

MOPITT
(Measurements of Pollution in the Troposphere)
Version 7 Product User's Guide

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1 MOPITT Version 7 Product Highlights

This guide describes new product features in the MOPITT Version 7 (V7) Level 2 products for tropospheric carbon monoxide (CO). V7 product users may need to also consult the earlier V5 and V6 User's Guides (also available on the MOPITT website). Any updates to this document will be announced on the MOPITT News webpage at .

Featured improvements in the V7 retrieval product include:

- **Improved radiative transfer modeling. Details in Sec. 3.1.**
- **Improved meteorological fields used in Level 2 processing. Details in Sec. 3.2.**
- **Improved cloud detection. Details in Sec. 3.3.**
- **Improved radiance bias correction. Details in Sec. 3.4**
- **Improved NIR calibration method for archival products. Details in Sec. 3.5**

2 Review of Earlier MOPITT Products

Following the launch of Terra near the end of 1999, the MOPITT Version 3 product became available in 2000 [1]. This was the first satellite dataset for tropospheric CO featuring global coverage. This product was followed in 2009 by the Version 4 (V4) product [2]. Significant improvements first introduced in the V4 product included (1) temporally and geographically variable a priori for CO based on the chemical transport model MOZART, (2) representation of CO variability by log-normal statistics, (3) extension of the forward radiative transfer model MOPFAS to simulate much higher CO concentrations, and (4) improved observation-based a priori values for surface emissivity. Processing of the V4 product ended at the end of 2012. The V5 product became available in 2011 in three retrieval configurations: thermal infrared-only (“TIR-only”), near infrared-only (“NIR-only”) and “TIR/NIR”. (The previous V3 and V4 products were TIR-only products.) V5 retrieval products also benefited from a new time-dependent radiative transfer model to reduce the influence of long-term instrumental changes on retrieval biases (i.e., “bias drift”). The V5 product has been validated using a variety of in-situ and satellite datasets [3,4]. The V6 product was released in 2013 and featured (1) correction of a systematic geolocation error, (2) use of the MERRA (Modern-Era Retrospective Analysis For Research And Applications) reanalysis for needed meteorological fields and (3) an updated model-based a priori for CO [5].

3 Features of the MOPITT Version 7 Retrieval Algorithm

Improvements to the content of the V7 retrieval products are described in the following section. Especially significant changes in the V7 product (with respect to both scientific content and format) are emphasized in **bold** text.

3.1 Radiative Transfer Modeling

The radiative transfer model on which the MOPITT retrieval algorithm is based has been updated for V7. The model now accounts for the steady growth of atmospheric N₂O concentrations over the MOPITT mission. Global-mean N₂O concentrations increased between 2000 and 2015 at a rate of ~ 0.28%/yr (see <http://www.esrl.noaa.gov/gmd/hats/combined/N2O.html>). Because of the proximity of CO and N₂O spectral absorption lines in the TIR region, increasing N₂O concentrations are believed to have contributed to long-term bias drift in previous MOPITT products. Preliminary validation results indicate that bias drift for V7 products is smaller than for V6 products. The operational radiative transfer model has also been updated with the HITRAN 2012 spectral database [6].

3.2 Meteorological Fields

For each retrieval, the MOPITT retrieval algorithm requires temperature and water vapor profiles as well as a priori surface temperature values. For V6 processing, meteorological profiles were derived from the NASA MERRA reanalysis product (<http://gmao.gsfc.nasa.gov/merra/>). **For all V7 products, meteorological profiles are extracted from the recently released MERRA-2 product.** As described here (<http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/>), MERRA-2 “... was introduced to replace the original MERRA dataset because of the advances made in the assimilation system that enable assimilation of modern hyperspectral radiance and microwave observations, along with GPS-Radio Occultation datasets. It also uses NASA ozone observations after 2005. Additional advances in both the GEOS-5 model and the GSI assimilation system are included in MERRA-2. Spatial resolution remains about the same (about 50 km in the latitudinal direction) as in MERRA.” **Generally higher quality retrieval results for V7 are expected using MERRA-2 due to the assimilation of more satellite datasets (e.g., IASI) and other improvements.**

