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TROPOSPHERIC EMISSIONS: MONITORING OF POLLUTION (TEMPO) PROJECT

Level 1 Data Products: User Guide

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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

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 3 products, released on May 20, 2024. The products are generated by the Science Data Processing Center (SDPC) at the Smithsonian Astrophysical Observatory (SAO).

All products are pushed to NASA Atmospheric Science Data Center (ASDC) from SAO after production by SDPC. Under rare circumstances, geolocated Earth radiances files might be missing; image navigation and registration (INR) has sometimes failed under special conditions (e.g., due to a lot of missing data, missing spacecraft ephemeris, etc.).

TEMPO products are in the commonly-used, self-explanatory NetCDF format. The content of a NetCDF file can be listed by a 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 (or aurora) during twilight hours.

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). 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 for users to check the corresponding information while utilizing the 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 algorithm theoretical basis document (ATBD). 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 s^{-1} cm^{-2} nm^{-1} (sr^{-1})). Then, the radiance processing employs additional steps, including INR, to generate geolocated Level 1b outputs. For the RADT product, however, nominal geolocations are assigned without INR. The photon derivation in the irradiance processing is followed by several steps, including correction for the bidirectional transmittance distribution function (BTDF) of the diffusers and spectral calibration, to produce irradiance L1b outputs.

Table 1. TEMPO Level 1 products.

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

Beta maturity is defined as: the product is minimally validated but may still contain significant errors; it is based on product quick looks using the initial calibration parameters.

Because the products at this stage have minimal validation, users should refrain from making conclusive public statements regarding science and applications of the data products until a product is designated at the provisional validation status.

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_V03_{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_V03_{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_V03_{YYYY}{MM}{DD}T{HH}{NN}{SS}Z.nc
RAD, RADT	TEMPO_{PPP(P)} _L1_V03_{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 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 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 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(T) products, respectively. The definition of each bit of the “pixel_quality_flag” (in all products) and “ground_pixel_quality_flag” (in the RAD and RADT products) variables are described in Tables 6 and 7, respectively. 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 and RADT products. 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
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 (mirror_step, xtrack)	degree (°)	Solar azimuth 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)

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 involves 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

3.3. Wavelength grids

The IRR, IRRR, and RAD files provide two variables related to the wavelength registration: (i) nominal_wavelength and (ii) wavecal_params. It is recommended to utilize the latter because it corresponds to the output of spectral calibration. The ‘nominal_wavelength’ variables in the IRR and IRRR products provide static wavelength grids derived from the first-light solar measurements on August 1, 2023. On the other hand, the RAD and RADT processing algorithms extract the spectral calibration results from the most recent IRR file and write them out to the ‘nominal_wavelength’ variables. The RADT product does not provide ‘wavecal_params’ variables because the RADT processing does not involve spectral calibration.

The TEMPO spectral calibration algorithm provides a set 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 a given CCD pixel. On the other hand, the ‘wavecal_params’ in the RAD product describes wavelength shifts. In either case, however, the wavelength grid can be reconstructed using the Chebyshev polynomial formula with 1028 spectral grid pixels for each mirror step and each spatial CCD index.

First, the Chebyshev polynomials $T(x)$ can be constructed using the recurrence relation with a variable x on the interval [–1, 1]:

$T_0(x) = 1,$

$T_1(x) = x,$

$T_{m+1}(x) = 2xT_m(x) - T_{m-1}(x)$ (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 wavelengths 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 3 Level 1 products described in this document are derived using an updated Level 0-1 processor, compared to Version 2 released on February 26, 2024. Below is the list of updates made for Version 3.

(1) The RADT product has been added with the use of nominal geolocations (without INR).
(2) For more accurate INR, the Global Positioning System Receiver (GPSR) has been added as the primary source of spacecraft ephemeris (applied to the period after May 1, 2024). If the GPSR fails, the Dynamic Orbit Propagator (DOP) and predicted ephemeris are attempted in order. For previous data, the spacecraft ephemeris was taken from the DOP. Before the GPSR-1 failure (January 24, 2024), the DOP was informed by the GPSR, but between February 1 and May 1, 2024, the DOP was informed by ground ranging.
(3) The dark current correction has been updated for RAD and IRR(R) by deriving the in-flight relationship between dark current and FPA temperature.
(4) Stray light correction has been activated for RAD and IRR(R) using 1-dimensional (spectral) point spread functions.

(5) The anomaly in the radiometric calibration coefficients at the spatial index 1027 (0-based) has been mitigated.
(6) The BTDF table for the reference diffuser (IRRR) has been updated.
(7) The dependence of gain on FPA and focal plane electronics (FPE) temperatures has been revised.
(8) The transient signal detection has been turned off for RAD and IRR(R), considering possible over- or under-detections (see Table 6).
(9) Some of the fill-values in the 'ground_pixel_quality_flag' variable have been replaced with physical values. (However, there are remaining fill-values; see Section 5.)

5. Known issues

Below are known issues in the current version of the TEMPO Level 1 Version 3 products, which are planned to be updated in the future.

(1) Radiance and diffuser polarization correction has not been applied.
(2) Further radiometric calibration improvement is desired:
(a) TEMPO irradiance measurements show discrepancies from theoretical references, likely due to errors in gain, BTDF, or radiometric calibration coefficients. If the radiometric calibration coefficients are the cause, the error may be canceled out when calculating Sun-normalized radiances.
(b) Etaloning structures are found at wavelengths > 650 nm.
(3) 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.
(4) 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

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