Algorithm Theoretical Baseline Document:
Level 2C Tropopause Height

Version 2.1

14 May 2020

ROM SAF Consortium
Danish Meteorological Institute (DMI)
European Centre for Medium-Range Weather Forecasts (ECMWF)
Institut d'Estudis Espacials de Catalunya (IEEC)
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<tr>
<th>Author(s)</th>
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DOCUMENT CHANGE RECORD

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<th>Date</th>
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- RID 175: Ch. 3, "error" exchanged with "uncertainty" where possible.  
- RID 210 Ch. 3, paragraph 4 was rewritten. [RD.10] left out.  
In addition the following update was implemented:  
Reference to new ROPP user guide [RD.10] |
| 1.5     | 20/12/2018 | JKN    | Updated version based on ICDR concept discussions at ROM SAF SG22:  
- p3, updated ROM SAF description.  
- Sec 1.1, update GRM table.  
- Sec 1.4, changed “Definitions”.  
- Ch 5, mentioned ICDR in title. |
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- Section 1.1: New subsection 1.1.1  
- P10 changed NRT/Offline definition  
- P18 removed CDR ICDR version numbers  
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- None |
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- Sec. 1.1.1: text and table about future EPS-SG Day 1 products removed [RIDs 43, 98]  
- Sec. 1.3: removed EPS-SG from acronyms [RIDs 43, 98] |
ROM SAF
The Radio Occultation Meteorology Satellite Application Facility (ROM SAF) is a decentralised processing centre under EUMETSAT which is responsible for operational processing of radio occultation (RO) data from the Metop and Metop-SG satellites and radio occultation data from other missions. The ROM SAF delivers bending angle, refractivity, temperature, pressure, humidity, and other geophysical variables in near real-time for NWP users, as well as reprocessed Climate Data Records (CDRs) and Interim Climate Data Records (ICDRs) for users requiring a higher degree of homogeneity of the RO data sets. The CDRs and ICDRs are further processed into globally gridded monthly-mean data for use in climate monitoring and climate science applications.

The ROM SAF also maintains the Radio Occultation Processing Package (ROPP) which contains software modules that aid users wishing to process, quality-control and assimilate radio occultation data from any radio occultation mission into NWP and other models.

The ROM SAF Leading Entity is the Danish Meteorological Institute (DMI), with Cooperating Entities: i) European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading, United Kingdom, ii) Institut D'Estudis Espacials de Catalunya (IEEC) in Barcelona, Spain, and iii) Met Office in Exeter, United Kingdom. To get access to our products or to read more about the ROM SAF please go to: http://www.romsaf.org

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List of Contents

1. INTRODUCTION ................................................................................................................................. 6
   1.1 PURPOSE .............................................................................................................................................. 6
   APPLICABLE AND REFERENCE DOCUMENTS .......................................................................................... 7
      1.1.1 Applicable Documents .................................................................................................................. 7
      1.1.2 Reference Documents .................................................................................................................. 7
   1.2 ACRONYMS AND ABBREVIATIONS .................................................................................................. 8
   1.3 DEFINITIONS .................................................................................................................................... 8
   1.4 OVERVIEW OF THIS DOCUMENT ................................................................................................... 10

2. BACKGROUND ..................................................................................................................................... 11

3. TROPOPAUSE HEIGHT ......................................................................................................................... 12
   3.1 DESCRIPTION OF ALGORITHM ........................................................................................................... 12
   3.2 PROCESSING STEPS .......................................................................................................................... 13
   3.3 QUALITY CONTROL ........................................................................................................................... 14

4. ASSUMPTIONS AND LIMITATIONS .................................................................................................... 16

5. DESCRIPTION OF DIFFERENCES FOR NRT, OFFLINE CDR AND ICDR ............................................. 17

APPENDIX A ............................................................................................................................................ 18
   A.1 RUNNING THE PROGRAM ................................................................................................................... 18
   A.2 INPUT FILES ..................................................................................................................................... 18
   A.3 OUTPUTS .......................................................................................................................................... 19
1. Introduction

1.1 Purpose

This ATBD document describes the algorithms used to derive the Level 2C tropopause height produced by the Radio Occultation Meteorology (ROM) Satellite Application Facility (SAF). The document covers Offline, CDR and ICDR-products. The complete list of products covered by this ATBD is provided in Table 1.1. Note that this table may include both products in development and products with operational status. The status of all ROM SAF data products is available at the website: http://www.romsaf.org.

