EUMETSAT

Topside Total Electron Content (tTEC) Product Format Specification

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Document Change Record

Version	Date of Version	Document Change Request (DCR) Number	Description of Changes
v1B	04.07.2018	—	Initial version.
v1C	29.08.2018	—	• Added `_utc` to the name of "time" related global attributes. • Added `product_name` as global attribute. • Changed the `/status/satellite` group variable name `leap_second_utc` to `leap_second_time_utc`. • Changed the `/status/satellite` group variable name `leap_second` to `leap_second_value` and updated its type into "short". • `creation_time_utc` is not anymore an attribute but a variable of the `/status/processing` group.

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1 INTRODUCTION

1.1 Purpose and Scope

This document is the Product Format Specification (PFS) for the files generated at EUMETSAT containing information about the topside Total Electron Content, which is the Total Electron Content (TEC) in the ionosphere above a certain orbit altitude. These kind of information can be derived for any satellite mission flying below the GNSS satellites (for example in a LEO orbit) equipped with a dual frequency GNSS receiver and a zenith looking antenna for POD purposes. The format of the topside Total Electron Content (tTEC) data file is netCDF-4 [AD–1].

This document describes the **v1.0** of the tTEC file format.

1.2 Applicable Documents

[AD–1] NetCDF data format description, cited 30 November 2016, http://www.unidata.ucar.edu/software/netcdf/docs/.

1.3 Reference Documents

[RD–1] CF Conventions v1.7, available at http://cfconventions.org/Data/cf-conventions/cf-conventions-1.7/cf-conventions.pdf.

[RD–2] The Multi-GNSS Experiment and Pilot Project (MGEX), data available at http://mgex.igs.org/IGS_MGEX_Products.php.

[RD–3] J. Zhong, J. Lei, X. Yue and X. Dou, Determination of Differential Code Bias of GNSS Receiver Onboard Low Earth Orbit Satellite, in IEEE Transactions on Geoscience and Remote Sensing, vol. 54, no. 8, pp. 4896-4905, Aug. 2016, doi: 10.1109/TGRS.2016.2552542.

[RD–4] Foelsche, U., and G. Kirchengast, A simple "geometric" mapping function for the hydrostatic delay at radio frequencies and assessment of its performance, Geophys. Res. Lett., 29(10), doi:10.1029/2001GL013744, 2002.

[RD–5] J. A. Klobuchar, Ionospheric Time-Delay Algorithm for Single-Frequency GPS Users, in IEEE Transactions on Aerospace and Electronic Systems, vol. AES-23, no. 3, pp. 325-331, May 1987. doi: 10.1109/TAES.1987.310829.

[RD–6] RINEX - The Receiver Independent Exchange Format, Version 3.03, available at ftp://igs.org/pub/data/format/rinex303.pdf.

1.4 Acronyms

CF	Climate and Forecast
DCB	Differential Code Bias
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GNSS	Global Navigation Satellite System
IPP	Ionospheric Pierce Point
LEO	Low Earth Orbit
netCDF-4	Network Common Data Format, version 4
PFS	Product Format Specification
POD	Precise Orbit Determination
PRN	Pseudo-Random-Noise
RINEX	Receiver Independent Exchange Format
RO	Radio Occultation
RX	receiver
sTEC	slant Total Electron Content
TEC	Total Electron Content
tTEC	topside Total Electron Content
TX	transmitter
UTC	Coordinated Universal Time
vTEC	vertical Total Electron Content

1.5 Conventions and Terminology

Generic conventions and terminology incorporated for defining the tTEC format are generally following [RD–1].

1.6 Document Structure

The document is structured as follows:

Chapter 1: Introduction (this chapter)

Chapter 2: Zenith Total Electron Content Overview

Chapter 3: Zenith Total Electron Content format specification details

2 TOPSIDE TOTAL ELECTRON CONTENT OVERVIEW

2.1 Introduction

The zenith antenna connected to a GNSS receiver on board a LEO satellite is necessary for the Precise Orbit Determination (POD) of the satellite. But GNSS signals acquired through the zenith antenna cross solely the ionosphere. Thanks to its dispersive nature, signals characterized by different carrier frequencies experience different delays and such delays are proportional to the Total Electron Content (TEC) which is the total number of electrons present along the path between the transmitter and receiver.

