An Efficient Approach for VIIRS RDR to SDR Data Processing

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***Abstract*—The Visible Infrared Imaging Radiometer Suite (VIIRS) Raw Data Records (or Level-0 data) are processed using the current standard Algorithm Development Library (ADL) to produce Sensor Data Records (SDR; or Level-1B data). The ocean color Environmental Data Records (EDR), one of the most important product sets derived from VIIRS, are processed from the SDR of the visible and near-infrared moderate resolution (M) bands. As the ocean color EDR are highly sensitive to the quality of the SDR, the bands from which the EDR data arise must be accurately calibrated. These bands are calibrated on-orbit using the onboard Solar Diffuser, and the derived calibration coefficients are called F-factors. The F-factors used in the forward operational process may have large uncertainty due to various reasons, and thus, to obtain high-quality ocean color EDR, the SDR needs to be regularly reprocessed with improved F-factors. The SDR reprocessing, however, requires tremendous computational power and storage space, which is about 27 TB for one year of ocean-color-related SDR data. In this letter, we present an efficient and robust method for reduction of the computational demand and storage requirement. The method is developed based on the linear relationship between the SDR radiance/reflectance and the F-factors. With this linear relationship, the new SDR radiance/reflectance can be calculated from the original SDR radiance/reflectance and the ratio of the updated and the original F-factors at approximately 100th or less of the original central processing unit requirement. The produced SDR with this new approach fully agrees with those generated using the ADL package. This new approach can also be implemented to directly update the SDR in the EDR data processing, which eliminates the hassle of a huge data storage requirement as well as that of intensive computational demand. This approach may also be applied to other remote sensors for data reprocessing from raw instrument data to science data.**

***Index Terms*—Computation efficiency, reflective solar bands (RSB), reprocessing, Sensor Data Records (SDR), storage, Visible Infrared Imaging Radiometer Suite (VIIRS).**

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I. Introduction

THE Visible Infrared Imaging Radiometer Suite (VIIRS) is one of the five instruments onboard the Suomi National Polar-Orbiting Partnership satellite that was launched on October 28, 2011, and acquired its first measurements on November 21, 2011 [1], [2]. VIIRS has 22 spectral bands covering visible, near-infrared (NIR), shortwave infrared (SWIR), and infrared wavelengths from 0.410 to 12.01 μm, among which 14 are reflective solar bands (RSBs) [2]. The RSBs are calibrated on-orbit with an onboard Solar Diffuser (SD) and monitored using lunar observations [1]–[3]. With the derived calibration coefficients which are called F-factors, the VIIRS Raw Data Records (RDR; or Level-0 data) can be processed using the Algorithm Development Library (ADL) package to produce Sensor Data Records (SDR; or Level-1B data) [4]. The ocean color Environmental Data Records (EDR; or Level-2 data) are processed from the SDR and are highly sensitive to the SDR data quality [5]. The ocean color EDR is one of the most important product sets [6] and can be derived from VIIRS visible and NIR bands [5], [7]–[9], as well as the SWIR bands [10]–[12]. Some preliminary evaluations have shown that VIIRS has great potential to provide science and user communities with high-quality global ocean color products [5], [13], [14]. To reduce the uncertainty of the forward processed SDR, it is necessary to reprocess the SDR with offline improved F-factors, following the same process applied to the Moderate Resolution Imaging Spectroradiometer (MODIS) science data that have been reprocessed over several collections [15].

The reprocessing of the SDR from the RDR using the ADL package is computationally very intensive. However, in the SDR reprocessing, the geolocation calculation consumes most of the computations compared to radiometric calibration where updated F-factor lookup tables (F-LUTs) are used [16]. In radiometric calibration, the data processing includes background instrument response subtraction, instrument temperature effect correction, data quality checking, radiance/reflectance calculation, etc. The radiance/reflectance calculation takes much less computational times than others in the radiometric calibration. Among all of these computations including geolocation calculation in the RDR to SDR reprocessing, only radiance/reflectance calculation is affected by the F-LUT update and needs to be recalculated. Another hurdle in the SDR reprocessing is the requirement of the huge disk space to store the reprocessed SDR that needs about 27 TB per year for ocean-color-related SDR data. In addition, there may be several versions of the reprocessed SDR, increasing the computational and the storage demands by several folds. Thus, both the reduction of the data storage requirement and the improvement of computational efficiency are critical. In

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this letter, a new method having the advantage in both of these aspects for the SDR reprocessing is described. In Section II, the VIIRS SDR radiance and reflectance calculation algorithms are reviewed, and the linear relationship between the radiance/reflectance and F-factors is examined. In Section III, the algorithm to reprocess the SDR using the linear relationship is described, and issues related to the data reprocessing using the proposed approach are discussed. In Section IV, the test results are reported and discussed; in particular, the computational efficiency of the new approach is assessed.