3.3 Cloud Detection

Only MOPITT observations made in clear sky conditions are used in Level 2 retrieval processing. The clear/cloudy determination is based both on MOPITT's thermal-channel radiances and the MODIS cloud mask. Since about 2010, electronic crosstalk affecting MODIS thermal-channel Bands 29 to 31 ([documented here](#)) has resulted in a false trend towards increasing cloudiness, particularly for tropical nighttime scenes over the ocean. This issue affects MODIS products from both Collections 5 (used until February 2016 in MOPITT Versions 5 and 6) and 6 (used since March 2016 in MOPITT Versions

5 and 6). **For the cloud detection algorithm used for MOPITT V7 products, two changes have been made. First, MODIS Collection 6 cloud mask files are used consistently for processing the entire MOPITT mission. (Characteristics of the Collection 6 cloud mask files are described in http://modis-atmos.gsfc.nasa.gov/Webinar2014/MODIS_C6_MOD35_Ackerman.pdf.) Second, a new Level 2 Cloud Description diagnostic index value (6) is assigned to night and day ocean scenes where the MODIS cloud mask-based tests finds that the area was cloudy (with the exception of scenes with low clouds) but the test based on MOPITT's thermal-channel radiances finds that the area was clear; such MOPITT scenes were previously discarded but are now retained. Compared to earlier MOPITT products, the addition of this new “clear” class of may significantly increase the number of MOPITT retrievals in a given scene. The other possible Cloud Description diagnostic values (1-5) retain their original meanings, as defined in the V5 User's Guide. Users can use the Level 2 Cloud Description diagnostic index values to filter retrievals according to their “clear” status assignment.**

3.4 Radiance Bias Correction

The MOPITT Level 2 processor exploits a set of radiance-bias correction factors to compensate for relative biases between (1) simulated radiances calculated by the operational radiative transfer model and (2) actual calibrated Level 1 radiances. Without some form of compensation, radiance biases produce biases in the retrieved CO profiles. Radiance bias correction factors compensate for a variety of potential bias sources including errors in instrumental specifications, forward model errors, spectroscopy errors, and geophysical errors. **New strategies were developed for deriving radiance-bias correction factors for V7 products. For the TIR radiances (Channels 5 and 7), radiance-bias scaling factors were determined by minimizing observed retrieval biases at 400 and 800 hPa as determined using in-situ CO profiles from the HIPPO (HIAPER Pole to Pole Observations) field campaign [3,4,5].** To the extent that the HIPPO campaign produced a near-global set of in-situ CO profiles (i.e., over a wide latitudinal range spanning both the Northern and Southern Hemispheres), this strategy effectively yields globally-minimized retrieval biases. **For the NIR radiances (Channel 6), radiance bias scaling factors were determined by minimizing NIR-only retrieval biases as determined using the NOAA aircraft profile set.** (The HIPPO dataset primarily represents oceanic scenes and was therefore not useful for optimizing the NIR radiance-bias scaling factors.) Validation results confirming the success of the radiance bias correction methods used for V7 will be published in the near future.