Being the TEC measured by a receiver flying on a LEO satellite, it is generally referred to as the topside Total Electron Content (tTEC). When it is measured on the line of sight between transmitter and receiver it is often referred to as slant Total Electron Content (sTEC). When sTEC is projected (or mapped) into the vertical direction it is referred to as vertical Total Electron Content (vTEC).

2.2 Processing Strategy

In order to derive tTEC data, carrier phases and pseudoranges for two different carrier frequencies must be available at each measurement epoch. These variables are taken by the RINEX files associated to the GNSS observations collected by the zenith antenna. Let's call L1 and L2 the two carrier phases and P1 and P2 the two pseudoranges.

An outline of the main processing steps is summarized in Fig. 2.1.

After having corrected for the POD antenna phase pattern effects (if any) and having corrected for the fluctuations induced by local multipath (if any), the (topside) sTEC can be obtained by levelling the L1-L2 carrier phases difference to the P2-P1 pseudoranges difference. This result is referred in the literature to as uncalibrated sTEC because it is offset from the true value due to unknown P2-P1 delays introduced by both the transmitter and receiver hardware. Such delays are called Differential Code Biases (DCBs). The transmitters DCBs are normally available from external providers in charge of routinely estimating the value for each GNSS satellite[1]. The receiver DCB is instead directly estimated by the available observations, as a preprocessing step[2].

Once calibrated sTEC is computed (by removing the two DCBs from the uncalibrated value), the topside vertical Total Electron Content (vTEC) value can be derived by using a suitable mapping function[3], which requires the availability of precise transmitter and receiver positions. Assuming that the ionosphere is a thin, uniform-density shell above the receiver orbit, the intersection between the LEO-GNSS line of sight and this shell is called the Ionospheric Pierce Point (IPP)[4]. The latter is the point used to geolocate the vTEC value.

[1] In our current configuration we have used those estimated in the framework of the Multi-GNSS Experiment and Pilot Project (IGS/MGEX) (see [RD–2]).
[2] In our current configuration we have followed the procedures described in [RD–3].
[3] In our current configuration we have used the mapping function described in [RD–4].
[4] The procedure to geolocate the Ionosheric Pierce Point is described in [RD–5].

