NISTAR Data Quality Report

May 28, 2020

Goddard Space Flight Center
Greenbelt, Maryland

National Aeronautics and Space Administration

CM FOREWORD

This document is an L-1 Configuration Management (CM)-controlled document. It is written to describe factors of consideration for users interesting in using the NISTAR Level 1 data product. It is intended to be the supplemental material for the NISTAR Data Format Control Book with more detailed information and in-depth discussion on these topics. As of written, the latest version of NISTAR L1B data to be released is v3.0.

Since the v3.0 processing introduced a monthly L1B filtered data product, users should note that the “Level 1B/L1B product” in this document always refers to the original L1B product with the daily cadence, while the new filtered product is referred as “L1B filtered” or “monthly L1B filtered”.

References to datasets in the HDF files are given in the form:
{HDF Level 1(A/B)} → {Group Name} → {Dataset Name} → {Field Name}
(The punctuation mark “/” is interchangeably used with the arrow sign.)

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DSCOVR PROJECT

DOCUMENT CHANGE RECORD Sheet: 1 of 1

REV LEVEL	DESCRIPTION OF CHANGE	APPROVED BY	DATE APPROVED
Rev-	Initially released by DSCOVR Science Team		
Rev-A	Currently released by L-1 Standards and Technology, Inc. The content has been updated to adapt to the latest format of NISTAR Version 2.1 data, and to provide more detailed and rigorous guidance for users.	S. Lorentz	5/17/2019
Rev-B	Released by L-1 Standards and Technology, Inc. The content has been updated to adapt to the latest format of NISTAR Version 3.0 data, and to provide more detailed and rigorous guidance for users. Version 3.0 of the data includes a new gap filling technique for short periods of missing data in the time series. A filtered new product which produces data on a 10 second cadence which has been filtered to remove low frequency noise. Both of these are described in Section III.	S. Lorentz	5/28/2020

1 Table of Contents

I. GENERAL INFORMATION/ISSUES

1.1 EARTH-DSCOVR DISTANCE DEPENDENCY

Users should be aware that for all L1A datasets, the radiometric data is NOT corrected by the distance from DSCOVR to the Earth. For L1B datasets, the only distance-corrected radiometric data are the Earth radiance (reported in 1 second, 4 hours and daily cadence) and the photodiode current, which is normalized to the L-1-to-Earth distance when the Earth-Sun distance is 1 AU. For monthly L1B filtered datasets, all radiometric data including the photodiode current are distance independent. See the table below for reference:

L1B Group/Object/Field	Corrected by the distance?
Demodulated_Power/DemodulatedRadiometerPower/(all fields)	No
Earth_Irradiance/BandA_EarthIrradiance/EarthIrradiance	No
Earth_Irradiance/BandA_EarthIrradiance/EarthRadiance	Yes
Binned_Averages/EarthIrradianceFourHour/RadiometerBandA	No
Binned_Averages/EarthIrradianceFourHour/RadiometerBandARadiance	Yes
Binned_Averages/EarthIrradianceFourHour/Photodiode	No
Binned_Averages/EarthIrradianceFourHour/PhotodiodeNormalized	Yes
(L1B Filtered Data) Earth_Radiance_Filtered/Band_A_(Total)	Yes
(L1B Filtered Data) Earth_Radiance_Filtered/Photodiode_Current	Yes

Table 1 Distance Dependency of L1B Datasets

For example, the 4-hour averaged Earth radiance in the Band A is given by the path:

/Binned_Averages/EarthIrradiancesFourHour/RadiometerBandARadiance.

And the 4-hour averaged Earth irradiance in the Band A, which is NOT corrected by the Earth distance, is given by the path:

/Binned_Averages/EarthIrradiancesFourHour/RadiometerBandA.

Similarly, the distance-corrected 4-hour averaged photodiode current is given by the path:

/Binned_Averages/EarthIrradiancesFourHour/PhotodiodeNormalized.

This is the 4-hour averaged photodiode current normalized to the Lagrange 1 point with the Earth at 1 AU from the Sun. The photodiode current uncorrected by the distance is given by the path:

/Binned_Averages/EarthIrradiancesFourHour/Photodiode.

The data of the solid angle of the Earth (calculated from Earth's lit surface area/distance squared) is provided in both datasets given by the group /Binned_Averages for users to derive distance-corrected radiometry products of their own choosing. Users may also refer to *L1A → Geolocation_Data → SpacecraftEphemeris → Position* to derive the distance in a finer time grid. The lit surface area of the Earth, however, is calculated as a constant based on the mean Earth radius (6371 km) regardless the Solar-Earth-Vehicle angle variations of approximately 5 to 6 degrees that occur throughout the mission.

1.2 SIGNIFICANT DIGITS

Users should be aware that the L1B and L1B filtered data is rounded before being written in the HDF product to remove meaningless digits. For the L1A product, however, such a rounding procedure is not implemented. Therefore, for certain datasets in L1A products, the number of significant digits does not coincide with the number of digits represented in the data. For example, the radiometer power data in *L1A → Radiometer_Power → ModulatedRadiometerPower* contains more than 15 digits after the decimal point but at least the last 10 digits are meaningless.

The significant digits of calibration data, including both ground and on-orbit, reflect their own uncertainties as they were loaded directly from textual files.

1.3 TIME RESOLUTION

For data products V3.0 and above, consider using the L1B filtered radiance product in-lieu-of the 4-hr averaged product described below. The former minimizes noise but preserves low-frequency signals of interest better than the latter. The L1B data product provides averaged Earth irradiances and radiances in a 4-hour and daily window, respectively, which both meet the science requirement of 1.5 % or less uncertainty in the total channel. Over time scales less than several hours, variations in the Earth signal are obscured by instrument noise; however, the full time resolution (1 second cadence) of Earth irradiance data is provided to allow the user to apply a filter of their choosing. The full time resolution data is saved in the datasets:

L1B → Earth_Irradiance → Band*x*_EarthIrradiance → EarthIrradiance
L1B → Earth_Irradiance → Band*x*_EarthIrradiance → EarthRadiance,

where *x* represents Band A, B, or C.

1.4 DATA UNDER DIFFERENT OPERATING MODES

The configuration of the NISTAR operation mode has not been changed since January 27, 2017. Prior to that, the operating mode was changed multiple times, for example, the shutter cycle period varied from 4 to 30 minutes and the ESR PID control parameters differed over time. These changes were made in an effort to optimize instrument performance. The quality of data collected earlier than this is significantly reduced. As a result, data collected prior to January 27, 2017 has been excluded from the V2.1 release.