3.5 NIR Calibration

Calibration of MOPITT's NIR channels (e.g., Channel 6) relies on a two-point calibration scheme involving both cold-calibration (“cold-cal”) events and hot-calibration (“hot-cal”) events. Cold-cals occur many times per day, while hot-cals are performed only about once per year. Ideally, NIR

channels are calibrated with gain and offset values determined by interpolating the information from hot-cals occurring both before and after the time of observation. While this method is feasible in retrospective processing mode (i.e., processing previous years of data), it is not possible in forward processing mode (i.e., when processing recently acquired observations). Thus, in forward processing mode, only information from the most recent hot-cal is used to calibrate MOPITT's NIR radiances. Recent comparisons of NIR-only retrieval products generated in retrospective and forward processing modes have revealed significant differences (10% to 20%) in total column results, with the retrospectively processed data in better agreement with daytime/land TIR-only total column values and time dependence. **Therefore, because of the lower quality of MOPITT products processed in forward processing mode, V7 products generated in this manner will be labeled as "beta" products. These products will be reprocessed and replaced by standard archival files following the next hot-cal. Typically, this will occur no more than a year from the time of a particular observation (depending on the date of the most recent hot-cal). The beta products should not be considered for examining long-term records of CO although these products should still be useful for some applications. See Section 5.**

4 Product Format and Content

Beginning with the MOPITT V6 products, the format of the archival Level 1, Level 2 and Level 3 data files switched from HDF-EOS2, based on HDF4 libraries, to HDF-EOS5, based on HDF5 libraries. **V7 products are in the same HDF5 format as V6 products and should be readable with analysis tools developed for V6 products.** HDF is a standard format for large datasets (<http://www.hdfgroup.org/>). The HDF-EOS format is an extension of HDF developed by the HDF-EOS group (<http://hdfeos.org/index.php>). Files distributed in the HDF-EOS5 format can be accessed with a wide range of software tools including IDL, NCL and MATLAB (<http://www.hdfgroup.org/tools/earthscience.html>).

4.1 Level 1 Data

The content of the Level 1 product files containing the MOPITT calibrated radiances is unchanged for V7, with the exception of a new diagnostic, "Daily Gain Dev." This diagnostic provides the standard deviation of the gain values used to calibrate the radiances for a particular channel and pixel on one day. This diagnostic may be useful as a metric for the Channel 5 calibration issue described in Section 5. The Daily Gain Dev diagnostic is also included in V7 Level 2 data files.

4.2 Level 2 Data

The contents of the V7 Level 2 product files are tabulated in Appendix A. The file content is nearly identical to the content of the V6 Level 2 files, with the exception of several new diagnostics. New diagnostics include

- **Total Column Averaging Kernel.** This diagnostic allows users to properly compare MOPITT total column retrievals with total columns derived from in-situ profiles or model simulations. Use of the total column averaging kernel is discussed in Sec. 7.4 of the V4 User's Guide.
- **Averaging Kernel Row Sums.** This diagnostic provides a single scalar value for each row of the averaging kernel matrix equal to the sum of the elements in that row. Small row-sum values indicate retrieval levels heavily weighted by the a priori while values approaching unity indicate levels with relatively weak sensitivity to the a priori.
- **Dry Air Column and Water Vapor Column.** Along with the retrieved CO total column, these diagnostics facilitate the computation of the equivalent dry-air or moist-air mixing ratio averaged over the atmospheric column.
- **Smoothing Error and Measurement Error Covariance Matrices.** These diagnostics represent the two components of the Retrieval Error Covariance Matrix. Smoothing error represents the retrieval uncertainty due to the influence of a priori and the features of the weighting functions. Measurement error represents the retrieval uncertainty due to uncertainties in the measured radiances (including instrument noise). These diagnostics are described further in Section 3.2 of Rodgers' book [7].
- **Retrieval Anomaly Flags.** These flags are set to true when particular anomalous conditions are observed, suggesting that the retrievals should either be ignored or used cautiously. The first four flags (i.e., elements 1-4 of the Retrieval Anomaly Diagnostic array) are set to true (i.e., a value of 1) when one of the thermal channel weighting functions exhibits a sign change vertically. This can occur, for example, in some nighttime/land scenes when the surface skin temperature is less than the temperature of the air immediately above the surface. Elements 1-4 correspond respectively to the 5A, 5D, 7A, and 7D weighing functions. The fifth flag of the Retrieval Anomaly Diagnostic array is set to true when the retrieval averaging kernel matrix includes at least one negative element on the matrix diagonal.

