CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

VERSION: 3.0
RELEASE DATE: January 6, 2026

TROPOSPHERIC EMISSIONS: MONITORING OF POLLUTION (TEMPO) PROJECT

Level 1 Data Products: User Guide

January 6, 2026

DOI: 10.5067/doc/tempo/L1UserGuide/V3.0

AUTHORS

Heesung Chong (Center for Astrophysics | Harvard & Smithsonian)

Xiong Liu (Center for Astrophysics | Harvard & Smithsonian)

John Houck (Center for Astrophysics | Harvard & Smithsonian)

David E. Flittner (NASA Langley Research Center)

James Carr (Carr Astronautics)

Weizhen Hou (Center for Astrophysics | Harvard & Smithsonian)

Raid M. Suleiman (Center for Astrophysics | Harvard & Smithsonian)

Kelly Chance (Center for Astrophysics | Harvard & Smithsonian)

CONTRIBUTIONS:

TEMPO Science Team, Center for Astrophysics | Harvard & Smithsonian

TEMPO Ground System Team, Center for Astrophysics | Harvard & Smithsonian

NASA Langley Research Center

BAE Systems, Inc.

REVISION HISTORY

Version	Item	Description	Release date
1.0	All	Initial version	February 26, 2024
1.1	All	Revision made to describe the new Version 3 products (including the addition of the RADT product)	May 20, 2024
1.2	Sections 2, 3.2, and 5	- Validation status updated to 'Provisional' - Level 1 performance assessment updated and reflected (Section 5) - Variable descriptions enhanced	December 6, 2024
2.0	All	Revision made to describe the new Version 4 products	September 15, 2025
3.0	All	Revision made to describe the new RADT Version 4 product, as well as minor updates to the other Version 4 products	January 6, 2026

PRODUCT and SCIENCE DATA PROCESSING CENTER PIPELINE VERSION

Product Version Designation	Science Data Processing Center Pipeline Version	Release
V03	4.4.0	May 20, 2024; first public release of TEMPO Level 2 and Level 3 products
V04 NRT V02	4.7.0	September 17, 2025; TEMPO standard version 4 and NRT version 2
V04 NRT V02	4.8.0	January 6, 2026; TEMPO standard version 4 and NRT version 2 (mid-version minor updates)

Contents

1. Introduction

The Tropospheric Emissions: Monitoring of Pollution (TEMPO) is a geostationary satellite mission to monitor air quality over North America (Zoogman et al., 2017). This User Guide document provides a quick guide for the TEMPO Level 1 Version 4 products. Detailed descriptions of the Level 0-1 processing procedures can be found in the algorithm theoretical basis document (ATBD) (Chong et al., 2025). The post-processing for the Version 4 RADT product has been updated since the work of Carr et al. (2025). The background subtraction has been improved, especially at ultraviolet wavelengths. Detailed descriptions of the methodology will be provided through a separate documentation. This document introduces how to model the subtracted background.

The Level 1 products are generated by the Science Data Processing Center (SDPC) at the Smithsonian Astrophysical Observatory (SAO). All products are pushed to the NASA Atmospheric Science Data Center (ASDC) from SAO after production by SDPC. If any special activities or issues arise in operations or Level 1 file production, they are documented in the Operations Log (https://github.com/Smithsonian/TEMPO-Observations-log/blob/main/daily_log.md). Activities during the commissioning period (June 07, 2023 – October 16, 2023) are listed in the Commissioning Log (https://github.com/Smithsonian/TEMPO-Observations-log/blob/main/TEMPO_Daily_Log_during_Commissioning.md).

TEMPO products are in the commonly-used, self-explanatory NetCDF format. The content of a NetCDF file can be listed by the command “ncdump -h {FILENAME}” on Linux systems or explored on a graphical interface using the software “Panoply,” distributed by NASA Goddard Institute for Space Studies (https://www.giss.nasa.gov/tools/panoply/).

2. Algorithm Overview

The TEMPO Level 1 (L1) products collectively refer to dark exposure (DRK, L1a), solar irradiance (L1b), and geolocated Earth radiances (L1b). Solar irradiance data has two types, depending on the diffuser selection: working (IRR) and reference (IRRR). Geolocated Earth radiances data also has two types: nominal (RAD) and twilight (RADT), with the latter aiming to capture city lights, nightglow and aurorae, moonlit clouds, gas flares, and lightning. RADT scans are performed on the dark side of a partially illuminated Earth, earning the "twilight" moniker.

The DRK, IRR, IRRR, and RAD products are part of the TEMPO baseline products, while the RADT product was developed additionally for nighttime Earth observations. The Version 4 baseline products were released on September 15, 2025. The Version 4 RADT product has been upgraded to allow users to utilize the data without an additional post-processing step and was released on January 6, 2026. This document covers an overview of the Version 4 RADT processing.

Table 1 summarizes the main features of the TEMPO Level 1 products, including the nominal sampling frequencies. The DRK exposure typically occurs before the beginning of the other types of exposure and after the end of daylight RAD measurements. Therefore, it has a variable sampling frequency. The nominal Earth scanning frequency is one hour during most daylight hours; the frequency may be higher for optimized scans in the early morning in eastern North America and the late afternoon/evening in western North America. Different settings are possible for special observations. The RADT exposure occurs during times that meet the safety constraint (solar boresight angle > 60º) and that are not suitable for nominal radiance scanning (solar zenith angles > 80º throughout most of the field of regard). The twilight time duration supports city lights data collection through ~9 months of the year, with the exception of the months centered around mid-summer (Carr et al., 2017; Carr et al., 2025). The duration is maximum at mid-winter. Exposure times and target areas of the RADT measurements vary depending on the uplink commands. It is recommended that users check the corresponding information when using the RADT data (see Table 5).