The product requirements baseline is the PRD [AD.3]. The system software package referred to in this ATBD is GPAC 2.4.0.1. It is based on the ROPP-9.01 with adaptations made by DMI. Adaptations made by DMI will be included in a future official ROPP release.

Table 1.1 List of products covered by this ATBD:

*) The fifth column describes the original data source; satellite/instrument, data-level, institution. “Level 1A” refers to excess phase data.

<table>
<thead>
<tr>
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<th>Product name</th>
<th>Product acronym</th>
<th>Product type</th>
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<td>TPH</td>
<td>NRT, Offline</td>
<td>Product</td>
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<td>netCDF</td>
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<tr>
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<td>Reprocessed Tropopause height</td>
<td>RCHMET</td>
<td>Reprocessed Data Record</td>
<td>Metop Level 1A data from EUM Secretariat</td>
<td>web</td>
<td>netCDF</td>
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<td>web</td>
<td>netCDF</td>
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<td>RCHCHA</td>
<td>Reprocessed Data Record</td>
<td>CHAMP Level 1A data from CDAAC</td>
<td>web</td>
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<td>RCHGRA</td>
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<td>ICDR</td>
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1 ROPP stands for “Radio Occultation Processing Package”. It is a software package maintained by ROM SAF. See [RD.28] for an ROPP overview.
Applicable and reference documents

1.1.1 Applicable Documents
The following list contains documents with a direct bearing on the contents of this document:


[AD.2] CDOP-3 Cooperation Agreement: Agreement between EUMETSAT and DMI on the Third Continuous Development and Operations Phase (CDOP-3) of the Radio Occultation Meteorology Satellite Applications Facility (ROM SAF), Ref. EUM/C/85/16/DOC/19, approved by the EUMETSAT Council and signed at its 86th meeting on 7 December 2016


1.1.2 Reference Documents
The following documents provide supplementary or background information, and could be helpful in conjunction with this document:

[RD.1] ROM SAF ATBD: 1DVAR algorithms, SAF/ROM/DMI/ALG/1DV/002

[RD.2] ROM SAF ATBD: Level 2A Refractivity Profiles, SAF/ROM/DMI/ALG/REF/001


### 1.2 Acronyms and abbreviations

- **CDOP**: Continuous Development and Operations Phase
- **CDR**: Climate Data Record
- **DMI**: Danish Meteorological Institute
- **ECMWF**: European Centre for Medium-range Weather Forecasts
- **EDC**: EUMETSAT Data Centre (former UMARF)
- **EUMETSAT**: European organisation for the exploitation of METeorological SATellites
- **GNSS**: Global Navigation Satellite System
- **GPAC**: GNSS Processing and Archiving Center (ROM SAF)
- **GPS**: Global Positioning System (US)
- **GRAS**: GNSS Receiver for Atmospheric Sounding (Metop instrument)
- **IEEC**: Institut d’Estudis Espacials de Catalunya (Spain)
- **ICDR**: Interim Climate Data Record
- **LEO**: Low Earth Orbiter
- **Metop**: Meteorological Operational Polar satellite (EPS/EUMETSAT)
- **NRT**: Near-Real Time
- **NWP**: Numerical Weather Prediction
- **RO**: Radio Occultation
- **ROM SAF**: Radio Occultation Meteorology SAF (EUMETSAT), former GRAS SAF
- **SAF**: Satellite Application Facility (EUMETSAT)
- **UKMO**: The UK Meteorological Office (aka: Met Office)
- **UMARF**: Unified Meteorological Archive & Retrieval Facility (EUMETSAT)
- **WMO**: World Meteorological Organisation

### 1.3 Definitions

RO data products from the Metop and Metop-SG satellites and RO data from other missions are grouped in *data levels* (level 0, 1, 2, or 3) and *product types* (NRT, offline,
CDR, or ICDR). The data levels and product types are defined below\(^2\). The lists of variables should not be considered as the complete contents of a given data level, and not all data may be contained in a given data level.