Earlier releases, such as V2.0, contain radiometer data spanning different operating modes and having varied accuracy and precision. Although careful effort has been made to use appropriate dark offsets such that the final L1B product, e.g., *L1B → Earth_Irradiance → BandA_EarthIrradiance → EarthIrradiance*, is as accurate as possible, the user is cautioned against comparing data from different operating modes.

1.5 ANOMALOUS DATA

There are several periods of time during the mission where the data quality is not adequate for science products. The primary reasons include calibration activities, anomalies, and lack of a suitable dark offset measurement. The Level 1B Earth irradiance/radiance data product excludes time periods not coinciding with nominal operating configuration (Filter position 3, Earth completely within instrument field of view). The remaining sections which are not considered science worthy are tabulated (see: *L1A or L1B → On-orbit_Calibration → AnamalousData*). The final Level 1B product omits these time periods as well.

When encountering a section of missing L1B data where the raw data (*L1A → Science_Data → ScienceData*) was present, it has likely been filtered out during processing. In this case, the missing data can be found in the intermediate products, such as the *L1B → Demodulated_Power → DemodulatedRadiometerPower*. Use of this data is discouraged; it should be used only with an understanding of why the data was filtered during processing. The user can consult the NISTAR Activity Timeline document for hour-by-hour data quality reporting.

1.6 VC0 / VC1 DATA RATE SWITCHES

When the spacecraft is in real time contact with the ground, data is generated at the maximum data rate. This data is said to be made available through Virtual Channel 0 (VC0). The data rate is 1 Hz (one data packet per second) for Science data (AppID 82) and Miscellaneous data (AppID Misc), 0.1 Hz for Engineering data (AppID 86), and 1/30 Hz for Thermistor data (AppID 37). In addition, data is stored continuously in onboard memory to ensure data coverage when real time communication with the instrument is unavailable. This data is transmitted through Virtual Channel 1 (VC1). The VC1 data is available during real time contacts as well, but is duplicated within the VC0 data. Due to limited onboard memory, the VC1 science data is filtered (“decimated”) to 1/6 of the nominal cadence. The decimated VC1 data, however, when averaged by 4-boxcar filters, is noisier than the regular VC0 data due to under sampling.

Since July 2016, DSCOVR became the primary operational solar weather spacecraft, replacing Advanced Composition Explorer (ACE), and received 24 hour ground support. Prior to this, the VC0 data was only available when the US-based ground tracking stations had visibility of DSCOVR. The issue was most critical during winter months when there was less visibility of the spacecraft from the Northern Hemisphere ground stations, and therefore less availability of VC0 data. After the transition date of July 27, 2016, the VC0 data has been available for nearly continuously, with some small gaps remaining in the peak of winter seasons and with occasional drops near transitions between ground stations.

For all V2.1 data collected after January 2017, a gap in the VC0 data is not processed to Level 1B—even when VC1 data is available. For reference, the decimated (VC1) data is stored in the dataset: *L1A → Radiometer_Power → ModulatedRadiometerPowerDecimated*.

1.7 TIMING ANOMALY

A discrepancy between the commanding and actual shutter period was observed and subsequently investigated. When the instrument was commanded to have a shutter period of exactly ten minutes (600 seconds) at the beginning of the mission, the observed behavior was a shutter period of 638 seconds. A similar ratio was seen when the shutter period was changed to other values: With the current 4-minute setup, the actual shutter period observed is approximately 256 seconds. An investigation into the discrepancy revealed a phenomenon referred to as the NISTAR Timing Anomaly, which is caused by the NISTAR flight software (FSW). The potential high risk of correcting the FSW architecture onboard makes it an impractical option. The timing anomaly, however, is very manageable in the data processing and the only known effect is the constant deviation of the shutter period to its commanded value. Users should be aware that in all circumstances use of the term of "4-minute shutter period" in NISTAR documents actually refers to an approximately 256-second period.

II. UNCERTAINTY BUDGET

2.1 OVERVIEW

Table 2 below gives a summary of the NISTAR uncertainty estimated based on the data obtained throughout the “stable period” since January 27, 2017 during which the NISTAR operating mode and configuration[1] has not changed. The uncertainties shown below are expressed as percentages of the nominal Earth signal of each wavelength channel with a coverage factor of k = 1.

Filter Channel	Instrument Noise (Precision)			Responsivity (Calibration)			NISTAR Total Uncertainty
	Space View	Earth View 4 Hr / Daily	Total Noise 4 Hr / Daily	Laboratory Calibration	Stability on Orbit	Transient Correction	4 Hr / Daily
Total	1.0 %	0.7 % / 0.3 %	1.2 % / 1.0 %	<0.2 %	0.3 %	0.3 %	1.5 % / 1.3 %
SW	1.3 %	1.0 % / 0.4 %	1.7 % / 1.4 %	1 %	0.3 %	0.3 %	2.1 % / 1.8 %
NIR	3.5 %	4.2 % / 1.7 %	5.5 % / 3.9 %	1 %	0.3 %	0.3 %	5.6 % / 4.1 %

Table 2 NISTAR Uncertainty Budget

The contributions to NISTAR uncertainties are from both the on-orbit measurements and the ground calibrations. For all three radiometers, the uncertainties are dominated by the total on-orbit instrument noise, which is a quadrature sum of instrument noise during the Earth view and the background space view.

The noise of the background space view is estimated based on the 2-hour dark space calibrations performed monthly[2]. For the 4-minute shutter period, a 2-hour dark space view contains approximately 13 independent measurements. The standard deviation of the 2-hour dark space

[1] The “stable” operation mode means that the following parameters have been unchanged: 4-minute shutter autocycle period, PID (feedback) and precharge (feedforward) settings of receivers and heat sink.

[2] Starting from November 2018, the dark space calibration is extended to 3.5 hours to adapt to EPIC’s winter schedule, which further reduces the uncertainty a little bit. A few other special tests also include dark space calibrations longer than 2 hours.

calibration is about 20 nW, which corresponds to an uncertainty in the mean of 5 to 6 nW. The measured dark backgrounds of the total channel are fit to the heater power of the heat sink in a 12-month window, see Section 2.6; and the residual error of the fit corresponds to approximately 1 % of the nominal Earth signal in the total channel. For the filtered channels, the dark background is taken as the average value over a 3-month window due to its long-term stability, see Section 2.6, which reduces the uncertainty by a factor of √3.

The noise of the Earth view is calculated from the 4-hour or the daily averages of the Earth view signal. The total instrument noise and the total uncertainty are also calculated based on these two different average periods. Users should note that the total uncertainty calculated in here assumes no data loss in the averaging window.