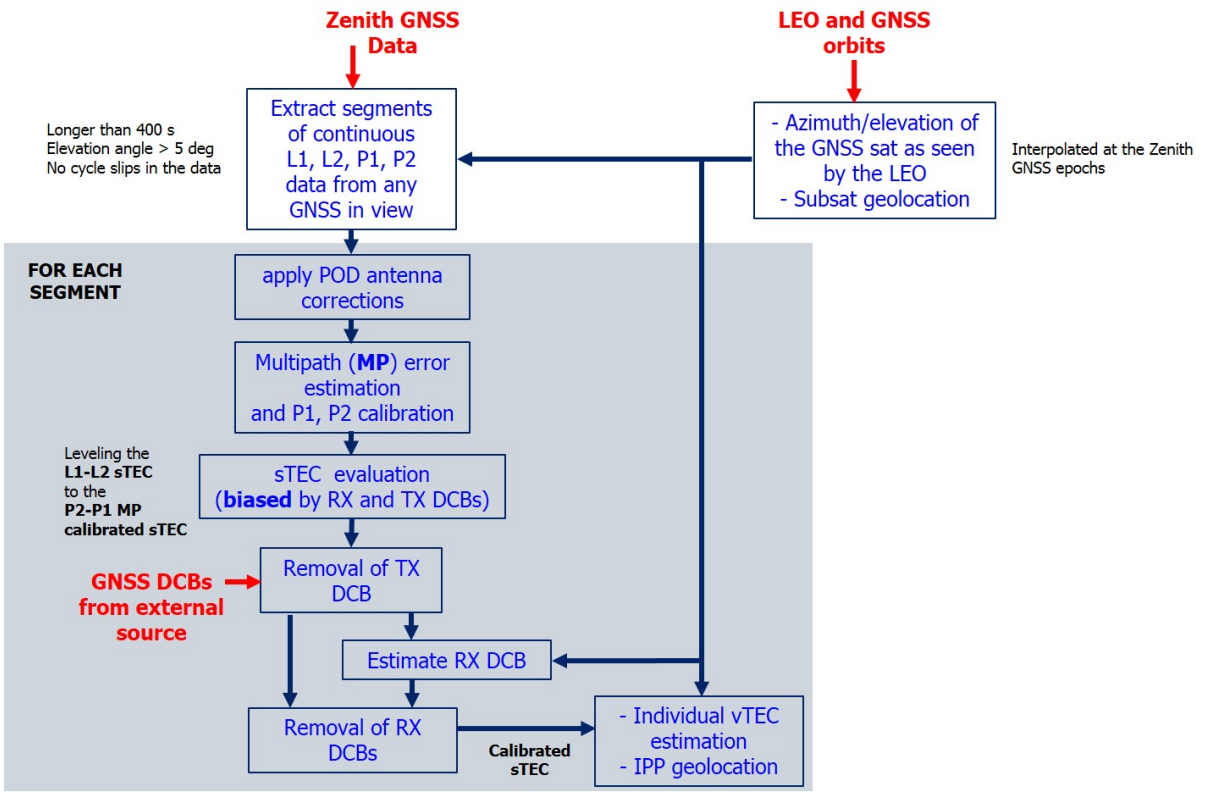

Fig. 2.1: Main processing steps for the estimation of the tTEC.

2.3 Topside Total Electron Content Filename

For the time being the tTEC will be distributed for testing purposes only. Test products use the following naming convention:

```
<inst>_TEC_1C_<sat>_<start_time>Z_<stop_time>Z_<create_time>Z.nc
```

where:

`<inst>`	4-characters instrument ID (e.g., `GRAS` for the GRAS instrument)
`<sat>`	3-characters satellite ID (e.g., `M02` for Metop-A, `M01` for Metop-B and `M03` for Metop-C)
`<start_time>`	14-digits sensing start UTC time (e.g., `20170101000000` for 00:00:00 UTC on 01 January 2017)
`<end_time>`	14-digits timestamp characterising sensing end UTC time
`<create_time>`	14-digits timestamp characterising product creation UTC time

Being this a netCDF-4 file, the extension is always "`nc`". Test data product typically cover a period of one day.

3 TOPSIDE TOTAL ELECTRON CONTENT FORMAT SPECIFICATION DETAILS

Details of the tTEC product format are provided in this section, just after having given some general information on the netCDF structure and details regarding the conventions used.

3.1 Overall Group Structure

Each tTEC product exploits netCDF's data group feature in order to structure its data contents as shown in Fig. 3.1. In particular, it consists of a root (`/`) group, holding global attributes as well as `/status` and `/data` subgroups.

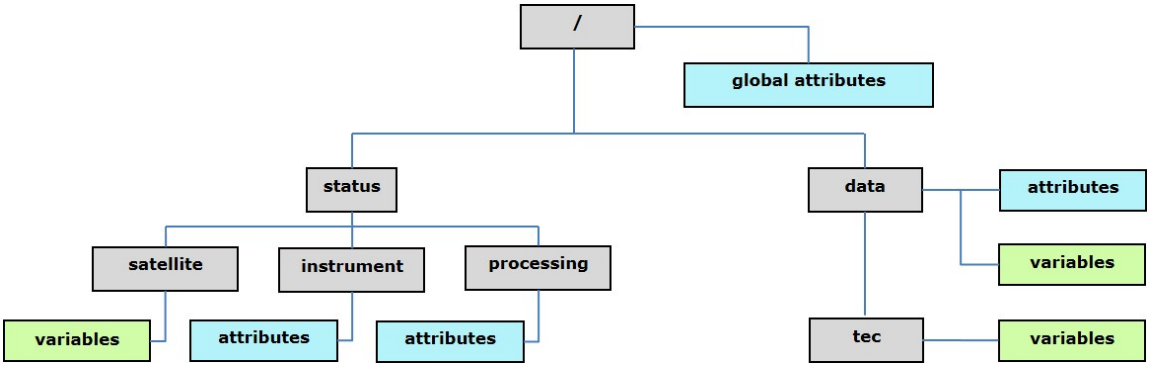

Fig. 3.1: NetCDF data group structure of topside Total Electron Content file.