II. VIIRS Radiance and Reflectance Calculation Algorithm

The sensor Earth view (EV) at-aperture radiance for a VIIRS RSB, band B, is calculated by (1) [1], shown at the bottom of the page, where $Sample$ is the sample along the scan direction, $Scan$ is the scan number, D is the detector number of band B, $L_B(Sample, Scan, D, t)$ is the radiance at the sample of the scan observed at time t by detector D of band B, H is the side number of the instrument half-angle-mirror (HAM) at the scan, and G is the gain status of the detector at the sample of the scan. $F(B, D, H, G, t)$ is the F-factor of band B, detector D, HAM H, and gain G at time t, which is inversely proportional to the on-orbit gain change due to the instrument degradation. $c_0(B, D, H, G)$, $c_1(B, D, H, G)$, and $c_2(B, D, H, G)$ are temperature-effect-corrected prelaunch measured calibration coefficients with a quadratic relationship between the background-subtracted instrument response and radiance. The term $dn^j_{ev,B}(Sample, Scan, D)$ is the jth term of the background-subtracted instrument response. $RVS(\theta_{ev}, B)$ is the response-versus-scan at the angle of incidence (AOI) θ_{ev} of the HAM, which is a function of the sample and normalized at the AOI of the SD. Equation (1) shows that the calculated radiance at any given pixel defined by sample, scan, and detector is *linearly* proportional to the corresponding F-factor, although a quadratic form is applied to convert the instrument response to the radiance. This is due to the fact that the offset and the nonlinear coefficient in the quadratic form change with the linear coefficient proportionally. Indeed, the EV reflectance is calculated from the ratio of the radiance with the Earth–Sun distance effect corrected and the detector-specific weighted solar irradiance. Thus, the EV reflectance is also linearly proportional to the F-factors.

The VIIRS RSB radiance and reflectance are contained in the SDR file, which is processed from the upstream RDR file containing the raw digital numbers from EV observations using (1). Geolocation parameters are also input for the SDR data processing, and thus, the SDR file contains the geolocation information for the EV observations. The National Oceanic and Atmospheric Administration (NOAA) Interface Data Processing System (IDPS) produces the operational forward SDR from RDR with the operational F-LUTs which are updated routinely [16]. The ADL software package provides an algorithm framework in which one can develop and execute new or existing IDPS-compatible algorithms. ADL contains the codes that are equivalent to the IDPS to process VIIRS data from RDR to SDR and SDR to EDR. The SDR data are grouped into granules, and each granule contains the data from 48 scans, which cover a time period of approximately 85 s. The radiance and reflectance of each RSB band are contained in a Hierarchical Data Format (HDF) 5 file. The information for flagged data is also included in the HDF5 file. Thus, for each granule, there are 14 files for RSB EV radiance and reflectance. There are also other files for the granule that contain the information for thermal emissive bands (TEB) and geolocation.

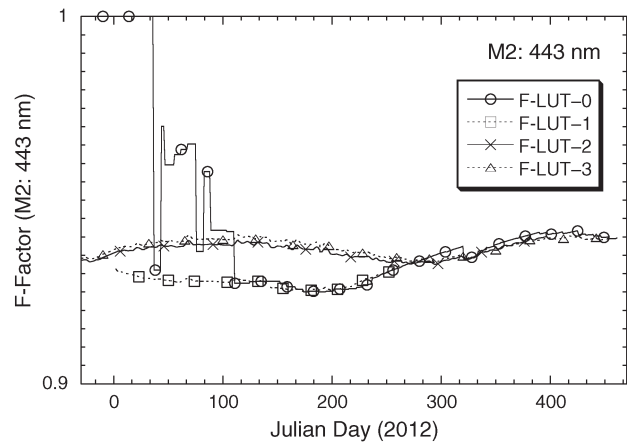

Fig. 1. IDPS F-LUTs and three sets of updated daily F-LUTs as a function of Julian day in 2012 for VIIRS M2 band (443 nm). These F-factor values are detector averaged with the high-gain setting and from instrument HAM side A. It is noted that the figure is reproduced from [5]. F-LUT-0 is the operational IDPS F-LUTs, and other three sets of F-LUTs are provided by Aerospace with various corrections [5].