The uncertainty in the responsivity has a component from the absolute ground calibration, on-orbit stability monitoring, and a correction to the ESR servo response. The first component includes the uncertainties in both the ESR responsivity and the filter transmission. For the two filtered channels, the uncertainty of the filter transmission dominates. On-orbit cavity and filter inter-comparisons are consistent with minimal differential degradation of the ESRs and filters. The uncertainty due to stability of the on-orbit scale is taken to be the uncertainty in the on-orbit inter-comparisons, or about 0.3%. The uncertainty in the servo-response correction is 0.3%, see Section 2.2 below.

2.2 SERVO-SETTLING ERROR CORRECTION

There is a transient in the ESR response following the abrupt change in signal that occurs after a change in the shutter state. The transient causes a small but significant error in the demodulated power. Normally such shutter induced changes in signal are anticipated by the instrument via its feedforward settings, and the effect of any transients induced by the relatively slow servo response is negligible. However, the servo feedforward was not properly configured, which resulted in a significant overshoot in the servo response after each shutter transition. The resulting instrument response differs from a square wave, which it was during calibration in the laboratory. This difference results in a slightly higher demodulated signal than during calibration. The non-square wave response (the overshoot) in the background-subtracted signals is normally obscured by both instrument noise and another non-square wave transient, which is purely a background effect that is subtracted using observations of dark space. It is only after background subtraction and significant averaging of data spanning numerous backgrounds, that the small deviation from a square wave is observable, see Figure 1, and a quantitative analysis of the transient error becomes viable. The analysis involves co-adding many waveforms spanning approximately 1.5 years to reduce noise levels which are dominated by the background measurements made while NISTAR views dark space.

Figure 1 shows the co-added background-subtracted waveforms, i.e., the Earth power measured in the total, shortwave and near-infrared channels. Each square wave contains 260 seconds of data points that exceed a full period by a few seconds. The background-subtracted waveforms shown are averages of a subset of data collected from February 2017 to October 2018. This period includes 20 monthly dark space calibrations and an extra, special test that contains 48 of Channel-B space view and 72 hours of Channel-A space view. The Earth view data are co-added over a time period of approximately one day either on the day prior to or following that of the corresponding dark space observation. The Earth power is determined from fit to the solid blue lines, where the lines are constrained to be horizontal, and the vertical difference between them, the Earth power, is a fit parameter. Note that the dashed blue lines are an extrapolation of the fit (solid blue lines) which begins at about 50 seconds after the shutter transitions to avoid the influence of the initial transients.

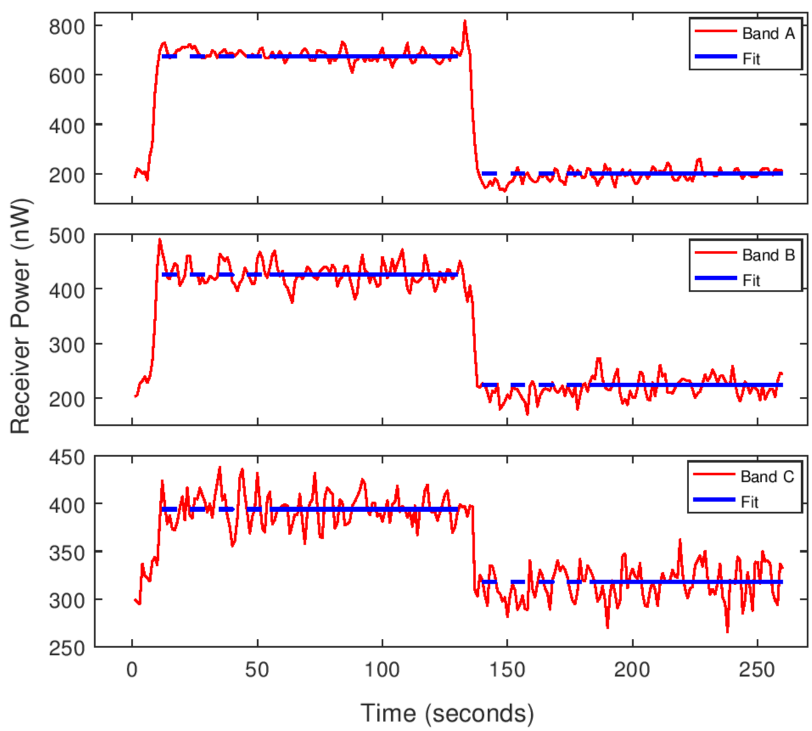

Figure 1 Background-subtracted receiver power as a function of time over a single shutter cycle for Bands A, B and C. The blue lines are a fit to a square wave using only the data corresponding in time with the solid line. Data following a shutter transition is not used for the fit to avoid settling transients.

By comparing the amplitude of the co-added, background-subtracted waveforms determined by the line fit and separately by demodulation, a correction factor for 4-minute shutter cycle data has been determined. The determination includes more data than was averaged to generate

Figure 1. The correction factor, which affects all the data collected with a 4-minute cycle, is approximately 0.982 with an uncertainty of 0.003. Note that this correction does not apply to the 4-minute cycle data before February 2017 due to the use of differing PID parameters.

2.3 DEMODULATION PHASE ERROR CORRECTION

Demodulation of the radiometer signals is part of Level 1B processing. The demodulated signals depend on the phase of the reference signal, which is determined by the shutter position and is nominally a square wave. The demodulation algorithm uses the shutter position telemetry, which is the commanded position of the shutter, for demodulation. However, there is a small but noticeable time-dependent phase shift between the total channel response and the reported shutter position. The phase shift is small in magnitude, however, its time dependence combined with the very large background component in the total channel signal potentially induces significant noise in the background subtracted signal. Correcting the phase shift significantly reduces any impact of its variability.

In nominal operation, the phase of the total channel radiometer power lags the shutter position by more than 1 second. The lag time consists of a constant offset, which is approximately 1.2 – 1.3 seconds, and a time-dependent component (jitter) of approximately +/-0.2 seconds. Comparison of the shutter reference of the remaining channels with the total channel shutter is consistent with similar behavior. And the investigation on the lag time in the other channels during receiver intercomparisons, where all three channels are unfiltered and therefore yield a response of square waves, indicates the same result. Therefore, the jitter is believed to be primarily a phase shift between in the actual and reported shutter positions for all channels. Note that the phase jitter and lag is should not affect the two filtered channels as their background signals are much smaller than the total channel. As shown in Fig. 2, the lag time is consistent over the past 2 years.

