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**TROPOSPHERIC EMISSIONS:
MONITORING OF POLLUTION (TEMPO)
PROJECT**

**Level 1 Data Products:
User Guide**

September 17, 2025

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2.0	All	Revision made to describe the new Version 4 products	September 17, 2025

Contents

1. Introduction	5
2. Algorithm overview.....	6
3. File descriptions.....	8
3.1. Filename format	8
3.2. Key variables	9
3.3. Wavelength grids	19
4. Updates from the previous version.....	20
5. Known issues.....	21
6. References	22

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 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 during twilight hours.

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 have been released on September 17, 2025. The Version 4 RADT product is currently undergoing an upgrade to allow users to utilize the data without an additional post-processing step and will be released separately from the other Level 1 products. This document covers an overview of the Version 4 RADT processing. At the time of the Version 4 RADT product release, an updated version of the User Guide document will also be published to provide detailed descriptions of the product, including key variables.

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 $> 60^\circ$) and that are not suitable for nominal radiance scanning (solar zenith angles $> 80^\circ$ 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 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 $\text{s}^{-1} \text{cm}^{-2} \text{nm}^{-1} \text{sr}^{-1}$). 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 $\text{s}^{-1} \text{cm}^{-2} \text{nm}^{-1}$, 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 post-processing, a background correction is applied to remove remaining artifacts in the images. 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. Details of the post-processing of the RADT product are described in Carr et al. (2025). 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.

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. As mentioned in Section 2, key variables in the RADT product will be described in an updated version of the User Guide document.

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).

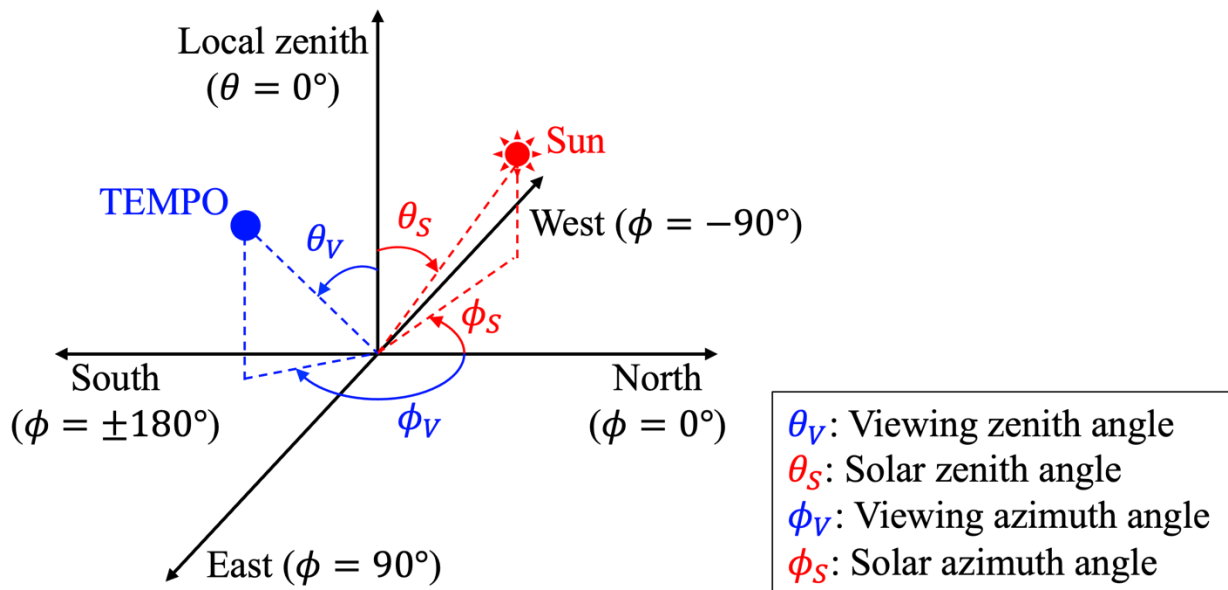


Figure 1. Coordinate system where zenith and azimuth angles are defined for the RAD product. The positions of TEMPO ($\phi_V = 150^\circ$, $\theta_V = 40^\circ$) and the Sun ($\phi_S = -60^\circ$, $\theta_S = 50^\circ$) are arbitrarily assigned to aid comprehension.

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.

3.3. 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 $[-1, 1]$:

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

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

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

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.

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 post-processing has been added for the RADT product to facilitate user applications.

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. 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*, accepted. <https://doi.org/10.22541/essoar.173482161.12303917/v1>
- 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*, under review. <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>
- 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://eosps.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).
- 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>