For ocean normalized water-leaving radiance $nL_w(\lambda)$ [7], [17]–[19], its uncertainty can be an order larger than that of the top-of-atmosphere radiance [20]. Thus, the EDR quality strongly depends on the accuracy of the SDR, which, in turn, depends on that of the F-LUTs. It is well known that the forward LUTs may contain large uncertainty and other errors from various sources as demonstrated in MODIS L1B data processing [15] as well as in VIIRS SDR processing, especially in the first year on-orbit [5]. Fig. 1 shows the operational forward and three different versions of improved VIIRS band M2 (443 nm) F-factors. There are clear differences between the four sets of F-LUTs [5]. With the knowledge of the instrument performance gathered and better understood, there will be more versions of the improved F-LUTs. To obtain high-quality EDR, it is critical that the SDR be reprocessed with improved F-LUTs on a regular basis as demonstrated from MODIS L1B data reprocessing [15].

$$L_B(Sample, Scan, D, t) = \frac{F(B, D, H, G, t) \sum_{j=0}^{2} c_j(B, D, H, G) dn^j_{ev,B}(Sample, Scan, D)}{RVS(\theta_{ev}, B)} \quad (1)$$

III. Ratio Approach for VIIRS SDR Data Reprocessing

When updated/improved F-LUTs become available, the current method to regenerate the SDR with improved data quality is to run the ADL package to reproduce the SDR from the RDR. However, this approach is computationally time-consuming and also requires large data storage for the reprocessed SDR data. Both the computational effort and the storage requirement using the current approach bring great difficulties to the SDR reprocessing that result in a bottleneck for the ocean color EDR data quality improvements. Thus, new approaches for the SDR data reprocessing in order to overcome the aforementioned difficulties are critical.

As mentioned previously, the accuracy of the SDR mainly depends on the F-LUTs. With the assumption that other input parameters remain unchanged except for the F-LUTs, the EV radiance calculated with the new F-LUTs can be related to the IDPS-produced or old EV radiance by

$$L_{\mathrm{new}}(Sample, Scan, D, t) = R(B, D, H, G, t) \times L_{\mathrm{old}}(Sample, Scan, D, t), \quad (2)$$

where

$$R(B, D, H, G, t) = F_{\mathrm{new}}(B, D, H, G, t)/F_{\mathrm{old}}(B, D, H, G, t) \quad (3)$$

is the ratio of the new and old F-LUTs, $F_{\mathrm{new}}(B, D, H, G, t)$ and $F_{\mathrm{old}}(B, D, H, G, t)$, which are used to produce $L_{\mathrm{new}}(Sample, Scan, D, t)$ and $L_{\mathrm{old}}(Sample, Scan, D, t)$, respectively, according to (1), e.g., using ADL. $L_{\mathrm{old}}(Sample, Scan, D, t)$ is not required to be the IDPS-generated EV radiance as long as it is produced with the F-LUTs $F_{\mathrm{old}}(B, D, H, G, t)$. Instead of F-LUTs, the IDPS uses the so-called "VIIRS-SDR-F-PREDICTED-LUT," which is a set of parameters that can be used to calculate the F-LUTs, in the SDR processing after August 9, 2012. In this letter, we assume that the F-LUTs can be calculated for each $L_{\mathrm{old}}(Sample, Scan, D, t)$. In fact, we have developed subroutines to calculate the IDPS F-LUTs for both before and after August 9, 2012. Using (2), the new SDR can be directly generated from the old SDR using the simple ratio of the two F-LUT sets. The computation requirement for the ratio of the two sets of F-LUTs is negligible compared to that of generating the SDR from the RDR data, and the storage requirement for the ratio tables is also negligible compared to the case of the SDR data reprocessing. In principle, the ratio of the two sets of F-LUTs can be computed for each scan, but in reality, it is good enough to calculate ratios just once for each granule, considering that the changes of the F-LUTs are negligible in 85 s, the time period that a granule covers. The F-LUT ratios can be calculated before the SDR reprocessing, and they can be stored under ~1.2 GB in binary format (~2.4 GB in ASCII format) for each year. Since the SDR data are stored in HDF5, the EV radiance and reflectance for a given band can be read from the SDR file without accessing other data. After the new radiance is calculated using (2), the old radiance in the SDR file can be replaced with the new values while other parts of the data set remain unchanged. In fact, there is a field in the SDR file to record the name of the corresponding F-LUTs that were used to produce the SDR data. This field can also be updated with the new F-LUT information.