The TEMPO Level 0-1 processor was developed from scratch, incorporating elements from existing space-borne hyperspectral spectrometers, including the Ozone Monitoring Instrument (OMI) (Levelt & Noordhoek, 2002; van den Oord et al., 2006), Tropospheric Monitoring Instrument (TROPOMI) (KNMI, 2022), and Geostationary Environment Monitoring Spectrometer (GEMS) (Kim et al., 2020). The algorithm elements of the TEMPO Level 0-1 processor are detailed in the ATBD (Chong et al., 2025). Here, we provide only a brief overview.

The processor first converts digital counts stored in Level 0 data into electric current (in units of electrons s^{-1}), regardless of data type. The DRK processing ends at this stage, while the others are processed further to derive the number of photons (in units of photons s^{-1} cm^{-2} nm^{-1} sr^{-1}). The photon derivation in the IRR and IRRR processing is followed by several steps, including correction for the bidirectional transmittance distribution function (BTDF) of the diffusers, which converts the unit to photons s^{-1} cm^{-2} nm^{-1}, and spectral calibration, to produce irradiance L1b outputs. The RAD processing also employs additional steps after photon derivation, including image navigation and registration (INR) and spectral calibration, to generate geolocated Level 1b outputs. For the RADT product, the Version 4 algorithm employs a two-step processing approach. First, the Level 0-1 processor computes the spectral radiances and assigns nominal geolocations, instead of performing INR, as in the RAD product. Then, in a second step, a reversible background subtraction is performed. A user wishing to recover the original radiances may do so by adding the background described in the NetCDF file to the radiance. Additionally, the geolocations are adjusted using nighttime imagery from the Day/Night Band (DNB) of the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument as reference. It was necessary for the user to perform these post-processing steps themselves with Version 3 as described in Carr et al. (2025). With Version 4, it is no longer required that a user perform post-processing on RADT files to use the data scientifically. The RADT processing does not involve spectral calibration.

Table 1. TEMPO Level 1 products.

Product	Level	Description	Nominal sampling frequency	Validation status
DRK	1a	Dark exposure	Variable (typically sampled before the beginning of the other types of exposure)	Provisional*
RAD	1b	Geolocated Earth radiances	Once per hour or more frequent (during daylight hours)	Provisional*
RADT	1b	Geolocated Earth radiances (twilight)	Variable (sampled during times that meet the safety constraint and that are not suitable for nominal radiance scanning)	Provisional*
IRR	1b	Solar irradiance (working diffuser)	Once per week	Provisional*
IRRR	1b	Solar irradiance (reference diffuser)	Once per 3 months	Provisional*

* Provisional maturity is defined as: product performance has been demonstrated through a large, but still (seasonally or otherwise) limited number of independent measurements. The analysis is sufficient for limited qualitative determinations of product fitness-for-purpose, and the product is potentially ready for testing by operational users and may be suitable for scientific publication.

3. File Descriptions

3.1. Filename Format

Table 2 shows the TEMPO Level 1 file naming convention. The DRK, IRR, and IRRR filenames have a format of

TEMPO_{PPP(P)}_L1_V04_{YYYY}{MM}{DD}T{HH}{NN}{SS}Z.nc,

with YYYY (year), MM (month), DD (day), HH (hour), NN (minute), and SS (second) denoting the GMT time stamp at the beginning of the time period covered by the file. The segment PPP(P) represents the product type. (Note that the curly brackets are added here for display purposes; they do not exist in actual filenames.)

The TEMPO RAD and RADT filenames have a format of

TEMPO_{PPP(P)} _L1_V04_{YYYY}{MM}{DD}T{HH}{NN}{SS}Z_S{XXX}G{YY}.nc,

where XXX and YY denote the scan and granule numbers, respectively.

Table 2. TEMPO Level 1 file naming convention.

Product	Filename format
DRK, IRR, IRRR	TEMPO_{PPP(P)}_L1_V04_{YYYY}{MM}{DD}T{HH}{NN}{SS}Z.nc
RAD, RADT	TEMPO_{PPP(P)} _L1_V04_{YYYY}{MM}{DD}T{HH}{NN}{SS}Z_ S{XXX}G{YY}.nc

3.2. Key Variables

The TEMPO instrument has two charge-coupled device (CCD) detectors: one covering the spectral range of 290–490 nm and the other covering 540–740 nm. Each has 1028 photoactive spectral pixels. For simplicity, we refer to them as ultraviolet (UV) and visible (VIS) CCDs, respectively. Spatially, each CCD has 2048 photoactive pixels. Within the fields of regard for Earth exposure, lower and higher spatial indices are projected on the northern and southern areas, respectively.

With the two CCDs combined, the TEMPO focal plane array (FPA) consists of 2056 × 2048 photoactive pixels. The DRK product provides measurements at these combined dimensions. In this case, the spectral dimension aligns wavelengths in descending order from VIS to UV.

For the IRR, IRRR, RAD, and RADT products, the two CCD measurements are provided separately. In the NetCDF files, they are stored in groups named "band_290_490_nm" (UV) and "band_540_740_nm" (VIS). Besides, the spectral dimension is rearranged in ascending wavelength order.

3.2.1. DRK, IRR(R), and RAD Products

Tables 3–5 present key variables in the DRK, IRR(R), and RAD products, respectively. Figure 1 presents the coordinate system where zenith and azimuth angles are defined for the RAD product. The definition of each bit of the "pixel_quality_flag" variable (in all products) and that of "ground_pixel_quality_flag" variable (in the RAD product) are described in Tables 6 and 7, respectively. Table 8 provides descriptions of the variables under the group "cloud_mask_group" in the RAD product. See Section 3.3 for detailed descriptions of the "wavecal_params" variable in the IRR, IRRR, and RAD products.