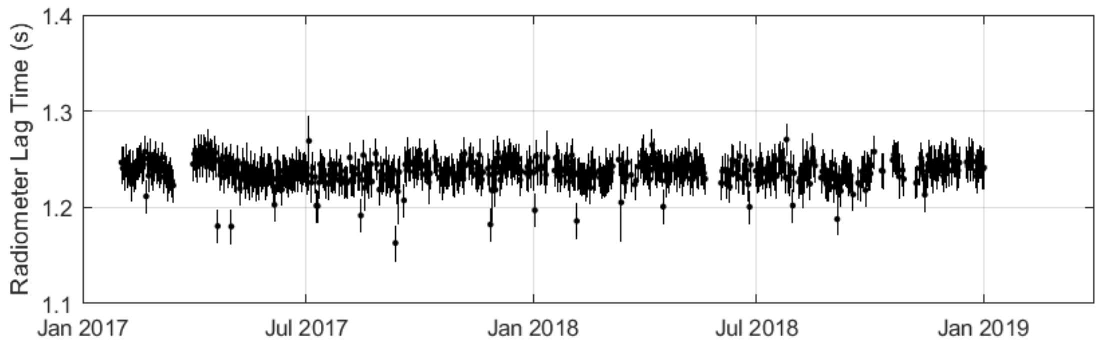

Figure 2 The daily average lag time of the total channel radiometer power during the past 2 years. This result excludes outliers due to spacecraft operations and anomalies.

If the phase shift varies minimally during a month, i.e., in-between background measurements, then the existing phase jitter in combination with the phase lag, should not induce significant measurement noise. Correcting the phase shift in processing, ensures that the jitter occurring over any time scale will contribute insignificantly to measurement noise in the total channel. Note that even without a phase correction noise from the jitter is insignificant in the filtered channels. For the Version 2.1 release the radiometric data with 4-minute shutter autocycle is corrected with the constant phase error (approximately 0.03 radian) removed for all the channels.

It should be noted that the lag time can increase up to 3 – 4 seconds due to certain anomalies such as shutter BIT failure, in which the case the radiometric data is filtered out rather than corrected.

2.4 RECEIVER RESPONSIVITY

By the principle of electronic substitution, NISTAR measures the optical power incident on the receiver, by monitoring the heater power required to maintain the receiver at a constant temperature. Changes in receiver heating from the optical power incident upon it are compensated by corresponding changes of opposite sign in the electrical power delivered to the receiver heater. As a result, there exists a scaling factor (inverse gain), known as the receiver responsivity, which converts changes in optical power to opposite changes in electric power. This scaling factor when multiplied by the measured area of the aperture in front of the receiver, provides the ratio of incident optical irradiance to nominal receiver heater power. Although it is associated with the receiver, it is taken as the radiometer irradiance responsivity, measured during calibration with a source of known irradiance, divided by the aperture area. The responsivities, as well as the corresponding uncertainties, are measured during ground calibration using a calibration light source at a wavelength of 532 nm.

The Earth outgoing irradiance data in L1B processing is given by

$$Earth\ Irradiance = -\frac{\mathcal{D}\{Earth\ View\} - \mathcal{D}\{Space\ View\}}{R},$$

where D{} indicates demodulation and its argument indicates whether the instrument views Earth or dark space (a background measurement), and R is the irradiance responsivity. The numerator is the background-subtracted demodulated nominal power of the receiver heater, i.e., the difference between Column 2 & 3 in the datasets *L1B → Earth_Irradiance → Bandx_EarthIrradiance*. The denominator R is the product of the responsivity and the aperture area of the receiver, as known as "receiver irradiance responsivity". These two datasets can be found in *L1A or L1B → Ground_Calibration → ReceiverPowerResponsivity* and *PrimaryApertureDimensions.*

The uncertainty of responsivities from ground calibration is 0.12 % (k = 1). The long-term on-orbit calibration of the receiver responsivities, known as receiver intercomparison, measures the relative receiver response on a quarterly basis to monitor differential stability. The results show that the ratio between the Earth irradiance in the same band (usually Band A), when measured by each two radiometers (RC1:RC2, RC2:RC3 and RC3:RC1), is very close to unity to within a few tenths of a percent. The fluctuations of the ratio are within the uncertainty set by the background measurement.

Note that In the Version 2.1 data, the receiver responsivity data are based on the ground calibration of 2010 instead of the 2013 calibration, which was used for prior records and is believed to be flawed.

2.5 FILTER TRANSMISSION

The NISTAR Level 1B Earth irradiance data product is purely derived from instrument data collected on-orbit and ground calibration. The Earth radiance data in the SW and NIR bands is measured with the filters placed in front of the receiver cavities. Relating the radiance measured by the receivers to the actual SW and NIR outgoing Earth radiation in the direction of DSOVR requires both knowledge of the filter wavelength-dependent transmittance and spectrum of the incident radiation. Therefore, the unfiltered radiance or flux in these bands, which is relevant to the study of Earth's climate, is not included in the L1B product. To calculate the unfiltered irradiance/radiance, the spectral transmission function of the filter needs to be weighted by the spectral distribution of the Earth irradiance and then averaged. The spectral irradiance distribution of the Earth is time and scene dependent, e.g., ocean vs. land vs. snow/ice surface and clear vs. cloudy sky; therefore, it must be determined from outside sources, such as EPIC and other Earth-observing satellites.

While the L1B data product does not include this correction, the spectral transmission functions of all SW and NIR band filters are provided for users to incorporate into their analysis. The data can be found in *L1A or L1B → Ground_Calibration → FilterBTransmissionCurves/ FilterCTransmissionCurves*. This dataset contains the table of filter transmission curves covering 200 nm to 18 μm for each of the 3 filters (3 Band B filters and 3 Band C filters). The field names correspond to the code *xyz* where *x* = wheel position (1-12), *y* = filter band (A-C) and *z* = the number of the filter. 7B1 and 1C1 are the nominal filters in use, see Figure 3.

Starting from Version 2.1 data, the filter transmission curves are based on the system-level filter transmittance measured in 2010 at NIST in-lieu-of the 2013 calibration which is believed to be flawed.