VIIRS has seven dual-gain bands, i.e., M1–M5, M7, and M13, one of which, M13, is a TEB. The gain status of each detector for a given dual-gain band at each sample of the scan is also needed to calculate the radiance using (2) and (3). However, the gain information is not contained in the SDR data but can be pulled from the RDR data. Pulling the gain status information from the RDR is about ten times more efficient than it is to produce a complete SDR data set. Since the gain status is recorded as binary result, high gain with a value of zero and low gain with a value of one, the gain values of the seven bands for a given pixel can be compacted into a digital number of a single byte, with gains of M1–M5, M7, and M13 installed in the first seven bits of the byte from the least to the most significant bits. This can significantly reduce the data size. The size of a gain data file is about one hundredth the size of a complete set of the SDR data. The size can be further reduced if a data compression technique is used. When the compressed gain information, stored as a byte value, is read from the file and applied in the calculation, the value of each bit from the byte must first be obtained. A method based on a transformation matrix with row index related to the bands (or bits) and column index to the value of the byte is used to obtain the gain status information for each of the seven dual-gain bands. A 16-b digital number dn_{rad} is used in the SDR to record a radiance value for bands I1–I3, M1–M2, M6, and M8–M11, and is related to the actual radiance by

$$L_B(Sample, Scan, D, t) = a_0(B) + a_1(B) dn_{\mathrm{rad}} \quad (4)$$

where $a_0(B)$ and $a_1(B)$ are the offset and scaling constants. For each of these bands, the 16-b digital numbers are read from the old SDR and then converted to radiance using (4). The values of the obtained radiance are multiplied by the corresponding ratios of the F-LUTs to get the values of the new radiance. After that, the computed radiance is converted back to the 16-b digital number by inversely using (4), and the digital numbers are finally written back into the SDR to replace the old values in the file. For bands M3–M5 and M7, a floating number is used to record the radiance. Then, the only thing needed is to read the radiance from the SDR, multiply by the ratio of the F-LUTs, and write the updated radiance back to the SDR. For reflectance, a 16-b digital number is used for all VIIRS RSB to record the reflectance for each pixel, which is related to the actual reflectance using an equation similar to (4). Updating reflectance in the SDR can then be done with the same procedure used for the radiance of bands I1–I3, M1–M2, M6, and M8–M11.

Finally, the flags in the SDR are unchanged since they provide information unrelated to the F-LUTs. The filled values for bad data due to various reasons in the SDR also remain the same.

IV. Results and Discussions

A tool to produce the SDR for updated F-LUTs has been developed using the ratio approach described in Section III. With the tool, the new SDR can be directly obtained from the old SDR with the ratio of the F-LUTs and the gain information from the dual-gain bands that are preprocessed. The tool can also be implemented into the ocean color EDR data processing system to bypass the production of the SDR and the associated output storage issue.

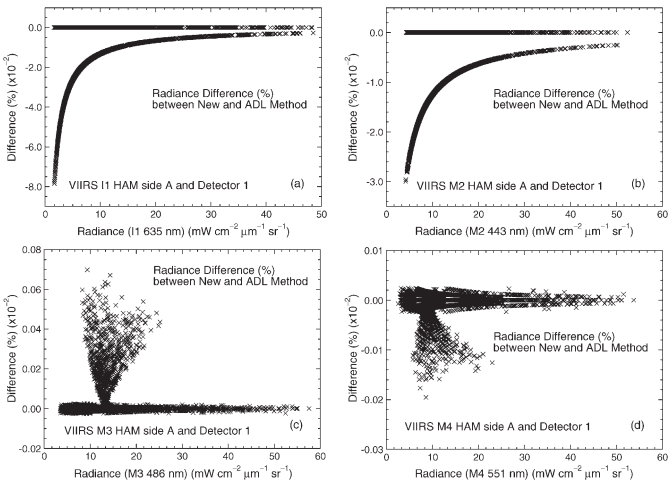

Fig. 2. Radiance difference (in percent) as a function of radiance value between using the new ratio approach and the original ADL data processing for producing VIIRS SDR data for (a) band I1 (635 nm), (b) band M2 (443 nm), (c) band M3 (486 nm), and (d) band M4 (551 nm). Results were derived from a VIIRS granule acquired on January 30, 2012.