Table 3. Key variables in the DRK product. The values of the dimension variables 'row' and 'col' are 2056 and 2048, respectively. The value of the 'time' variable is 1 for the average dark current and corresponds to the number of frames for per-frame dark current.

Group	Name	Format (dimension)	Unit	Description
-	image	float (time, row, col)	electrons s^{-1}	Average dark current for multiple frames
-	pixel_quality_flag	uint (time, row, col)	-	Pixel quality flag for average dark current
-	image_start_time	double (time)	seconds since 1980-01-06T00:00:00Z	Mean exposure start time for multiple frames
frames	image	float (time, row, col)	electrons s^{-1}	Dark current for each frame
frames	pixel_quality_flag	uint (time, row, col)	-	Pixel quality flag for each frame
frames	image_start_time	double (time)	seconds since 1980-01-06T00:00:00Z	Exposure start time for each frame

Table 4. Key variables in the IRR and IRRR products. The values of the dimension variables 'mirror_step,' 'xtrack,' and 'spectral_channel' are 1, 2048, and 1028, respectively. The 'wavecal_par' variable represents the number of Chebyshev polynomial coefficients, and its value varies depending on configuration (see Section 3.3).

Group	Name	Format (dimension)	Unit	Description
band_290_490_nm	irradiance	float (mirror_step, xtrack, spectral_channel)	photons s^{-1} cm^{-2} nm^{-1}	Solar irradiance (UV CCD)
band_290_490_nm	irradiance_error	float (mirror_step, xtrack, spectral_channel)	photons s^{-1} cm^{-2} nm^{-1}	Solar irradiance error (UV CCD)
band_290_490_nm	pixel_quality_flag	ushort (mirror_step, xtrack, spectral_channel)	-	Pixel quality flag (UV CCD)
band_290_490_nm	nominal_wavelength	float (xtrack, spectral_channel)	nm	Wavelength (UV CCD)
band_290_490_nm	wavecal_params	float (mirror_step, xtrack, wavecal_par)	-	Wavelength calibration parameters
band_540_740_nm	irradiance	float (mirror_step, xtrack, spectral_channel)	photons s^{-1} cm^{-2} nm^{-1}	Solar irradiance (VIS CCD)
band_540_740_nm	irradiance_error	float (mirror_step, xtrack, spectral_channel)	photons s^{-1} cm^{-2} nm^{-1}	Solar irradiance error (VIS CCD)
band_540_740_nm	pixel_quality_flag	ushort (mirror_step, xtrack, spectral_channel)	-	Pixel quality flag (VIS CCD)
band_540_740_nm	nominal_wavelength	float (xtrack, spectral_channel)	nm	Wavelength (VIS CCD)
band_540_740_nm	wavecal_params	float (mirror_step, xtrack, wavecal_par)	-	Wavelength calibration parameters

Table 5. Key variables in the RAD product. The values of the dimension variables 'xtrack' and 'spectral_channel' are 2048 and 1028, respectively. The 'mirror_step' variable represents the number of mirror steps. The value of the 'corner' variable is 4.

Group	Name	Format (dimension)	Unit	Description
-	exposure_time	float (mirror_step)	seconds	Exposure duration
band_290_490_nm	radiance	float (mirror_step, xtrack, spectral_channel)	photons s^{-1} cm^{-2} nm^{-1} sr^{-1}	Earthshine radiance (UV CCD)
band_290_490_nm	radiance_error	float (mirror_step, xtrack, spectral_channel)	photons s^{-1} cm^{-2} nm^{-1} sr^{-1}	Earthshine radiance error (UV CCD)
band_290_490_nm	pixel_quality_flag	ushort (mirror_step, xtrack, spectral_channel)	-	Pixel quality flag (UV CCD)
band_290_490_nm	ground_pixel_quality_flag	uint (mirror_step, xtrack)	-	Ground pixel quality flag (UV CCD)
band_290_490_nm	nominal_wavelength	float (xtrack, spectral_channel)	nm	Wavelength (UV CCD)
band_290_490_nm	latitude	float (mirror_step, xtrack)	degree North (°N)	Latitude at pixel center (UV CCD)
band_290_490_nm	latitude_bounds	float (mirror_step, xtrack, corner)	degree North (°N)	Latitude bounds (NE, NW, SW, SE) (UV CCD)
band_290_490_nm	longitude	float (mirror_step, xtrack)	degree East (°E)	Longitude at pixel center (UV CCD)
band_290_490_nm	longitude_bounds	float (mirror_step, xtrack, corner)	degree East (°E)	Longitude bounds (NE, NW, SW, SE) (UV CCD)
band_290_490_nm	solar_azimuth_angle	float	degree (°)	Solar azimuth