Appendices B and C provide examples of IDL and NCL code used to open and read the contents of V7 Level 2 data files.

4.3 Level 3 Data

At the time of writing, V7 Level 3 products were still in development. This User's Guide will be updated as V7 Level 3 products are released.

5 Data Quality Issues

Validation results for the V7 Level 2 products will be published in the near future. Compared to V6

validation results, preliminary results for V7 indicate (1) generally smaller retrieval biases and (2) reduced bias variability (as demonstrated by smaller standard deviations and larger correlation coefficients in validation scatterplots).

As described in Sec. 3.5, the MOPITT algorithm development team recently discovered a new source of retrieval bias affecting the V5 and V6 NIR-only and TIR/NIR retrieval products. Retrieval biases found in V5 and V6 products resulted from the fact that hot calibration events used to calibrate the MOPITT NIR radiances only occur approximately once per year. **Users of affected V5 and V6 MOPITT products are cautioned that the newly discovered source of bias might significantly affect multi-year analyses of CO.** For V7, the MOPITT team will release products generated in forward-processing mode as beta products, and will later reprocess these data following the next hot calibration. **Thus, the initial release of archival V7 data products (processed in retrospective mode) will include observations made from the beginning of the mission through February, 2016. For March, 2016 and later, archival data products will not be available until approximately April, 2017 (following the next hot calibration event). Until then, V7 Level 2 data products will be released as beta products, with the filename and metadata identifying these files as such.** Beta products are considered unvalidated and should generally be used with caution.

V7 "beta" products will be easily identifiable as the filenames of such files will include the word "beta" (e.g., "MOP02T-20160501-L2V17.8.1.beta.he5"). At the ASDC ftp and OPeNDAP sites (accessible at <https://eosweb.larc.nasa.gov/datapool>), beta files will also be stored in separate directories from archival products. For example, the archival V7 Level 2 TIR-only products will be found in subdirectories under the main directory "MOP02T.007"; this convention is consistent with previous MOPITT releases. Corresponding V7 beta TIR-only products will be found in subdirectories under "MOP02T.107".

Another type of retrieval anomaly has been noticed in a small number of nighttime/land scenes. This anomaly is typically revealed as a striping pattern in retrieved surface-level CO concentrations and surface temperature for one or two pixels in the four-element detector array over a series of tracks. This type of anomaly primarily affects Pixels 1 and 4 and appears to be partly the result of a calibration issue affecting Channel 5 radiances in which gain and offset values exhibit frequent sudden jumps throughout the day. These gain and offset jumps have been traced back to cold calibration (space-view) events. The new Daily Gain Dev diagnostic (included in both Level 1 and Level 2 files) may be useful for identifying days where this type of anomaly is most likely to occur. Analyses of "outlier" retrievals suggest that retrieval anomalies due to this effect are typically small (e.g., less than 10 ppbv).

6 References

[1] Deeter, M. N., et al. (2003). Operational carbon monoxide retrieval algorithm and selected results

- for the MOPITT instrument, *J. Geophys. Res.* 108, doi:10.1029/2002JD003186.
- [2] Deeter, M. N., et al. (2010). The MOPITT version 4 CO product: Algorithm enhancements, validation, and long-term stability. *J. Geophys. Res.* 115, doi:10.1029/2009JD013005.
- [3] Deeter, M. N., et al. (2013). Validation of MOPITT Version 5 Thermal-infrared, near-infrared, and multispectral carbon monoxide profile retrievals for 2000-2011. *J. Geophys. Res. Atmos.*, 118, 6710–6725, doi:10.1002/jgrd.50272.
- [4] Martínez-Alonso, S., et al. (2014). Comparison of upper tropospheric carbon monoxide from MOPITT, ACE-FTS, and HIPPO-QCLS. *J. Geophys. Res.* 119, 14,144–14,164, doi:10.1002/2014JD022397 .
- [5] Deeter, M. N. et al. (2014). The MOPITT Version 6 product: algorithm enhancements and validation. *Atmos. Meas. Tech.*, 7, 3623-3632, doi:10.5194/amt-7-3623-2014 .
- [6] Rothman, L. S. , et al. (2013). The HITRAN 2012 Molecular Spectroscopic Database. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 130, 4-50. doi:10.1016/j.jqsrt.2013.07.002
- [7] Rodgers, C. D.: *Inverse Methods for Atmospheric Sounding, Theory and Practice*, World Scientific, Singapore, 2000.

