright surfaces where the VIIRS aerosol retrievals are problematic.

2.3. Surface Albedo

[17] Albedo, the quantity that specifies the proportion of the shortwave radiative flux that is reflected by the surface, is one of the primary VIIRS Land EDRs as well as being one of the Global Climate Observing System's Essential Climate Variables [*Schaaf et al.*, 2011]. The VIIRS EDR specification calls for only a broadband (0.3–4.0 μm) value, retrieved on a

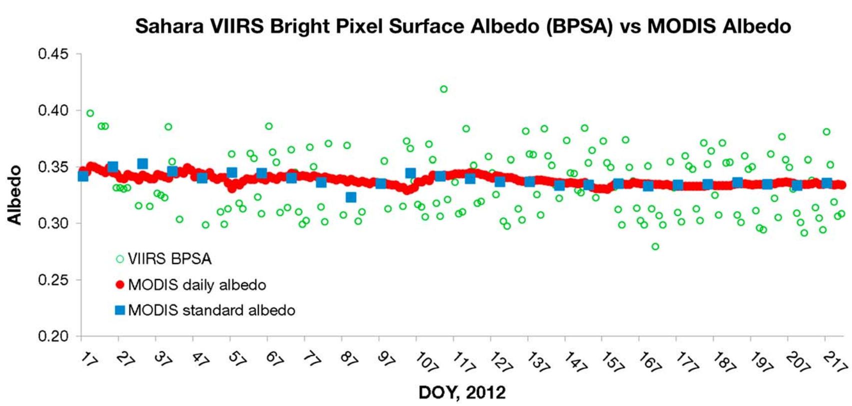

Figure 3. Comparison between VIIRS Bright Pixel Surface Albedo (BPSA) (green circles), MODIS Collection 5 eight-day standard product (blue squares), and MODIS Collection 6 daily albedo (analogous to the VIIRS Dark Pixel Surface Albedo (DPSA), red circles) over the Sahara site (a stable desert location: 26.450°N, 14.083°E) for 17 January to 4 August 2012. Daily BPSA varies between 0.29 and 0.40 in the Sahara. A recent look-up table (LUT) reduces this somewhat, but view-angle effects still dominate (LUT implemented 18 January 2013). A solution suggested to reduce variability is to simply implement a multiday average.