		(mirror_step, xtrack)		angle (UV CCD)
band_290_490_nm	solar_zenith_angle	float (mirror_step, xtrack)	degree (°)	Solar zenith angle (UV CCD)
band_290_490_nm	viewing_azimuth_angle	float (mirror_step, xtrack)	degree (°)	Viewing azimuth angle (UV CCD)
band_290_490_nm	viewing_zenith_angle	float (mirror_step, xtrack)	degree (°)	Viewing zenith angle (UV CCD)
band_290_490_nm	snow_ice_fraction	float (mirror_step, xtrack)	-	Fraction of pixel area covered by snow and/or ice (UV CCD)
band_290_490_nm	terrain_height	short (mirror_step, xtrack)	m	Area-weighted mean terrain height inside each pixel (UV CCD)
band_540_740_nm	radiance	float (mirror_step, xtrack, spectral_channel)	photons s^{-1} cm^{-2} nm^{-1} sr^{-1}	Earthshine radiance (VIS CCD)
band_540_740_nm	radiance_error	float (mirror_step, xtrack, spectral_channel)	photons s^{-1} cm^{-2} nm^{-1} sr^{-1}	Earthshine radiance error (VIS CCD)
band_540_740_nm	pixel_quality_flag	ushort (mirror_step, xtrack, spectral_channel)	-	Pixel quality flag (VIS CCD)
band_540_740_nm	ground_pixel_quality_flag	uint (mirror_step, xtrack)	-	Ground pixel quality flag (VIS CCD)
band_540_740_nm	nominal_wavelength	float (xtrack, spectral_channel)	nm	Wavelength (VIS CCD)

band_540_740_nm	latitude	float (mirror_step, xtrack)	degree North (°N)	Latitude at pixel center (VIS CCD)
band_540_740_nm	latitude_bounds	float (mirror_step, xtrack, corner)	degree North (°N)	Latitude bounds (NE, NW, SW, SE) (VIS CCD)
band_540_740_nm	longitude	float (mirror_step, xtrack)	degree East (°E)	Longitude at pixel center (VIS CCD)
band_540_740_nm	longitude_bounds	float (mirror_step, xtrack, corner)	degree East (°E)	Longitude bounds (NE, NW, SW, SE) (VIS CCD)
band_540_740_nm	solar_azimuth_angle	float (mirror_step, xtrack)	degree (°)	Solar azimuth angle (VIS CCD)
band_540_740_nm	solar_zenith_angle	float (mirror_step, xtrack)	degree (°)	Solar zenith angle (VIS CCD)
band_540_740_nm	viewing_azimuth_angle	float (mirror_step, xtrack)	degree (°)	Viewing azimuth angle (VIS CCD)
band_540_740_nm	viewing_zenith_angle	float (mirror_step, xtrack)	degree (°)	Viewing zenith angle (VIS CCD)
band_540_740_nm	snow_ice_fraction	float (mirror_step, xtrack)	-	Fraction of pixel area covered by snow and/or ice (VIS CCD)
band_540_740_nm	terrain_height	short (mirror_step, xtrack)	m	Area-weighted mean terrain height inside each pixel (VIS CCD)

In the TEMPO Level 1 products, a zenith angle is defined as the angle between an object and the local zenith (see Figure 1). In the RAD product, the variables 'solar_zenith_angle' and 'viewing_zenith_angle' are calculated using the Sun and TEMPO as the respective reference objects (see Table 5). Both angles are zero at the local zenith.

An azimuth angle is defined as the horizontal angle measured from true north. Clockwise (eastward) and counterclockwise (westward) directions correspond to positive and negative azimuth angles, respectively (see Figure 1). In the RAD product, the variables 'solar_azimuth_angle' and 'viewing_azimuth_angle' are calculated using the Sun and TEMPO as the respective reference objects (see Table 5).

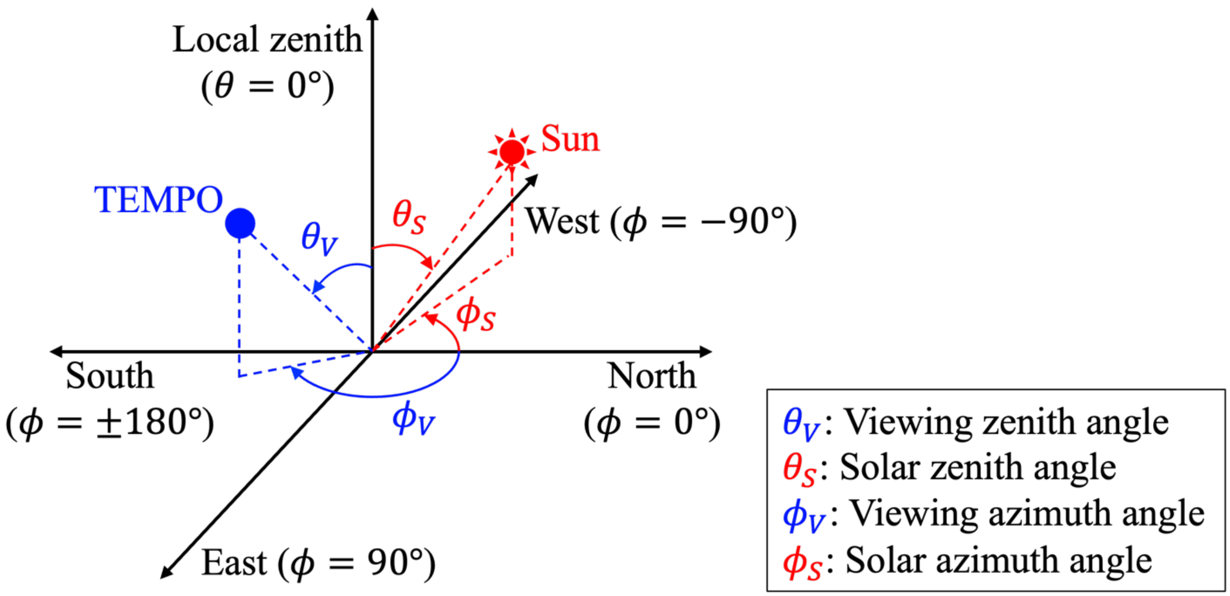

Figure 1. Coordinate system where zenith and azimuth angles are defined for the RAD product. The positions of TEMPO ($\phi_V = 150°$, $\theta_V = 40°$) and the Sun ($\phi_S = -60°$, $\theta_S = 50°$) are arbitrarily assigned to aid comprehension.