Data levels:

- **Level 0**: Raw sounding, tracking and ancillary data, and other GNSS data before clock correction and reconstruction;
- **Level 1A**: Reconstructed full resolution excess phases, total phases, pseudo ranges, SNRs, orbit information, I, Q values, NCO (carrier) phases, navigation bits, and quality information;
- **Level 1B**: Bending angles and impact parameters, tangent point location, and quality information;
- **Level 2**: Refractivity, geopotential height, “dry” temperature profiles (Level 2A), pressure, temperature, specific humidity profiles (Level 2B), surface pressure, tropopause height, planetary boundary layer height (Level 2C), ECMWF model level coefficients (Level 2D), quality information;
- **Level 3**: Gridded or resampled data that are processed from Level 1 or 2 data, and that are provided as, e.g., daily, monthly, or seasonal means on a spatiotemporal grid, including metadata, uncertainties and quality information.

Product types:

- **NRT product**: Data product delivered less than: (i) 3 hours after measurement (SAF Level 2 for EPS); (ii) 150 min after measurement (SAF online products for EPS-SG Global Mission); (iii) 125 min after measurement (SAF online products for EPS-SG Regional Mission);
- **Offline product**: Data product delivered from less than 5 days to up to 6 months after measurement, depending on the requirements. The evolution of this type of product is driven by new scientific developments and subsequent product upgrades;
- **CDR**: Climate Data Record generated from a dedicated reprocessing activity using a fixed set of processing software\(^3\). The data record covers an extended time period of several years (with a fixed end point) and constitutes a homogeneous data record appropriate for climate usage;
- **ICDR**: An Interim Climate Data Record (ICDR) regularly extends in time a (Fundamental or Thematic) CDR using a system having optimum consistency with and lower latency than the system used to generate the CDR\(^4\).

---

1. Note that the level definitions differ partly from the WMO definitions: http://www.wmo.int/pages/prog/sat/dataandproducts_en.php
2. (i) GCOS 2016 Implementation Plan; (ii) http://climatemonitoring.info/home/terminology/
3. http://climatemonitoring.info/home/terminology/ (the ICDR definition was endorsed at the 9th session of the joint CEOS/CGMS Working Group Climate Meeting on 29 March 2018)
1.4 Overview of this document

This document is organized as follows:

Chapter 1: Contains the introduction

Chapter 2: Contains a very brief summary of the processing from the RO basic observables to higher level data

Chapter 3: Contains the detailed description of the TPH algorithm

Chapter 4: Contains a discussion of some limitations for the algorithm

Chapter 5: Description of differences for NRT, Offline and Reprocessing

Annex A: Contains information about the source code
2. Background

A radio occultation (RO) instrument onboard a low-Earth orbit (LEO) satellite, e.g. the GRAS instrument onboard Metop, measures the L1 and L2 Doppler shifted radio signals from a GNSS satellite as the satellite sets or rises behind the Earth’s limb. Through a rather complex sequence of processing steps the Doppler shift as a function of time is converted to neutral-atmosphere profiles of bending angle, refractivity, dry pressure and dry temperature, and finally to 1D-Var pressure, temperature, and humidity. The latter three quantities require a priori information taken from an atmospheric model. A priori data are also used for bending angle initialization in order to retrieve refractivity.

Comprehensive descriptions of how the primary observables, phase and amplitude of the Doppler shifted signals, are processed to atmospheric profiles can be found in [RD.1, 2, 3].
3. **Tropopause Height**

The tropopause height (TPH) is most often derived from the rate of decrease of temperature with height, the lapse-rate.

In the ROPP processor apps module, the TPHs are derived via the tool: `ropp_apps/tools/ropp_apps_tph_tool` which allows diagnosing the TPHs from profiles of bending angle (level 1B product), refractivity (level 2A), dry temperature (level 2A) or (wet) temperature (level 2B). For each of the two temperature-based TPH’s two tropopause estimates are produced; one based on the lapse-rate and one based on the cold point.

The operational ROM SAF TPH product is defined to be the dry temperature lapse rate which is described in this document. The dry temperature lapse rate TPH is based on the standard WMO lapse-rate criterion and validation against other TPH results (radiosondes) is simple. Information on the other TPHs (internal products) can be found in the ROPP documentation [RD.10].

In [RD.6] (T. Schmidt, VS 22) some recommendations are listed regarding the TPH algorithms. One of the points raised in [RD.6], was to search for a TPH/CPT between 500 hPa and 70 hPa only. Instead of the 500 hPa and 70 hPa limits recommended, a latitude dependent TPH min and max height has been implemented (See Sec. 3.2 point 2). In [RD.6] it is also recommended to limit the cold point tropopause product to be nominal in the tropics (-30 deg to +30 deg), (implemented) and to add variables for recording the overall temperature minimum and height for all profiles (not implemented). Furthermore, [RD.6] recommends not to disregard cases with multiple tropopauses. This has also been implemented, but only the lowest (height) tropopause is reported.