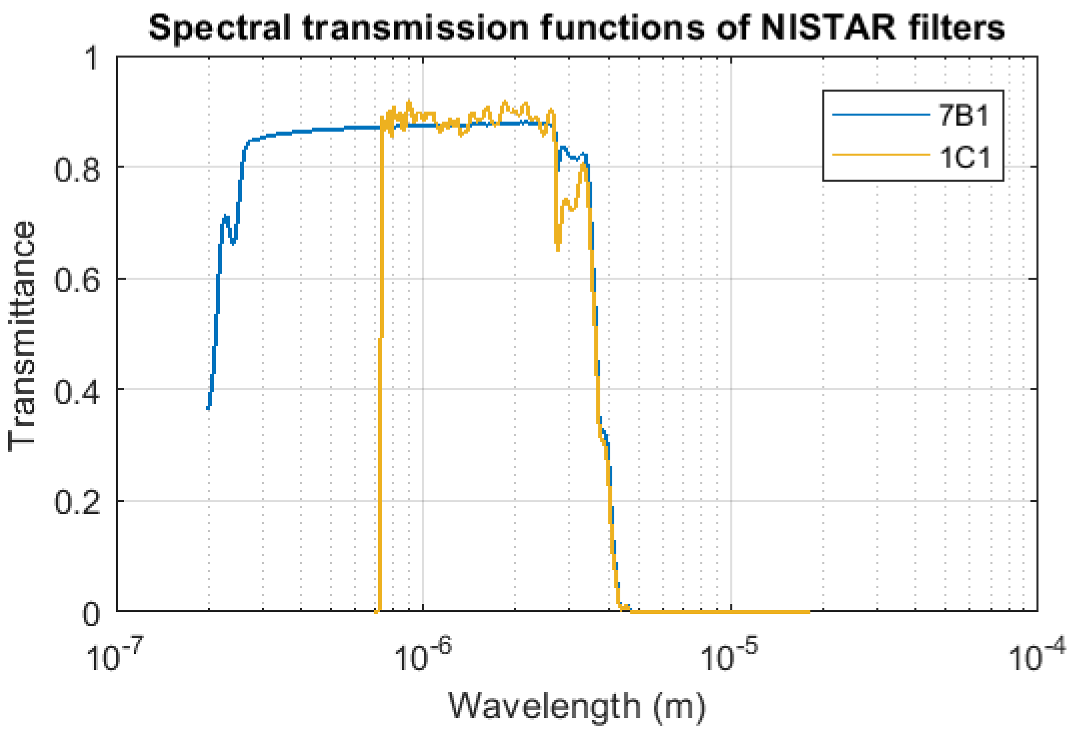

Figure 3 2010 spectral transmission curves for the 7B1 and 1C1 filters, which are in front of Receiver Cavities 3 and 1 during normal operations, respectively.

2.6 INTERPOLATION OF THE BACKGROUND MEASUREMENT

There are a few calibration tables which are updated periodically and rolled into the L1B processing algorithms, particularly the dark background radiometer measurements. Unless there has been a special test, such background measurements have occurred monthly while the instrument views dark space. However, the background measurement in the total channel tends to change throughout a month, and a simple linear interpolation, which was used earlier, has been found to be inadequate.

The updated interpolation algorithm is as follows: The monthly calibrations are first interpolated into an intermediate background data product, as discussed in detail below, which has a 2-hour cadence and is written into the on-orbit calibration dataset (*L1A or L1B → On-orbit_Calibration → RadiometerDarkPower*). During the final L1B data processing, the 2-hour intermediate background data is linear interpolated into the 1 second data rate. The following paragraphs detail how the intermediate background data is generated.

For the total channel, the shutter-modulated IR background is relatively large and depends on the temperature of the shutter and other structures within the instrument that are not actively temperature-controlled. Although uncontrolled parts of the instrument are relatively stable in temperature, there are none-the-less significant changes in the background from month-to-month. The monthly background changes correlate well both with the measured temperature of some uncontrolled structures, e.g. the shutter motor, as well as with the power required to maintain the heat sink at constant temperature, which changes inversely with the temperature of surrounding structures. As a result, the heat sink power is used as a proxy to track changes in the total channel background that occur in between monthly calibrations. Note that other temperature sensors within the instrument can also be used for the same purpose. To establish a relationship between the total channel background and the heat sink power, the latter is scaled and offset to match the former, see Figure 4. Specifically, the scale factor and offset are adjusted to minimize the sum of the squares of the differences between the heat sink power and background ESR measurements collected over a running 12-month window, with the first window covering February 2017 to February 2018. Therefore, the processing of the total channel usually has a latency of up to 1 month.

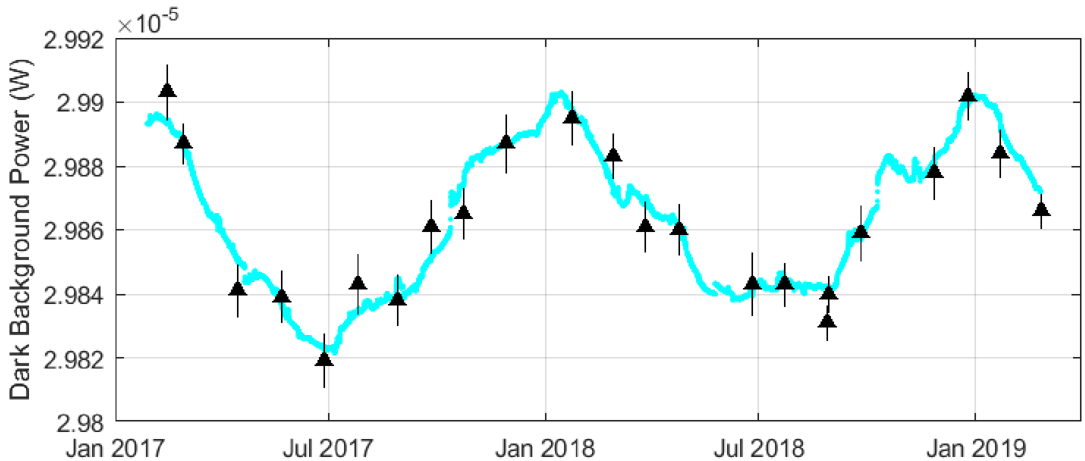

Figure 4 The monthly dark space calibration of the total channel and the interpolated dark background, which is derived by scaling and offsetting the heat sink power.

The estimate of the uncertainty in the background of the total channel is derived from the residual of the heat sink fit. For N measurements of the background in a 12-month window, if the 2-hour averaged heat sink power is given by $P_{\mathrm{HS}}(t)$, and the scale factor and offset are α and β, respectively, the uncertainty, σ_{Total}, is given by

$$\sigma_{\mathrm{Total}} = \sqrt{\frac{\sum_i^N (P^{\mathrm{Cal}}{}_i - P^{\mathrm{Model}}(t_\mathrm{i}))^2}{N-2}},$$

where $P^{\mathrm{Model}}(t) = \alpha P_{\mathrm{HS}}(t) + \beta$ and t_i is the time when the ith dark space calibration is taken.