Table 6. Definition of each bit of the 'pixel_quality_flag' variable.

Bit	Definition
0	Missing data
1	Bad pixel
2	Processing error
3	Transient signal
4	Random telegraph signal (RTS)
5	Saturation
6	Noise underflow
7	Dark current correction error
8	Electronic offset correction error
9	Smear correction error
10	Stray light correction error
11	Non-linearity range error
12	Hot pixel
13	Cold pixel

To filter out unreliable pixels, it is recommended to use bits 0, 1, 2, and 5. A stricter screening may involve bits 7–11. The most conservative approach to sorting out pixels with the least possibility of issues is to find those with 'pixel_quality_flag' values of zero. However, the definitions of bits 3, 4, 12, and 13 may change in future data releases (see Section 5). Furthermore, stricter criteria likely lead to fewer pixels available. Users are thus advised to adjust according to their tolerance.

Table 7. Definition of each bit of the 'ground_pixel_quality_flag' variable. Bits 0–3 and 16–23 are derived using the V051 Terra and Aqua MODIS Land Cover Type (MCD12Q1) product from 2013 (Friedl et al., 2010).

Bit	**Description**	
0–3	Value	Definition
	0	Shallow ocean
	1	Land
	2	Shallow inland water
	3	Shoreline
	4	Intermittent water
	5	Deep inland water
	6	Continental shelf water
	7	Deep ocean
	15	Land/water error
4	Sun glint possibility	
5	Solar eclipse possibility	
6	INR quality flag	
7–15	Placeholders	
16–23	Value	Definition
	1	Evergreen needleleaf forest
	2	Evergreen broadleaf forest
	3	Deciduous needleleaf forest
	4	Deciduous broadleaf forest
	5	Mixed forest
	6	Closed shrublands
	7	Open shrublands
	8	Woody savannas
	9	Savannas
	10	Grasslands
	11	Permanent wetlands
	12	Croplands
	13	Urban and built-up
	14	Cropland natural vegetation mosaic
	15	Snow and ice
	16	Barren or sparsely vegetated
	254	Unclassified
	255	Fill-value

Table 8. Variables under the group ‘cloud_mask_group’ in the RAD product. The value of the dimension variable ‘xtrack’ is 2048. The ‘mirror_step’ variable represents the number of mirror steps.

Name	Format (dimension)	Unit	Description
red	float (mirror_step, xtrack)	-	Image derived from 675.5 nm to 686.0 nm radiances that approximates true-color red
green	float (mirror_step, xtrack)	-	Image derived from 550.0 nm to 575.5 nm radiances that approximates true-color green
blue	float (mirror_step, xtrack)	-	Image derived from 450.0 nm to 471.0 nm radiances that approximates true-color blue
cloud_mask	ubyte (mirror_step, xtrack)	-	Cloud Mask derived from red/green/blue channels (0 indicates no cloud, 1 indicates cloudy.)

The variables in the ‘cloud_mask_group’ are derived during the INR process to identify tie-point cloudiness. The ‘red,’ ‘green,’ and ‘blue’ variables are derived using the channels presented in Table 8 and combined to produce the ‘cloud_mask’ variable. These variables are valid only for ground pixels with solar zenith angles smaller than 80°. Reflection factors represented by the ‘red,’ ‘green,’ and ‘blue’ variables can occasionally exceed one. It is recommended that values outside the normal range of 0 to 1 be clipped.

It is highly recommended that the variables in the ‘cloud_mask_group’ be used only for visual interpretation purposes. Scientific cloud masking should be performed using the TEMPO Level 2 cloud product.

3.2.2. RADT Product

The RADT product includes all the variables in the RAD product. RADT radiances have had the background (residual dark current and scattered off-axis light) subtracted, and geolocation variables have been modified if registration with a VIIRS-DNB monthly clear-sky composite was successful (otherwise, they are unchanged). Additional key variables in the RADT product are listed in Table 9. Background modeling parameters are provided for the VIS and UV CCDs so that the subtracted background can be reconstructed as described in Section 3.4. Context images are added, which are radiances integrated over designated spectral ranges. Context images show city lights, lightning activity, aurorae, or the full range of integrated radiance. Guidance on performing custom integrations (or reproducing the context images or their equivalents) is provided in Section 3.5. Collocated VIIRS-DNB radiances from the DNB product used for registration are included as an additional context image. Lunar illumination variables (analogous to the solar ones) provide a description of direct lunar illumination (if any). A tangent height above the limb is added as an additional geolocation variable, which can be useful when interpreting aurorae and nightglow (only space pixels are nonzero).

Table 9. Additional key variables in the RADT product. The values of the dimension variables 'xtrack' and 'spectral_channel' are 2048 and 1028, respectively. The 'mirror_step' variable represents the number of mirror steps. The 'params' variable represents the parameters of the background model.