3.2 Overall Conventions

Meta data handling is mostly based on the Climate and Forecast (CF) conventions [RD–1]. As this mainly provides guidance on netCDF-3 formatted data files, the original CF conventions are applied at the level of individual groups and subgroups, with the repetition of meta data being avoided as far as possible. The resulting use of variable attributes is described in Sec. 3.2.2, while conventions on representing times are described in Sec. 3.2.3.

3.2.1 Dimensions

The tTEC data format contains scalar, one-dimensional and two-dimensional variables. Examples for 1d variables are time series of derived quantities like sub-satellite point latitudes and longitudes or local times at the sub-satellite point. Other examples are the list of GNSS satellite IDs whose signals are used in the processing. Time series of uncalibrated and calibrated sTEC or vTEC for all the GNSS satellites in view are examples of 2d variables.

The tTEC data format uses standard dimension names in the `/status` and `/data` groups. The list is provided in Tab.3.1. In the tables describing the contents of the various groups in the following sections, the shape of array variables is given in terms of these dimension names. Thus a variable with a shape of `(t)` denotes a 1d time series variable, with a length defined by the time interval coverage of the product and by the input data sampling rate. A shape of `(t,s)` describes a 2d

Name	Description
-	Scalar variables
t	Time coordinates
s	GNSS Satellite IDs†

† formatted as SNN where S is the Satellite System Identifier and NN refers to the PRN number as defined by [RD–6].

Tab. 3.1: Standard dimension names and their meaning.

Unit	Abbr.	Comments
degrees	<deg>	angles if not expressed in rad
degrees_east	<degE>	geographical longitudes
degrees_north	<degN>	geographical longitudes
Total ELectron Content unit	<tecu>	1 tecu = 10^{16} el·m^{-2}
days since reference date†	<days>	compound times; see section 3.2.3
seconds since reference time†	<time>	

† The reference date/time is defined in the units attribute of the variable.

Tab. 3.2: Abbreviations for unit strings used in the Tab. 3.6, Tab. 3.9 and Tab. 3.10.

variable with size (t, s), where t is the number of epochs in the time series, and s is the number of GNSS satellites used to derive the product. Scalar variables are represented by '-', i.e. by no shape, and consist of single values.

3.2.2 Attributes

Every netCDF variable comes with standard attributes describing the meaning of the variable (long_name), its physical units (units) and a missing data indicator value (missing_value). Variables do not carry any other attribute.

3.2.2.1 Units

In order to simplify the listing of data units, abbreviations are used to represent long unit strings for angle, longitude, latitude, time and other variables. These are consistent with the CF convention guidelines, and are listed in Tab. 3.2.

Regarding the details on time representations, abbreviations like <days> and <time> are often used. These units represents respectively days and seconds since a certain reference date/time. Readers of these data can extract the reference information from the units attribute itself. More details on the adopted time representation are provided in Sec. 3.2.3.

3.2.2.2 Missing Data

"Missing data" (i.e. the missing_value attribute) is used to mark data not present in a data set or measurement, and its value depends only on the data type of the variable. For any of the data types used in the tTEC product, the corresponding missing_value is shown in Tab. 3.3.

Type	Missing value	Comments
double	NaN	IEEE 954 Not-a-Number (double)
byte	-128	Minimum representable value
int	-2^{31}	Minimum representable value
uint	2^{32} - 1	Maximum representable value
string	""	Empty string

Tab. 3.3: Standard missing data indicators.