### 3.1 Description of algorithm

The algorithm is developed to derive the TPH according to the WMO definition, where TPH is defined as “the lowest level at which the lapse-rate ($\Gamma_{WMO}$) decreases to 2°C/km or less, provided that the average lapse-rate between this level and all higher levels within 2 km does not exceed 2°C/km.” [RD.4]

The lapse rate method described by Reichler et al. (2003) [RD.5] is applied. The algorithm uses a thermal definition of the tropopause, based on the concept of a threshold lapse-rate. Interpolation is performed to identify the pressure at which this threshold is reached and maintained. In the event of multiple vertical levels meeting these criteria, the tropopause is assigned to the lowest position of occurrence. Furthermore, the derived tropopause height must be within a latitude dependent height range corresponding to approximately 75 hPa to 550 hPa to be accepted.

The algorithm is expressed in terms of pressure, which is not available as level 2A field in ROPP. Thus, dry pressure calculated from refractivity and dry temperature (both level 2A) is used in the steps below as proxies for the full pressure and temperature. [RD.3]
3.2 Processing steps

Below the main steps in the algorithm are described.

1. Ensure that the geometric heights \((h_i)\) are in ascending order and that enough level 2a data exist. If not, return to \texttt{ropp_apps_tph_tool}

2. Check numerical and scientific robustness of the input temperature.
   2.1) There must be at least three temperature – refractivity pairs \((T_i, N_i)\) of valid data and a valid latitude value defined. This is a technical limit, profiles with only two or less valid data points will be excluded in the following steps.
   2.2) The geometric heights \((h_i)\) must start below or at \(TPH_{min} = 2.5(3 + \cos(2 \times \text{lat}))\) and
   2.3) continue to or above \(TPH_{max} = 2.5(7 + \cos(2 \times \text{lat}))\)

3. Calculated dry pressure \((p)\) from the refractivity \((N)\) and dry temperature \((T)\) using:
   \[ p = \frac{NT}{\kappa_1} \]
   The standard value [RD.8] of \(\kappa_1 = 77.6 \times 10^{-2} \text{ KPa}^{-1}\) is used here.
   Recent studies have indicated the need for a small revision of the values, and have shown a weak dependence on deviations from the ideal gas law [RD.7]. When using a non-ideal gas law in applications that include forward modelling from model data, the coefficient used is instead \(\kappa_1 = 77.643 \times 10^{-2} \text{ KPa}^{-1}\) [RD.9]. This small change of coefficient will cause a change of the derived TPH of only a few meters.

4. Smooth pressure and temperature profiles according to
   \[
   T_i \rightarrow \frac{T_{i-1} + T_i + T_{i+1}}{3} \\
   p_i \rightarrow \frac{p_{i-1} + p_i + p_{i+1}}{3}
   \]

5. Calculate Exner pressure \((\Pi)\)
   \[
   \Pi_i = (p_i/p_{ref})^\kappa \text{ where } \kappa = R_{dry}/C_p \approx 0.285
   \]
   \(R_{dry}\) and \(C_p\) being the dry air specific gas constant and heat capacity, and calculate lapse rate \((\Gamma)\)
   \[
   -\Gamma_{i+1/2} = \left(-g/C_p\right) \frac{T_{i+1}-T_i}{\Pi_{i+1}-\Pi_i} \frac{\Pi_{i+1}+\Pi_i}{T_{i+1}+T_i}
   \]

6. Go through the profile and for each point \((i)\): if \(-\Gamma_{i+1/2}\) and the average over the 2 km above is greater than \(-\Gamma_{WMO} = -2 \text{ K/km}\) and the previous, \(-\Gamma_{i-1/2}\), is less than \(-\Gamma_{WMO}\), so that points \(i-1/2\) and \(i+1/2\) enclose the critical lapse rate, then the first estimate of the index of the lapse rate tropopause is taken to be \(i\).
7. Calculate TPH by linear interpolation of $\Gamma$ with $\Pi$, followed by linear interpolation of $\log(p)$ with height $h$.