For the filtered channels, the IR background is much more stable because the filters block the shutter modulated infrared light from reaching the detector, and infrared emissions from the filters are subtracted, in effect, every shutter cycle using the demodulation algorithm. In this case, knowledge of the dark background is limited by the instrument noise—determined by the nominal 2-hour dark space view. The background is therefore taken as the average value over a 3-month window, which reduces the instrument noise by a factor of √3. Specifically, linearly interpolated monthly background measurements are averaged over a 3-month running window, see Figure 5. This not only produces a latency up to 1 month but also leaves the latest 1.5 months of dark space offsets at a constant value due to lack of data for the 3-month window averaging. The user should be aware that the beginning 1.5 months (February-March 2017) L1B Earth irradiance data of the filtered channels may be less accurate due to this processing lag.

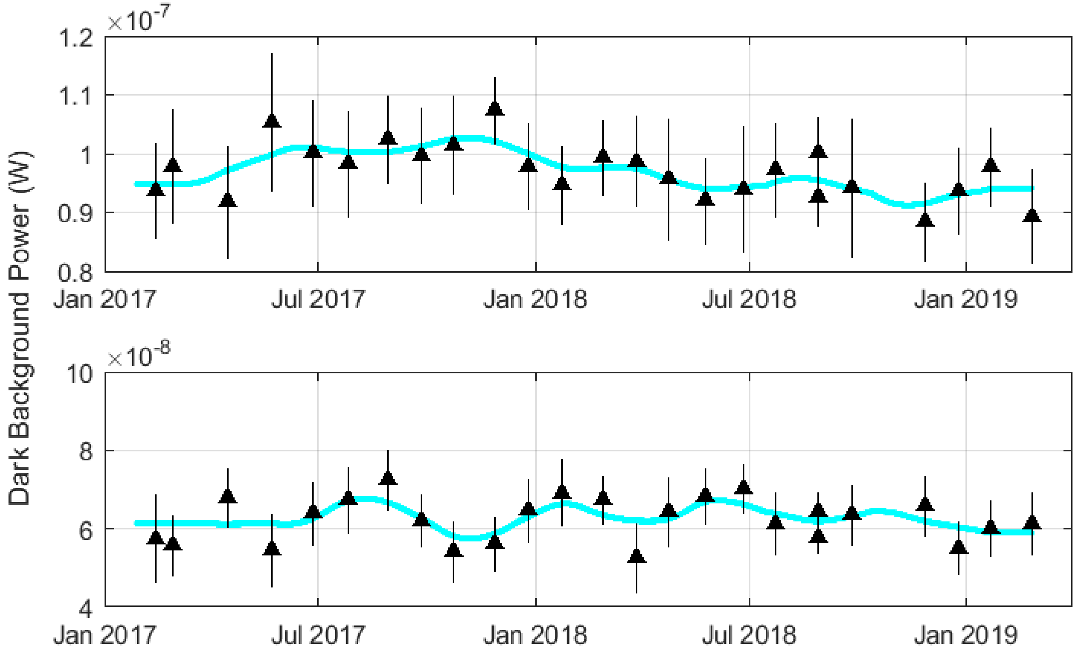

Figure 5 The monthly dark space calibration of the filtered channels (top: short wave; bottom: near-IR) and the interpolated dark background, which is derived by averaging the linear interpolated data over a 3-month running window.

III. DIGITAL FILTERING AND DATA INTERPOLATION

3.1 OVERVIEW

Starting in NISTAR Version 3 data products, two data quality issues have been addressed by changes in the processing software. These include:

- Implementation of a new noise-reduction low-pass filter applied to the L1B Earth radiance data product. The filtered radiance data is stored in an additional monthly data product.

- Addition of interpolation schemes for gaps with moderate lengths. The filling methods vary for different levels of processing and different spectral channels.

3.2 DIGITAL FILTER FOR L1B EARTH RADIANCE

The L1B Earth radiance data product with the full-time resolution carries excess high-frequency (> 0.1 mHz) noise, which is not informative to end users. Although users may average the data on their own or use the 4-hour running averages provided to reduce noise levels, the running average has its own limitations: The transfer function of a running average filter is a sinc function, which yields slow roll-off and poor attenuation in the stopband. As a result, for example, the 4-hour running average attenuates temporal components of the Earth radiance of potential scientific interest in order to achieve noise reduction.

Therefore, a more optimal filter with a steep slope and a maximally flat passband has been developed to solve both issues above. For numerical efficiency, the filter is implemented recursively as an infinite impulse response (IIR) filter. And, to eliminate the frequency-dependent phase distortion, the input data is filtered in both forward and reverse temporal directions, which is known as forward-backward filtering. It should be noted that this process squares the original transfer function and doubles the filter order.

The passband frequency of the filter is determined by comparing the spectrum of the shortwave band with the photodiode channel, which has a very high SNR. Figure 6 shows the spectrum of the NISTAR shortwave radiance (red) and the photodiode current (blue). The spectrum of the photodiode current features three major peaks (11.6 μHz, 23 μHz, 35 μHz) and two minor (46 μHz, 58 μHz) peaks that are at least an order of magnitude lower. The spectrum of the shortwave radiance has some similar, albeit broader, major peaks below 50 μHz, and, by contrast, significant noise at higher frequencies, which would obscure any minor peaks analogous to those in the photodiode spectrum. These observations provide a basis for the transfer function of the filter, which is designed to maintain frequency components of the Earth signal of interest, i.e., the major peaks below 50 μHz, while strongly suppressing the noise at higher frequencies.