Variable	Group	`units` attribute	Reference date/time
`epoch_time_utc`	`/status/satellite`	<time>, seconds since	2000-01-01 00:00:00
`leap_second_utc`	`/status/satellite`	<time>, seconds since	2000-01-01 00:00:00
`*_absdate`	`/data`	<days>, days since	2000-01-01 00:00:00
`*_abstime`	`/data`	<time>, seconds since	00:00:00
`dtime`	`/data/tec`	<time>, seconds since	the start epoch of the product

Tab. 3.4: Reference times used to define the `units <time>` and `<days>` attributes.

3.2.3 Time Representation

Three different time representations are provided in the tTEC file.

- The first and more general representation is a simple string for easy human readability (using e.g. the string format "2017-01-01 01:02:03.004"). This format is used for encoding the `sensing_start/end` and `receive_start/end` UTC times included as global attributes in the `/ (root)` group (see Tab. 3.5). It is also used to represent the `creation_time` included in the list of `/status/processing` group attributes (see Tab. 3.8).
- The second time representation is given as number of seconds since a certain reference time and it is stored as a `double`. This format is used for variables whose `units` attribute is defined as `<time>`. Examples of such variables are included in the `/status/satellite` (see Tab. 3.6), in the `/data` (see Tab. 3.9) and `/data/tec` groups (see Tab. 3.10).
- The third representation is used to store the "global" variables of the `/data` group (see Tab. 3.9); it shows times as a logical compound which is made up of
  - an `integer` variable carrying the days since a reference date. This variable is named `absdate` and has a `units` attribute of `<days>`;
  - a `double` variable carrying the seconds elapsed since midnight, i.e. since the start of the day. This variable is named `abstime` and is accompanied by a `units` attribute of `<time>`.

  These variable names are extended at the beginning with either `utc_start_`, `utc_end_`, `gps_start_` and `gps_end_`, depending on which time scale is used for their representation.

Tab. 3.4 lists the different reference times adopted for these last two time representations within the tTEC product.

3.3 / (Root) Group

The / (root) group of the tTEC data format does not contain variables, but several global attributes as listed in Tab. 3.5. These attributes provide high level information on the measurement type and spacecraft being involved, as well as generic processing information like the start and end times covered by the data as well as the orbit numbers having provided data to the current product. This information is generic for EUMETSAT products.

Name	Description	Shape	Type	Units
Attributes				
Conventions	Name of the conventions followed by the dataset	–	string	–
metadata_conventions	Name of the meta data conventions followed by the dataset	–	string	–
product_name	Product name	–	string	–
title	Short description of the data set or group contents	–	string	–
summary	Short description of the data set or group contents	–	string	–
history	One of "original generated product", "aggregated product", or "sub-setted product"	–	string	–
institution	Name of the institution where the data was produced	–	string	–
references	URL of the data provider	–	string	–
environment	One of "Operational", "Validation", "Integration & Verification", "Development", "Engineering", and "Offline"	–	string	–
keywords	The RO Level 1 data format currently does not set any keywords	–	string	–
spacecraft	Satellite identifier	–	string	–
instrument	Instrument or product identifier and flight model number	–	string	–
product_level	Product processing level	–	string	–
type	Type of product	–	string	–
mission_type	One of "Global" or "Regional"	–	string	–
disposition_mode	One of "Test", "Commissioning", "Operational", or "Validation"	–	string	–
sensing_start_time_utc	UTC time of the start of sensing data	–	string	–
sensing_end_time_utc	UTC time of the end of sensing data	–	string	–
orbit_start	Orbit number at sensing_start	–	int	–
orbit_end	Orbit number at sensing_end	–	int	–
receive_start_time_utc	UTC time of the start of data reception	–	string	–
receive_end_time_utc	UTC time of the end of data reception	–	string	–
receiving_ground_station	Receiving ground station identifier	–	string	–
subsetting	Subsetting applied to the data	–	string	–

Tab. 3.5: Attributes in the / group.