\[
2\Pi_{tph} = (\Pi_i + \Pi_{i-1}) + \frac{\Pi_{i+1} - \Pi_{i-1}}{\Gamma_{i+1/2} - \Gamma_{i-1/2}} (\Gamma_{WO} - \Gamma_{i-1/2})
\]

\[
p_{tph} = p_{ref} \frac{1}{\Pi_{tph}^{1/\kappa}}
\]

\[
h_{tph} = h_{i-1} + \frac{h_i - h_{i-1}}{\log(p_i/p_{i-1})} \log(p_{tph}/p_{i-1})
\]

\[
T_{tph} = T_i - 1 + \frac{T_i - T_{i-1}}{\log(p_i/p_{i-1})} \log(p_{tph}/p_{i-1})
\]

8. Check that the derived TPH is within the range $TPH_{min}$ to $TPH_{max}$ as defined above in step 2.

9. Overall profile minimum temperature and its geometric height are calculated.

10. Fill quality flags, lapse rate TPH and dry temperature at the TPH, and the entire profile heights and temperatures to their equivalents in the ROPP structure. Thus, the dry temperature derived TPHs are on geometric heights.

In step 6 above, the cold point tropopause is also calculated, as being the height of the minimum temperature between $TPH_{min}$ and $TPH_{max}$. If this height differs by more than 2 km from $h_{tph}$, then use the minimum temperature in the height interval $h_{tph} \pm 2$km.

Note that the cold point TPH is not an operational ROM SAF product, and that the cold point definition of THP is not meaningful outside the tropics. Therefore, at latitudes polewards of 30°, a bit is set to the cold point TPH QC flag and a missing value to the cold point TPH variable.

### 3.3 Quality control

The TPHs are associated with a 'bit-wise' encoded quality control flag as described in the ROPP documentation. [RD.3]

The flag is initialised at ropp\_MIFV=-999, and otherwise encoded bit by bit as:

\[
tph\_qc\_flag = \sum_{r=0}^{7} l(r)2^r
\]

The 8 components ($r$) are described as:

- $r=0$ Input data validity check
- $r=1$ Input data depth check
The value \( l(r) \) is 0 if the check is passed or irrelevant and 1 if the data check is not ok, e.g., if the derived dry temperature TPH is below the minimum accepted height, then \( l(6) = 1 \) and this bit contributes with \( 2^6 = 64 \) to the \( tph_qc\_flag \).

The relevant components for the dry temperature derived TPH are \( r = 0,1,2,6 \) and 7:

- \( r=0 \) relates to step 2.1 in section 3.2
- \( r=1 \) relates to step 2.2
- \( r=2 \) relates to step 2.3
- \( r=6 \) and \( r=7 \) relates to step 8 in section 3.2

If the QC flag is zero, the diagnosed TPH is considered to be good, any other values indicate some problems with the integrity of the derived TPH, problems that can be identified using the value of \( tph_qc\_flag \).

QC flags are copied to the ROPP variable: ro_data%lev2c%tphdry_lrt_flag
4. Assumptions and limitations

The dry temperature lapse rate tropopause depends on the vertical resolution of the profile which will lead to differences between model and observation tropopauses. Especially in double tropopause cases the observational dry temperature and model dry temperature may occasionally “catch” different tropopause estimates.
5. **Description of differences for NRT, Offline CDR and ICDR**

The algorithm is the same for all four types of processing.
Appendix A

A.1 Running the program

Calling the ROPP module for calculating TPH:

```bash
ropp_apps_tph_tool <inputROPPfile> -o <outputROPPfile>
```

Options:
- `-o <output_file>` name of ROPP netCDF output file
- `-b` calculate bending angle-based TPH only
- `-n` calculate refractivity-based TPH only
- `-y` calculate dry temperature-based TPH only
- `-t` calculate temperature-based TPH only
- `-h` help
- `-d` output additional diagnostics
- `-v` version information

If none of the `-b,-n,-y` or `-t` options are specified, the tool will attempt to calculate all four TPHs.

All TPHs are present in output netCDF file, if not calculated then filled with missing values.
If `-d` option is present the lapse rate (section 3.2, step 5) and corresponding geometric heights are added to the output file.