Group	Name	Format (dimension)	Unit	Description
-	VIIRS_registration_status	uint	-	Success (=1) or failure of registration to VIIRS
-	VIIRS_product_name	string	-	Name of NASA Black Marble product used for registration and VIIRS radiances
band_290_490_nm	CITY_UV	float (mirror_step, xtrack)	nW cm^{-2} sr^{-1}	Integrated radiance 390 nm to 490 nm
band_290_490_nm	FULL_UV	float (mirror_step, xtrack)	nW cm^{-2} sr^{-1}	Integrated radiance 290 nm to 490 nm
band_290_490_nm	LIGHTNING	float (mirror_step, xtrack)	nW cm^{-2} sr^{-1}	Integrated radiance 310 nm to 340 nm
band_290_490_nm	AURORA	float (mirror_step, xtrack)	nW cm^{-2} sr^{-1}	Integrated radiance 389.5 nm to 392.0 nm
band_290_490_nm	lunar_zenith_angle	float (mirror_step, xtrack)	degree (°)	Lunar zenith angle (UV CCD)
band_290_490_nm	lunar_azimuth_angle	float (mirror_step, xtrack)	degree (°)	Lunar azimuth angle (UV CCD)

band_290_490_nm	lunar_distance	float (mirror_step, xtrack)	km	Lunar distance (UV CCD)
band_290_490_nm	tangent_height	float (mirror_step, xtrack)	km	Tangent height (UV CCD)
band_290_490_nm	twilight_quality_flag	ushort (mirror_step, xtrack, spectral_channel)	-	Pixel quality flag (UV CCD)
band_290_490_nm	subtracted_background	float (mirror_step, params, spectral_channel)	photons s^{-1} cm^{-2} nm^{-1}	Background model parameters (UV CCD)
band_540_740_nm	CITY_VIS	float (mirror_step, xtrack)	nW cm^{-2} sr^{-1}	Integrated radiance 540 nm to 640 nm
band_540_740_nm	FULL_VIS	float (mirror_step, xtrack)	nW cm^{-2} sr^{-1}	Integrated radiance 540 nm to 740 nm
band_540_740_nm	VIIRS	float (mirror_step, xtrack)	nW cm^{-2} sr^{-1}	Collocated VIIRS radiances
band_540_740_nm	lunar_zenith_angle	float (mirror_step, xtrack)	degree (°)	Lunar zenith angle (VIS CCD)
band_540_740_nm	lunar_azimuth_angle	float (mirror_step, xtrack)	degree (°)	Lunar azimuth angle (VIS CCD)
band_540_740_nm	lunar_distance	float (mirror_step, xtrack)	km	Lunar distance (VIS CCD)
band_540_740_nm	tangent_height	float (mirror_step, xtrack)	km	Tangent height (VIS CCD)
band_540_740_nm	twilight_quality_flag	ushort (mirror_step, xtrack, spectral_channel)	-	Pixel quality flag (VIS CCD)
band_540_740_nm	subtracted_background	float	photons s^{-1} cm^{-2} nm^{-1}	Background model

		(mirror_step, params, spectral_channel)		parameters (VIS CCD)
geometry	lunar_phase_angle	float	degree (°)	Lunar phase angle
scan_quality/inr	mu_dx	float	pixel	Mean registration error along track for scan
scan_quality/inr	mu_dy	float	pixel	Mean registration error cross track for scan
scan_quality/inr	sig_dx	float	pixel	Standard dev. of registration error along track for scan
scan_quality/inr	sig_dy	float	pixel	Standard dev. of registration error cross track for scan
scan_quality/inr	number	uint	-	Number of verification points for scan

The RADT radiances have their own twilight radiance quality flags, which should be used along with the INR quality flags for identifying nominal pixels. Table 10 provides the interpretation of these flags (Carr et al., 2025).

Table 10. Definition of each bit of the 'twilight_pixel_quality_flag' variable.

Bit	Definition
0	Persistently hot pixel
1	Anomalously noisy pixel
2	Anomalous dark current subtraction
3	Edge pixel
4	Saturated

3.3. Wavelength Grids

The TEMPO Level 1b files provide two variables related to the wavelength registration. The first is 'nominal_wavelength.' This variable in the IRR and IRRR products provides static wavelength grids derived from the first-light solar measurements on August 1, 2023. On the other hand, the 'nominal_wavelength' variable in the RAD and RADT products represents the spectral calibration results from the most recent IRR file.

The second is 'wavecal_params' in the IRR, IRRR, and RAD products. It is recommended to utilize this variable because it provides the latest in-flight spectral calibration results. The RADT product does not provide 'wavecal_params' because its processing does not involve spectral calibration.

The TEMPO spectral calibration results are produced in the form of Chebyshev polynomial coefficients for each spatial position in each CCD. The results are stored in the 'wavecal_params' variable with dimensions of (mirror_step, xtrack, wavecal_par), where 'mirror_step' is the number of scan mirror steps (nominally 1 for Sun exposure), 'xtrack' is the number of spatial CCD pixels (2048), and 'wavecal_par' is the number of Chebyshev polynomial coefficients (i.e., the degree of polynomial plus one).

The 'wavecal_params' variable is stored in both the 'band_290_490_nm' and 'band_540_740_nm' groups since spectral calibration is performed separately for each CCD. It should be noted that the definitions of 'wavecal_params' differ between IRR(R) and RAD. In the IRR(R) product, it represents the reconstructed wavelength value for each CCD pixel. On the other hand, the 'wavecal_params' in the RAD product describes the wavelength shift relative to the nominal wavelength. In either case, the formulas below can convert the Chebyshev polynomial coefficients from the 'wavecal_params' into the wavelength-related quantity (wavelength value or wavelength shift). The result is assigned to each of the 1028 spectral grid pixels.

First, the Chebyshev polynomials $T(i, j, x)$ from a given mirror step (i) and spatial CCD index (j) can be constructed using the recurrence relation with a variable x on the interval [–1, 1]:

$T_0(i,j,x) = 1,$

$T_1(i,j,x) = x,$

$T_{m+1}(i,j,x) = 2xT_m(i,j,x) - T_{m-1}(i,j,x)$ (where $m \geq 1$).