Appendices

A. Contents of V7 Level 2 Product Files

(new content in bold)

V7 HDF5 Product Path	Units	Dimension ₁
Geolocation Fields ('/HDFEOS/SWATHS/MOP02/Geolocation Fields/...')		
'.../SecondsinDay'	s	ntime
'.../Latitude'	deg	ntime
'.../Longitude'	deg	ntime
'.../Pressure'	hPa	9
Data Fields ('/HDFEOS/SWATHS/MOP02/Data Fields/...')		
'.../APrioriCOMixingRatioProfile'	ppbv	2,9,ntime
'.../APrioriCOSurfaceMixingRatio'	ppbv	2,ntime
'.../APrioriCOTotalColumn'	mol/cm ²	2,ntime
'.../APrioriSurfaceEmissivity'		2,ntime
'.../APrioriSurfaceTemperature'	K	2,ntime
'.../AveragingKernelRowSums'		10,ntime
'.../CloudDescription'		ntime ²
'.../DEMAltitude'	m	ntime
'.../DailyGainDev'		2,8,4
'.../DegreesofFreedomforSignal'		ntime
'.../DryAirColumn'	mol/cm²	ntime
'.../Level1RadiancesandErrors'	W/m ² Sr	2,12,ntime ₄
'.../MODISCloudDiagnostics'		10,ntime
'.../MeasurementErrorCovarianceMatrix'		10,10,ntime
'.../PressureGrid'	hPa	9
'.../RetrievalAnomalyDiagnostic'		5,ntime²
'.../RetrievalAveragingKernelMatrix'		10,10,ntime ₃
'.../RetrievalErrorCovarianceMatrix'		10,10,ntime
'.../RetrievalIterations'		ntime ²
'.../RetrievedCOMixingRatioProfile'	ppbv	2,9,ntime
'.../RetrievedCOSurfaceMixingRatio'	ppbv	2,ntime

V7 HDF5 Product Path	Units	Dimension₁
'.../RetrievedCOTotalColumn'	mol/cm ²	2,ntime
'.../RetrievedCOTotalColumnDiagnostics'	mol/cm ²	2,ntime
'.../RetrievedSurfaceEmissivity'		2,ntime
'.../RetrievedSurfaceTemperature'	K	2,ntime
'.../SatelliteZenithAngle'	deg	ntime
'.../SignalChi2'		ntime
'.../SmoothingErrorCovarianceMatrix'		10,10,ntime
'.../SolarZenithAngle'	deg	ntime
'.../SurfaceIndex'		ntime ²
'.../SurfacePressure'	hPa	ntime
'.../SwathIndex'		3,ntime ²
'.../TotalColumnAveragingKernel'	mol/cm²	10,ntime
'.../TotalColumnAveragingKernelDimless'		10,ntime
'.../WaterVaporColumn'	mol/cm²	ntime

¹ Array indices ordered according to IDL convention. ntime = number of retrievals (varies), ordered chronologically; for data fields which include associated variability/uncertainty, first element is the parameter and second element is variability/uncertainty.

² Integer-valued product (all others floating point)

³ Dimensions of Retrieval Averaging Kernel Matrix are ordered (nrow, ncolumn, ntime)

⁴ First index of Level 1 Radiances and Errors corresponds to radiances/uncertainties; second index corresponds to channel (in sequence 7A, 3A, 1A, 5A, 7D, 3D, 1D, 5D, 2A, 6A, 2D, 6D).