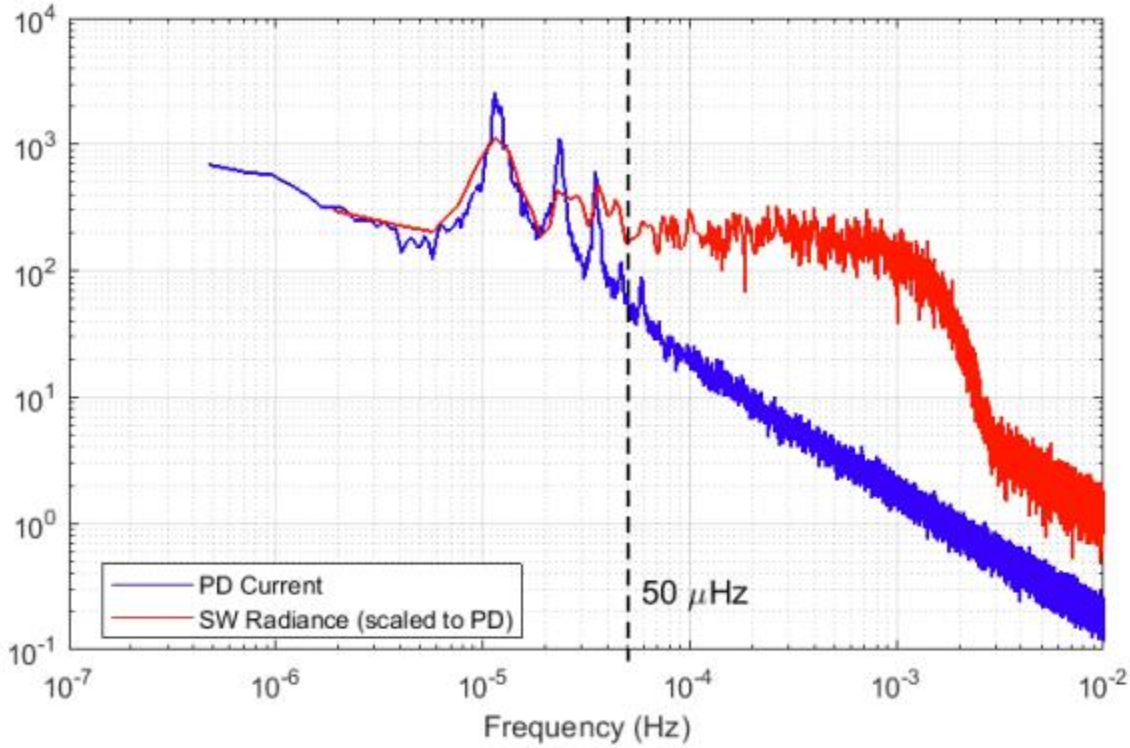

Figure 6 The spectrum of the photodiode current and the shortwave radiance derived from the NISTAR L1B data product. The filter is designed to suppress the noise above 50 µHz, see the vertical line, while minimally attenuating lower frequencies.

The design of the digital filter is based on a 4th-order Chebyshev Type II filter with a sampling frequency of 0.1 Hz (vs 1 Hz) to reduce numerical rounding errors. The implementation of the filter employs the direct form type II, with initialization chosen to minimize transients following a large data gap. The filter resets in the presence of a sufficiently large temporal gap (see next section), whereby the initial output values are set equal to the mean of input data within first 3 hours, which is comparable to the temporal length of the impulse-response of the filter.

The input data is filtered in both the forward and reverse temporal directions to zero out the phase shifts, which squares the transfer function of the Chebyshev filter. The effective transfer function of the implemented filter, which yields a gain of 0.97 at 35 µHz, and its noise suppression performance is shown in Figure 7.

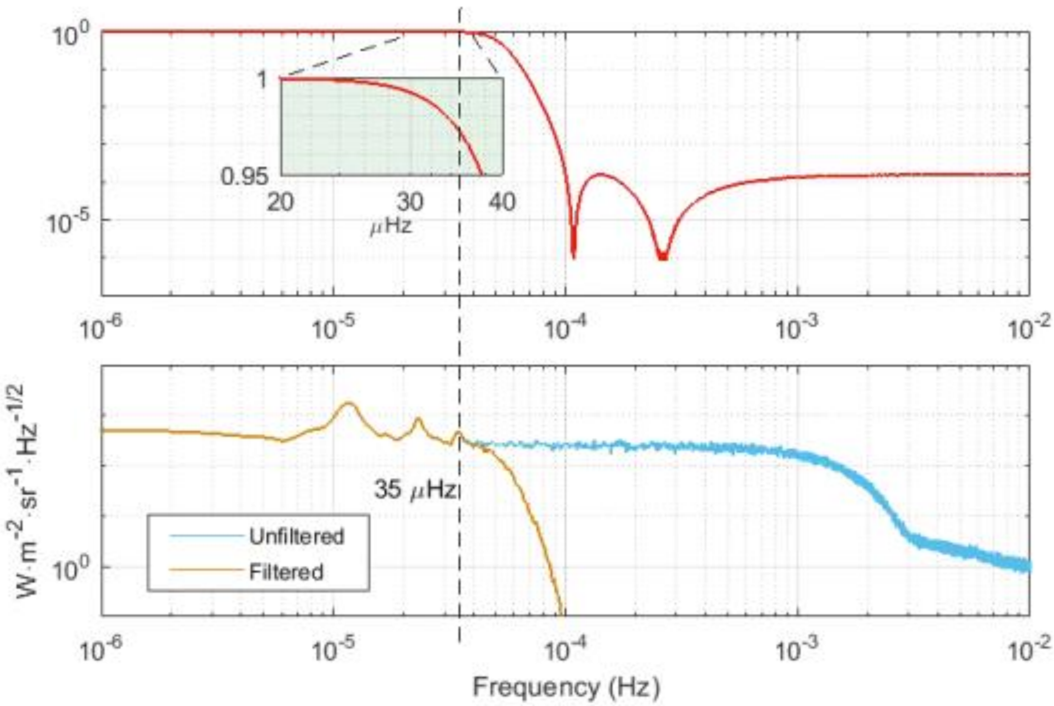

Figure 7 (Top) the transfer function of 2-way 4th-order Chebyshev Type II filter, which has gains of approximately 0.97 at 35 µHz (also shown in the zoom-in window) and 10^{-4} in the stopband. (Bottom) the spectrum of unfiltered and filtered Earth SW radiance. The three major peaks of the Earth signal are well maintained in the passband.

3.3 DATA INTERPOLATION SCHEME

NISTAR's Earth radiance data contains frequent gaps due to missing telemetry and spacecraft activities. Therefore, the radiometric data cannot be filtered continuously. A survey of the 2017-2018 science data indicates that most gaps are relatively short: about 90% are less than one shutter period (256 seconds) and about 97% are less than 1 hour, interpolating through gaps with moderate lengths significantly reduces the number of artifacts due to demodulation and filter resets, while having a negligible impact on accuracy.

3.3.1 Level 1A

Interpolation of level 1A data has been previously limited to gaps less than 6 seconds, however, there are numerous larger gaps that are short enough to warrant interpolation given the relatively slowly changing earth signal. Gaps of up to 4 shutter periods in length are now removed via interpolation prior to demodulation.

- For gaps less than 6 seconds, the processing software linearly interpolates across the gaps during the process of selecting the Earth view data (for both radiometer and photodiode). The interpolation label for this kind of data is 1.

- For gaps greater than or equal to 6 seconds but less than 4 shutter periods, since the Earth signal does not change much on that time scale, it is possible to estimate the missing L1A data by averaging data from adjacent shutter periods, which is illustrated in Figure 8. The interpolation label for this case is 2.