For the TEMPO wavelength-grid reconstruction, x should be calculated on a regularly spaced grid from –1 to 1 with 1028 points, including the two boundaries (i.e., $-1 \leq x \leq 1$). Then, the combined output can be calculated for mirror step i, spatial CCD index j, and spectral CCD index k as

$$w(i, j, x(k)) = \sum_{p=0}^{n} [c_p(i, j) \times T_p(i, j, x(k))],$$

where $w(i, j, x(k))$ denotes the output, n represents the polynomial degree (i.e., the 'wavecal_par' value minus one), and c_p is the coefficient for each order of polynomial obtained from the 'wavecal_params' variable. The output variable w has dimensions of (mirror_step, xtrack, spectral_channel), where 'spectral_channel' corresponds to 1028.

As mentioned above, $w(i, j, k)$ represents the final wavelengths for IRR(R), but the wavelength shifts for RAD. Therefore, to reconstruct the radiance wavelength grid, $w(i, j, k)$ should be added to the nominal wavelength stored in the RAD file. Since the 'nominal_wavelength' variable does not have the 'mirror_step' dimension, the radiance wavelength is reconstructed by

$$\lambda(i, j, k) = \mu(j, k) + w(i, j, k),$$

where $\lambda(i, j, k)$ denotes the final radiance wavelength, and $\mu(j, k)$ represents the nominal wavelength at spatial CCD index j and spectral CCD index k from the 'nominal_wavelength' variable in the RAD file.

3.4. Twilight Radiance Background Model

Chebyshev polynomials are used to model the subtracted background as a smooth function of an along-slit (cross-track) coordinate $y = 2j/2047 - 1$, where j is the spatial CCD index starting from zero at the northernmost row of each CCD. The reconstructed background radiance is

$$b(i, j, k) = \sum_{n=0}^{N} p(i, n, k) \times T_n(y(j)),$$

where $p(i, n, k)$ are the 'subtracted_background' model parameters (spectral index k, cross-track step i), and N is the maximum degree of the Chebyshev series from the middle dimension of 'subtracted_background'. The background radiance plus the signal radiance in the 'radiance' variable recovers the total radiance from each CCD frame to the precision of single-precision arithmetic.

The background is much larger for the UV due to a large Rayleigh scattering peak centered about 450 nm. The background radiance has easily seen Fraunhofer lines from the solar spectrum (Carr et. al., 2025; Xue et. al., 2025).

3.5. Twilight Radiance Integrations

Radiance images, like the context images, can be formed for any spectral subset (e.g., emission lines or broad spectral bands). Similarly, spatially averaged spectra can be formed. When doing either, it is necessary to take the 'twilight_quality_flag' into account, where $qf_{twilight}(i, j, k) = 0$ are those pixels with nominal quality. If S is the subset of the radiance cube $r(i, j, k)$ satisfying the desired criteria (e.g., $\lambda_{min} \leq \lambda(j, k) \leq \lambda_{max}$ and $qf_{twilight}(i, j, k) = 0$) then the integrated radiance image would be,

$$R(i, j) = (\lambda_{max} - \lambda_{min}) \sum_{(i,j,k)\in S} r(i, j, k) \cdot \frac{hc}{\lambda(j,k)} / \sum_{(i,j,k)\in S} 1.$$

Notice that the radiances have been multiplied by the energy per photon at each wavelength to convert radiances from photon units to energy units (e.g., nW cm^{-2} sr^{-1}), more commonly used in the NASA Black Marble community (h and c are respectively Planck's constant and the speed of light). For many purposes, it is sufficient to replace $\lambda(j, k)$ with an average over the spatial index j, $\bar{\lambda}(k)$.

The radiance image $R(i, j)$ may exhibit horizontal streaks that are due to small calibration irregularities. The signal radiance is typically smaller than the background (much so at blue wavelengths), and small irregularities in the calibration can cause the background to be over- (under-) estimated, leaving small streaks in the integrated radiance. A Median Absolute Difference (MAD; Huber and Ronchetti, 2011) filter on each spatial CCD position is very effective in reducing the streaks. Let n be the desired threshold to be used (e.g., $n = 3$) in numbers of robustly estimated standard deviations σ for spatial CCD index j, which is

$$\sigma_j = 1.4826 \times med_i(z(i, j)),$$

with $z(i,j) = \left|R(i,j) - med_i\big(R(i,j)\big)\right|$, then the estimated calibration artifact for index j would be $\mu_j = mean(\{R(i,j) \mid z(i,j) \leq n\sigma_j\})$. The de-streaked image is then $R(i,j) - \mu_j$.

Integrated radiance images can also be formed from the subtracted background radiances. These will show small vertical bars that indicate residual temperature variations in the dark current.

4. Updates from the Previous Version

The Version 4 Level 1 products described in this document are derived using an updated Level 0-1 processor, compared to Version 3 released on May 20, 2024. Below is the list of updates made for Version 4.