B. Sample IDL Code for Opening and Reading V7 Level 2 files

```

pro example_v7_lev2
; sample IDL code for opening and reading MOPITT Version 7 Level 2 files
; note different paths for 'Geolocation Fields' and 'Data Fields'
infile = 'MOP02T-20030101-L2V17.8.1.he5'
print, infile
print, 'open hdf5 file'
file_id = H5F_OPEN(infile)
; read latitudes into variable 'moplat'

```

```

print, 'read latitudes'
dataset_id = H5D_OPEN(file_id, '/HDFEOS/SWATHS/MOP02/Geolocation Fields/Latitude')
moplat = H5D_Read(dataset_id)
H5D_CLOSE, dataset_id

; read longitudes into variable 'moplon'
print, 'read longitudes'
dataset_id = H5D_OPEN(file_id, '/HDFEOS/SWATHS/MOP02/Geolocation Fields/Longitude')
moplon = H5D_Read(dataset_id)
H5D_CLOSE, dataset_id

; read retrieved profiles into variable 'rtvprofil'
print, 'read retrieved CO profiles'
dataset_id = H5D_OPEN(file_id, '/HDFEOS/SWATHS/MOP02/Data Fields/RetrievedCOMixingRatioProfile')
rtvprofil = H5D_Read(dataset_id)
H5D_CLOSE, dataset_id

; read averaging kernel matrices into variable 'avkrn'
print, 'read AK matrix'
dataset_id = H5D_OPEN(file_id, '/HDFEOS/SWATHS/MOP02/Data Fields/RetrievalAveragingKernelMatrix')
avkrn = H5D_Read(dataset_id)
H5D_CLOSE, dataset_id

H5F_CLOSE, file_id

; print lat and lon of first retrieval
print, moplat(0), moplon(0)
; print retrieved profile of first retrieval (fixed-levels only, surface retrieval missing)
print, rtvprofil(0,0:8,0)
; print AK matrix for first retrieval
print, avkrn(0:9,0:9,0)

return
end

```

C. Sample NCL Code for Opening and Reading V7 Level 2 files

```

=====;
; example-mopitt-v7-lev2.ncl
=====;
;
; Concepts illustrated:
; - For use with MOPITT CO version 7, level 2 product
; - Loading CO data, AK, latitude and longitude from
;   MOPITT level 2 hdf5 file
;
; To run type:
;   ncl example-mopitt-v7-lev2.ncl
;
=====;

begin

; -----
; MOPITT file location
; -----

```

```
indir = "/MOPITT/V7T/Archive/L2/200301/0101/"
fname = "MOP02T-20030101-L2V17.8.1.he5"
infile = indir+fname
print(infile)

;-----
; load file and extract data structures
;-----
; -----
; names of data structures
; determined from an ncl_filedump
print("load hdf5 file")
fin = addfile(infile, "r")
; extract longitude
moplon = fin->"Longitude_MOP02"$
; extract latitude
moplat = fin->"Latitude_MOP02"$
; extract profile
ret_profile = fin->"RetrievedCOMixingRatioProfile_MOP02"$
; extract averaging kernel
avkrn = fin->"RetrievalAveragingKernelMatrix_MOP02"$

;-----
; print data structure information
;-----
; Determine dimensions of data structures
printVarSummary(moplon)
printVarSummary(moplat)
printVarSummary(ret_profile)
printVarSummary(avkrn)

; print lat, lon of first retrieval
print("Latitude: "+ moplat(0)+" Longitude: "+moplon(0))
; print first retrieved profile on fixed levels - surface retrieval is in a separate data structure
print(ret_profile(0,:,0))
; print AK matrix for first retrieval
print(avkrn(0,:,:))

end
```