A.2 Input files

**Input data:** For any GNSS RO satellite sensor supported: profiles of bending angle, refractivity, dry temperature or temperature

**NRT:**

The NRT file name version is the filename version that is used in the NRT processing chain, for both level 1 and level 2 products. It contains 6 fields separated by underscores:

```plaintext
<TYPE><DATE>_<TIME>_<MISSION_ID>_<OCC_ID>_<MODE><SWVER>_<FREEE><EXT>
```

Where:

- `<TYPE>` can be one of “atm”, ”bfr”, ”bgr”, ”dis”, ”occ” or “wet”
  For the calculation of TPH the following types are used.
  “atm” files contain ROPP level 1A and 2A data, necessary for calculating dry temperature TPH (as well as bending angle TPH, refractivity TPH)
“occ” files contain ROPP level 1A data, necessary for bending angle TPH
“wet” files  contain ROPP level 2B data, necessary for (wet) temperature TPH

- `<DATE>_<TIME>` is the start date and time of the observation, as YYYYMMDD_HHMMSS.
- `<MISSION-ID>` is the EPS name of the observing satellite.
- `<OCC_ID>` is the occultation id (EPS format which includes id of occulting satellite)
- `<MODE>` is the processing mode and one of “N” (Near Real Time), “T” (Test), “V” (Validation).
- `<SWVER>` is a four digit code denoting the system software version
- `<FREE>` is a free field, “XXXX”
- `<EXT>` is the extension, “nc” for NetCDF, “bin” for BUFR

**Offline:**

The offline level 1 and 2 file name version is the filename version that is used in the offline and re-processing chain. It contains 8 fields separated by underscores:

```
<TYPE>_ <DATE>_ <TIME>_ <MISSION_ID>_ <OCC_ID>_ <MODE>_ <SWVER>_ <FREE>_ <EXT>
```

Where:

- `<TYPE>`, `<DATE>_` `<TIME>`, `<MISSION-ID>`, `<SWVER>`, and `<EXT>` is as explained above.
- `<OCC_ID>` is an ID that identifies the GNSS satellite used for the specific occultation.
- `<MODE>` is the processing mode and one of “O” (offline), “R” (Reprocessing), “T” (Test), “V” (Validation)

**A.3 Outputs**

The output variables in the ROPP structure (ro_data%lev2c%):

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>tph_tdry_lrt</td>
<td>Dry temperature-based TPH derived from lapse rate</td>
</tr>
<tr>
<td>tpt_tdry_lrt</td>
<td>Tropopause dry temperature, based on tph_tdry_lrt</td>
</tr>
<tr>
<td>tph_tdry_lrt_flag</td>
<td>Dry temperature-based TPH QC flag (lapse rate)</td>
</tr>
<tr>
<td>tph_bangle</td>
<td>Bending angle-based TPH</td>
</tr>
<tr>
<td>tpa_bangle</td>
<td>Tropopause bending angle, based on tph_bangle</td>
</tr>
<tr>
<td>tph_bangle_flag</td>
<td>Bending angle-based TPH QC flag</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------------------------------------------------</td>
</tr>
<tr>
<td>tph_refrac</td>
<td>Refractivity-based TPH</td>
</tr>
<tr>
<td>tph_refrac</td>
<td>Tropopause refractivity, based on tph_refrac</td>
</tr>
<tr>
<td>tph_refrac_flag</td>
<td>Refractivity-based TPH QC flag</td>
</tr>
<tr>
<td>tph_tdry_cpt</td>
<td>Dry temperature-based TPH derived from cold point</td>
</tr>
<tr>
<td>tpt_tdry_cpt</td>
<td>Tropopause dry temperature, based on tph_tdry_cpt</td>
</tr>
<tr>
<td>tph_tdry_cpt_flag</td>
<td>Dry temperature-based TPH QC flag (cold point)</td>
</tr>
<tr>
<td>tph_temp_lrt</td>
<td>Temperature-based TPH derived from lapse rate</td>
</tr>
<tr>
<td>tpt_temp_lrt</td>
<td>Tropopause temperature, based on tph_temp_lrt</td>
</tr>
<tr>
<td>tph_temp_lrt_flag</td>
<td>Temperature-based TPH QC flag (lapse rate)</td>
</tr>
<tr>
<td>tph_temp_cpt</td>
<td>Temperature-based TPH derived from cold point</td>
</tr>
<tr>
<td>tpt_temp_cpt</td>
<td>Tropopause temperature, based on tph_temp_cpt</td>
</tr>
<tr>
<td>tph_temp_cpt_flag</td>
<td>Temperature-based TPH QC flag (cold point)</td>
</tr>
</tbody>
</table>