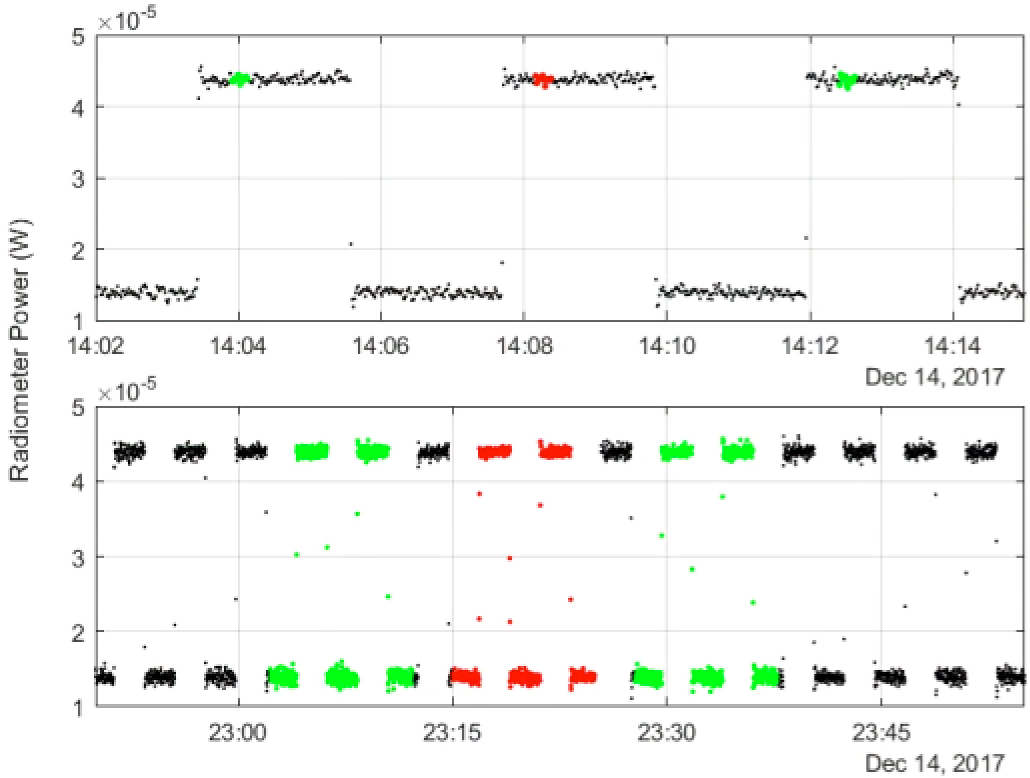

Figure 8 The interpolation method for gaps (at the position of red points) in the L1A radiometer data: (top) gap length less than half shutter period; (bottom) gap length greater than one shutter period. The values of interpolated data are estimated using the average of the data in corresponding segments of the adjacent shutter cycles (green).

3.3.2 Level 1B

In Level 1B processing, only gaps in the shortwave radiance data are interpolated. Due to the similarity in the time series between the shortwave and photodiode channels, the photodiode current data is exploited to fill gaps in the shortwave radiance during the same time interval provided the gap is less than 2-hours.

In addition, any gaps less than 2 hours in the photodiode current are also filled using a 3rd order polynomial fit, which interpolates the gap using prior and subsequent data within 1 hour of the gap. The interpolation label for this kind of photodiode data is 2. Then, the corresponding gap in the shortwave channel is estimated by scaling the photodiode current to the shortwave data. The scaling factor is determined by the ratio of the two channels' average value in the 1-hour time intervals on either side of the gap. The value of the interpolation label for this kind of data is 3. The interpolation procedure is shown in Figure 9.

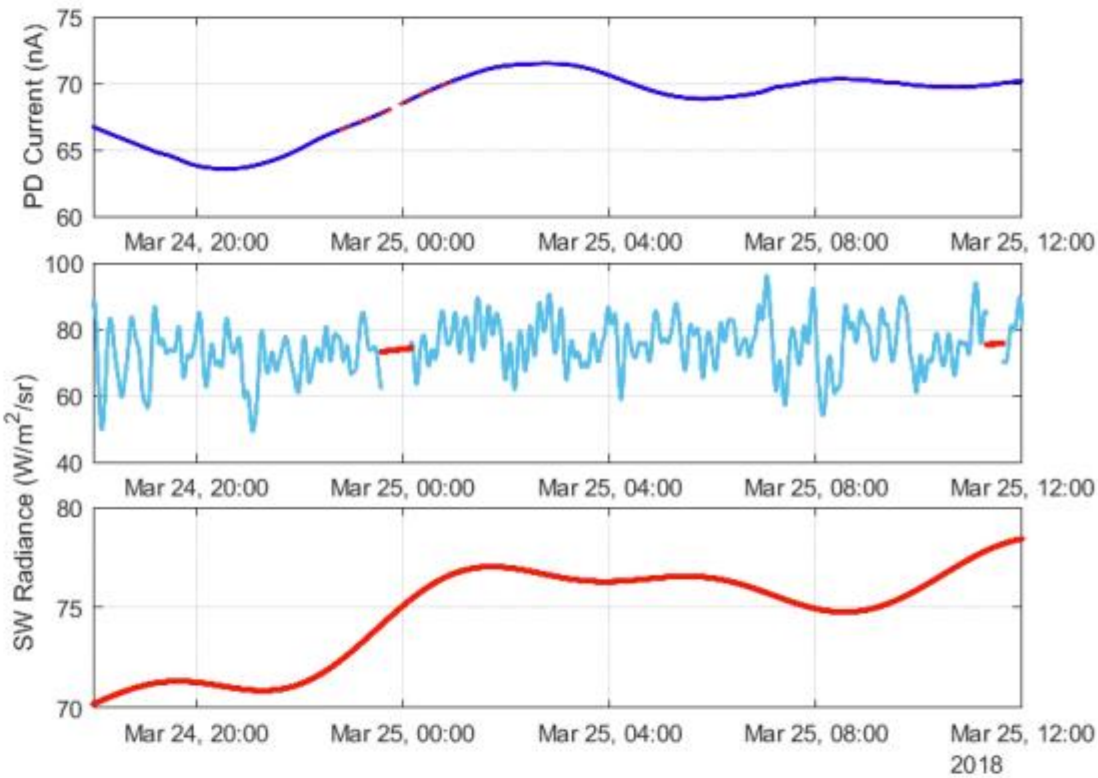

Figure 9 The procedure of interpolating gaps in L1B shortwave radiance data using the photodiode current: (top) Gaps in the photodiode data are interpolated by applying a 3rd order polynomial fit to the adjacent data (the red dashed line); (middle) Gaps in the SW radiance data are interpolated with the scaled photodiode current data (the red dots); (bottom) The filtered output of the interpolated SW radiance data in the middle.

IV. REFERENCES

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Analysis of the NISTAR On-orbit Absolute Radiometric Scale, Allan W. Smith, Yinan Yu and Steven R. Lorentz, 2018 American Geophysical Union Fall Meeting