3.4 Status Group

The /status group characterises the status of the satellite, of the instrument and of the on-ground processing. The information is distributed over the three following subgroups:

- the `/status/satellite` subgroup (see Sec. 3.4.1);
- the `/status/instrument` subgroup (see Sec. 3.4.2);
- the `/status/processing` subgroup (see Sec. 3.4.3).

3.4.1 Satellite Status

The list of variables in the `/status/satellite` group is described in Tab. 3.6. Note that the position and velocity data provided in this data group is either obtained from the GNSS navigation receiver onboard the spacecraft, or from a Flight Dynamics estimate of the spacecraft's orbit, and is not used for data processing. This information is also generic for EUMETSAT products.

Name	Description	Shape	Type	Units
Variables				
epoch_time_utc	Epoch time in UTC of the orbital elements and the orbit state vector	-	double	<time>
semi_major_axis	Semi major axis of the orbit at epoch time	-	double	m
eccentricity	Eccentricity of the orbit at epoch time	-	double	–
inclination	Inclination of the orbit at epoch time	-	double	<deg>
perigee_argument	Argument of perigee of the orbit at epoch time	-	double	<deg>
right_ascension	Right ascension of the orbit at epoch time	-	double	<deg>
mean_anomaly	Mean anomaly of the orbit at epoch time	-	double	<deg>
x_position	X position of the orbit state vector in the orbit frame at ascending node [EARTH+FIXED]	-	double	m
y_position	Y position of the orbit state vector in the orbit frame at ascending node [EARTH+FIXED]	-	double	m
z_position	Z position of the orbit state vector in the orbit frame at ascending node [EARTH+FIXED]	-	double	m
x_velocity	X velocity of the orbit state vector in the orbit frame at ascending node [EARTH+FIXED]	-	double	m/s
y_velocity	Y velocity of the orbit state vector in the orbit frame at ascending node [EARTH+FIXED]	-	double	m/s
z_velocity	Z velocity of the orbit state vector in the orbit frame at ascending node [EARTH+FIXED]	-	double	m/s
earth_sun_distance_ratio	Ratio of current Earth-Sun distance to Mean Earth-Sun distance	-	double	–
location_tolerance_radial	Nadir Earth location tolerance radial	-	double	m
location_tolerance_crosstrack	Nadir Earth location tolerance cross-track	-	double	m
location_tolerance_alongtrack	Nadir Earth location tolerance along-track	-	double	m
yaw_error	Yaw attitude bias	-	double	<deg>
roll_error	Roll attitude bias	-	double	<deg>
pitch_error	Pitch attitude bias	-	double	<deg>
subsat_latitude_start	Latitude of sub-satellite point at start of the product	-	double	<degN>
subsat_longitude_start	Longitude of sub-satellite point at start of the product	-	double	<degE>
subsat_latitude_end	Latitude of sub-satellite point at end of the product	-	double	<degN>
subsat_longitude_end	Longitude of sub-satellite point at end of the product	-	double	<degE>

Tab. 3.6: Variables in the `/status/satellite` group.

Name	Description	Shape	Type	Units
leap_second_time_utc	UTC time of occurrence of a leap second in this product (0: no leap second)	-	double	<time>
leap_second_value	Value of leap second in product (1, 0, or -1)	-	short	s

Tab. 3.6: Variables in the /status/satellite group.

3.4.2 Instrument Status

Instrument status is described by attributes only, see Tab. 3.7. The instrument_mode is the measurement mode of the instrument. As stated in the introduction, tTEC product can be generated using data observed by any kind of GNSS receiver flying on board a satellite and used for POD purposes. EUMETSAT also manages Radio Occultation (RO) receivers. A RO receiver has two different measurement modes: Navigation (when it can be used only for POD) and Occultation (which includes also the Navigation mode).

Name	Description	Shape	Type	Units
Attributes				
onboard_sw_version	Instrument onboard software version number	–	string	–

Tab. 3.7: Attributes in the /status/instrument group.

3.4.3 Processing Status

Processing status is also described by attributes only (see Tab. 3.8). In case of the tTEC data format, various version numbers along with information on the generating facility as well as the version of the Instrument Data Base (if any) are available in this data group.