A test is conducted to illustrate the approach and to compare results. Two different sets of F-LUTs are applied to a VIIRS granule acquired on January 30, 2012, to generate the SDR using the ADL package (the original approach). Two SDR files are generated for each band, one from the application of the first set of F-LUTs and the other from the second set of F-LUTs. Then, from the SDR associate with the first F-LUTs, the ratio approach is applied using the ratio of the two sets of F-LUTs and the gain data to generate another set of SDR for the second F-LUTs. Then, two SDR files are available for comparison for the second set of F-LUTs for each band, one from the original approach using the ADL and another from the new ratio approach.

The percentage differences of the radiance read from the two SDR files are shown in Fig. 2 for bands I1 and M2–M4. Fig. 2(a) shows the percentage differences in radiance for band I1 (635 nm) that appear distributed along two lines in the plot, one showing a straight line having an exact value of zero and the other showing a change of 0.003%–0.08%. The largest difference is 0.08% at the lowest radiance value of $\sim$1.5 mW cm^{-2} μm^{-1} sr^{-1}. The two distributions correspond to two constant radiance differences, 0 and 0.001316 mW cm^{-2} μm^{-1} sr^{-1}, although the second distribution in the plot is not a constant. The nonzero constant is the radiance scaling constant in (4) for band I1. The differences of the radiance are due to the conversion of the calculated radiance from floating precision to 16-b digital numbers. When the ADL package is used, the conversion is performed just once for each pixel, while there is a second conversion when the new ratio approach is applied. The extra conversion in the new ratio approach may bring a radiance difference of ± 0.001316 mW cm^{-2} μm^{-1} sr^{-1}. These differences are at the level of the precision of the data, and their impact on any EDR product is negligible, considering that the sensor calibration uncertainty is much larger than that. Fig. 2(b) shows the percentage differences in radiance for band M2 (443 nm). As for band I1, there are two distributions in the plots, a straight line with an exact value of zero and another one that changes from 0.003%–0.03%. Similarly, the second distribution represents a constant radiance difference, 0.001258 mW cm^{-2} μm^{-1} sr^{-1}, which is the radiance scaling constant of the band. The largest difference is 0.03% at the lowest radiance value of $\sim$4.2 mW cm^{-2} μm^{-1} sr^{-1}. Since the lowest radiance value of band M2 is larger than that of band I1, band M2 consequently has a smaller (absolute) value for the largest radiance percentage difference.

The radiance percentage differences for bands M3 (486 nm) and M4 (551 nm) are shown in Fig. 2(c) and (d), respectively. Since the radiance for these bands is recorded in the SDR as a floating number, which has a much higher precision than that of a 16-b digital number, the radiance percentage differences between the radiances from the two SDR files are about two orders of magnitude smaller. In Fig. 2(c) and (d), much larger percentage differences are seen around 13 and 9 mW cm^{-2} μm^{-1} sr^{-1} for bands M3 and M4, respectively, which are the radiance regions where the gain status of the two bands switches from high gain to low gain or from low gain to high gain. In order to reduce the horizontal spatial resolution difference, an aggregation scheme is applied along scan with a VIIRS "pixel" formed by three detector footprints around nadir, two in the scan angle ranges from -47.87° to -31.71° and 31.71° to 47.87°, and one for larger scan angles. For dual gain bands, the aggregation has been implemented in the data processing from RDR to SDR. Thus, the radiance in the original SDR is the aggregated value for the region with absolute scan angle smaller than 47.87°, and there is no information for the radiance of each detector footprint before aggregation in the SDR. In the new ratio approach, a combination of the F-factor ratio of the two gains according to the gain status information of nonaggregated pixels is used in the radiance calculation using (4). It is demonstrated in Fig. 2(c) and (d) that the combination scheme works well but cannot completely remove the small errors due to the incomplete information of the original radiance of each pixel before aggregation. However, the uncertainty due to the incomplete information of the radiance brings negligible impact on any EDR applications, considering that the largest percentage differences in radiance are about 0.0007% and 0.0002% for bands M3 and M4, respectively. Results in Fig. 2 clearly show that the SDR data reprocessed using the ratio approach agree with the original set obtained by running the ADL package. The same analysis has been performed for the radiance of other bands and also for the reflectance for all VIIRS RSB. We have also tested several other cases, including the cases where the VIIRS-SDR-F-PREDICTED-LUTs are used in the IDPS SDR data processing. Specifically, the same results were obtained for cases on September 30, 2012, and June 15, 2013, using the VIIRS-SDR-F-PREDICTED-LUTs. It is concluded from all of these analyses that the ratio approach provides the same accuracy and quality of the SDR data as from the application of the ADL package (RDR to SDR).