(1) Absolute calibration has been improved.
(a) The definition of BTDF has been updated in the TEMPO Level 0-1 processor to be consistent with the on-ground calibration, resulting in a decrease of ~13.4% in Sun-normalized radiances.
(b) The magnitudes of the radiometric calibration coefficients have been reduced through comparisons of Earth observations among the TEMPO, Advanced Baseline Imager (ABI), and VIIRS instruments. Constant adjustments of 11% and 7% have been made to the UV and VIS CCDs, respectively, without spectral dependence.
(c) The etalon fringe patterns have been mitigated by spectrally shifting the radiometric calibration coefficients.
(2) The diffuser goniometry correction has been refined through analyses of in-flight solar irradiance measurements.
(3) Stray light correction has been enhanced:
(a) The point spread functions (PSFs) have been updated.
(b) A background stray light correction has been added.
(c) A capability that reconstructs Earth radiances from CCD pixels with signal saturation has been added.
(4) Spectral calibration has been updated:
(a) The spectral fitting for solar irradiance calibration has been stabilized by excluding the asymmetry factor from the super-Gaussian slit function parameterization.
(b) The performance of Earth radiance calibration has been enhanced by updating the absorption cross sections of trace gases and by replacing the reference solar spectrum from Version 3 to Version 4 of the TEMPO first-light measurement.
(5) The smear correction method has been updated for the RAD, IRR, and IRRR processing.
(6) The INR performance has been enhanced by enabling cloud motion tracking.

(7) A second processing step has been added for the RADT product to facilitate user applications so that the post-processing required for Version 3 is no longer necessary.
(8) *January 2026 minor update*: Dark current correction for the RAD and IRR(R) products has been slightly improved by updating the approach to sampling the focal plane array (FPA) strap temperature.
(9) *January 2026 minor update*: The gains and radiometric calibration coefficients have been refined to mitigate the discrepancy in (ir)radiance between the odd and even spatial CCD indices.

5. Known Issues

Below are known issues in the current version of the TEMPO Level 1 Version 4 products, which are planned to be updated in the future.

(1) Further radiometric calibration improvement is desired:
(a) Sun-normalized radiances are found to have spectral-dependent biases at wavelengths < 325 nm. These biases are partly due to imperfect stray light correction, which affects IRR(R) and RAD independently.
(c) Biases in TEMPO solar irradiance against a high-resolution reference solar irradiance spectrum show a magnitude difference of several percent.
(b) Although to a reduced extent, the etalon fringe patterns are still present in IRR(R) and RAD images, mainly at wavelengths > 650 nm. These patterns occur possibly due to time-dependent wavelength shifts.
(2) Solar irradiance still shows a weak seasonal variability, typically below 1%, despite the updated diffuser goniometry correction and the Earth–Sun distance correction.
(3) Earth radiance and solar diffuser polarization corrections have not been applied.
(4) In the oceanic regions, fill-values are present in the ‘ground_pixel_quality_flag’ variable due to the lack of land cover information in the source data.
(5) The threshold for the transient, RTS, hot, and cold pixels in the ‘pixel_quality_flag’ variable will be revisited to address possible over- or under-detections.
(6) Radiance calibration improvements may be made to reduce irregularities that cause streaking in RADT radiance images, and dark current modeling improvements may be undertaken to reduce residual modeled dark current below already low values.

6. References

Carr, J., Liu, X., Baker, B., & Chance, K. (2017). Observing nightlights from space with TEMPO. *Int. J. Sustain. Light.*, 19, 26–35. https://doi.org/10.26607/ijsl.v19i1.64

Carr, J., Chong, H., Liu, X., Houck, J. C., Kalb, V., Madani, H. et al. (2025). TEMPO at night. *Earth and Space Science*, 12, e2024EA004157. https://doi.org/10.1029/2024EA004157

Chong, H., Liu, X., Houck, J., Flittner, D. E., Carr, J., Hou, W. et al. (2025). Algorithm theoretical basis for Version 3 TEMPO Level 0-1 processor. *Earth and Space Science*, accepted. https://doi.org/10.22541/au.174923107.71876512/v1

Friedl, M. A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A. et al. (2010). MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. *Remote Sensing of Environment*, 114, 168–182. https://doi.org/10.1016/j.rse.2009.08.016

Huber, P. J. & Ronchetti, E. M. (2011). Robust statistics. *John Wiley & Sons.*

Kim, J., Jeong, U., Ahn, M.-H., Kim, J. H., Park, R. J., Lee, H. et al. (2020). New era of air quality monitoring from space: Geostationary Environment Monitoring Spectrometer (GEMS). *Bulletin of the American Meteorological Society*, 101(1), E1–E22. https://doi.org/10.1175/BAMS-D-18-0013.1

KNMI (Royal Netherlands Meteorological Institute) (2022). Algorithm theoretical basis document for the TROPOMI L01b data processor. Available at: https://sentinels.copernicus.eu/documents/247904/2476257/Sentinel-5P-TROPOMI-Level-1B-ATBD

Levelt, P. F. & Noordhoek, R. (2002). OMI Algorithm Theoretical Basis Document, Volume I, OMI Instrument, Level 0-1b processor, Calibration & Operations. Available at: https://eospso.gsfc.nasa.gov/sites/default/files/atbd/ATBD-OMI-01.pdf

van den Oord, G. H. J., Rozemeijer, N. C., Schenkelaars, V., Levelt, P. F., Dobber, M. R., Voors, R. H. M. et al. (2006). OMI Level 0 to 1b processing and operational aspects. *IEEE Transactions on Geoscience and Remote Sensing*, 44(5), 1380–1397. https:doi.org/10.1109/TGRS.2006.872935

Xue, Z., Zhou, M., Wang, J., Xiao, Q., Carr, J. L., & Liu, X. (2025). Spectral-resolved light at night: TEMPO observations and background correction. *Earth and Space Science,* under review. https://doi.org/10.22541/au.176496081.14335600/v1

Zoogman, P., Liu, X., Suleiman, R., Pennington, W., Flittner, D., Al-Saadi, J. et al. (2017). Tropospheric Emissions: Monitoring of Pollution (TEMPO). Journal of Quantitative Spectroscopy and Radiative Transfer, 186, 17–39. https://doi.org/10.1016/j.jqsrt.2016.05.008