The source attribute lists the configuration data used to create the product, as well as the products that were used for its creation.

Name	Description	Shape	Type	Units
Attributes				
processor_name	Name of the product processor	–	string	–
processor_version	Processor version number	–	string	–
processing_mode	One of "NRT", "Reprocessing", "STC" or "NTC"	–	string	–
format_version	Format version number	–	string	–
source	The method of production of the original data	–	string	–
generating_facility	Name of the originating / generating facility	–	string	–
baseline	Reprocessing baseline version number	–	string	–
idb_info	Information characterising which Instrument Data Base version was used	–	string	–
processing_centre	Processing centre identifier	–	string	–
Variables				

Tab. 3.8: Attributes and variables in the /status/processing group.

Name	Description	Shape	Type	Units
creation_time_utc	Start time of product creation in UTC	-	double	<time>

Tab. 3.8: Attributes and variables in the /status/processing group.

3.5 Data Group

The /data group contains one attribute and several global scalar variables defining the start date/time information of the product (see Tab. 3.9). It also contains the /data/tec subgroup which is actually used to store the tTEC information. Variables included in this subgroup are shown in Tab. 3.10. Information regarding the adopted dimensions and their names are provided in Sec. 3.2.1.

Name	Description	Shape	Type	Units
Attributes				
title	Short description of the data set or group contents	–	string	–
Variables				
utc_start_absdate	Start (reference) UTC time for all observation epochs / date	-	int	<days>
utc_start_abstime	Start (reference) UTC time for all observation epochs / time	-	double	<time>
gps_start_absdate	Start (reference) GPS time for all observation epochs / date	-	int	<days>
gps_start_abstime	Start (reference) GPS time for all observation epochs / time	-	double	<time>

Tab. 3.9: Attributes and variables in the /data group.

Name	Description	Shape	Type	Units
Variables				
gns_id	GNSS satellites IDs	(s)	string	–
dtime	Measurement epoch	(t)	double	<time>
local_time	Local time	(t)	double	s
latitude_rec	Receiver latitude	(t)	double	<degN>
longitude_rec	Receiver longitude	(t)	double	<degE>
altitude_rec	Receiver altitude (above ellipsoid)	(t)	double	m
wgs84_radius	WGS84 radius at the receiver sub satellite point	(t)	double	m
dcb_rec	Receiver DCB	-	double	<tecu>
dcb_rmse_rec	Receiver DCB RMSE	-	double	<tecu>
overall_pairs_available	Overall number of sTEC pairs available	-	uint	–
pairs_for_dcb	sTEC pairs available for DCB calculation in high latitudes and during night	-	double	%
pairs_after_thresholding	sTEC pairs available for DCB calculation after thresholding	-	double	%

Tab. 3.10: Variables in the /data/tec group.

Name	Description	Shape	Type	Units
pairs_after_outl_removal	sTEC pairs available for DCB calculation after outliers removal	-	double	%
azimuth_antenna	Antenna azimuth angle of the GNSS satellite as seen by the LEO (velocity direction: 270 degrees)	(t,s)	double	<deg>
elevation_antenna	Antenna elevation angle of the GNSS satellite as seen by the LEO (zenith: 90 degrees)	(t,s)	double	<deg>
altitude_ipp	Ionospheric Pierce Point altitude (above ellipsoid)	(t,s)	double	m
longitude_ipp	Ionospheric Pierce Point longitude	(t,s)	double	<deg>
latitude_ipp	Ionospheric Pierce Point latitude	(t,s)	double	<deg>
local_time_ipp	Local time at the Ionospheric Pierce Point	(t,s)	double	s
stec_uncalibrated	Not calibrated sTEC after code-carrier offset removal	(t,s)	double	<tecu>
stec_calibrated	Calibrated sTEC	(t,s)	double	<tecu>
vtec_calibrated	Calibrated vTEC for each individual sTEC	(t,s)	double	<tecu>

Tab. 3.10: Variables in the `/data/tec` group.