A Dell PowerEdge R900 computer with 32 processors is used to compare the computational efficiency of the ratio approach and the current one using the ADL package. For this test, only one processor of the computer is used to process the data for both approaches, and a central processing unit (CPU) is used for comparison. It takes about 27.66 s of system time and 338.09 s of user time (total CPU of 365.75 s) using the ADL package to reprocess one granule, while it only needs 0.70 s of system time and 2.66 s of user time (total CPU of 3.36 s)

TABLE I
SUMMARY OF THE TEST RESULTS FOR THE SDR REPROCESSING USING THE CURRENT APPROACH WITH THE ADL PACKAGE AND THE NEW RATIO APPROACH

CPU Requirement and Improvement with New Approach									
Method	RDR to SDR using ADL			The New Ratio Approach			Ratio (Old vs. New)		
CPU† Usage	One Granule	10 Granules	100 Granules	One Granule	10 Granules	100 Granules	One Granule	10 Granules	100 Granules
System	27.66	282.18	2852.78	0.70	8.79	75.60	39.51	32.10	37.74
User	338.09	3222.75	32030.60	2.66	29.17	279.35	127.10	110.48	114.66
Total	365.75	3504.93	34883.38	3.36	37.96	354.95	108.85	92.33	98.28

†Unit: Seconds

to reprocess all SDR data (M1–M8 and M10–M11) required for ocean color EDR data processing. The CPU time used by the new ratio approach is about a factor of 109 times less than that using the ADL approach. The test has also been done for 10 and 100 granules, respectively. Table I provides a summary of the test results. The ratios of the times consumed by the two approaches to process 10 and 100 granules are about 92 and 98, respectively, consistent with the result from the one-granule test. Thus, the new ratio approach is a very efficient and robust method compared to the current ADL approach for SDR reprocessing. In actual SDR reprocessing, however, all 32 processors of the computer will be used. In reality, 32 processors do not result in a 32-time faster processing speed, and the current ADL approach has an even lower rate of speed improvement in multiprocessing due to a much larger random-access memory (RAM) requirement by the ADL approach compared to the ratio approach. When all improvements are combined and considered, the efficiency of the SDR reprocessing is far more efficient by a factor of 100 or more when the ratio approach is used. An additional advantage of the ratio approach is that it requires much less RAM than the ADL package—it can be run on much smaller machines. When the ratio approach is implemented in the SDR to EDR data processing, it is even more efficient since the output and input of the radiance or reflectance from the SDR are reduced and the storage of the reprocessed SDR becomes unnecessary. Since it requires about 27 TB of storage to store one year of ocean-color-related VIIRS SDR data, eliminating the storage need for the reprocessed SDR is a great relief on the computation facility.

V. SUMMARY

Based on the linear relationship between the radiance/reflectance and the on-orbit calibration coefficient (F-factor), an efficient ratio approach has been developed for the VIIRS RSB SDR data reprocessing. The new approach produces the SDR with the same accuracy as the current official approach using the ADL package but with a far greater efficiency that is about 100 or more times faster than the current approach. The new approach can either be used to produce new SDR or be directly implemented into any EDR data processing system. The latter case achieves even greater computational efficiency due to the reduction of the input and output processes, and relieves the storage requirement that has been hampering the SDR data reprocessing. This ratio approach will be used to provide updated SDR for the VIIRS ocean color EDR reprocessing. It can also be generally made for other satellite sensors in the RSB Level-1B data reprocessing as long as the structure is similar such as for MODIS L1B data reprocessing. This is a significant step forward for improving remote sensing data processing and reprocessing.

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