Radio Occultation
Level 1 Product Format Specification

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CONTENTS

1 INTRODUCTION

1.1 Purpose and Scope

This document describes the data format(s) of Radio Occultation (RO) level 1 data as generated by EUMETSAT's operational and reprocessing systems for RO data. Also discussed are the mutual relations between these data formats and their meta data.

This version of the document describes RO level data formats as applicable to v1.4 of EUMETSAT's RO science prototype (Yaros) and v4.3.1 of the operational GRAS Product Processing Facility (PPF), where the latter does not yet implement full wave optics processing. With the finalisation of the wave optics implementation foreseen for Yaros v1.5 and GRAS PPF v4.4, respectively, details of the data formats are still subject to changes.

1.2 Applicable Documents

[AD1] NetCDF data format description

[AD2] EPS Programme Generic Product Format Specification, Issue 6 Rev. 5 from 16.02.2005, EPS/CGS/SPE/96167.

[AD3] WMO RO BUFR Format Specification

[AD4] RO excel sheet / MDR header definition

[AD5] SP3 definition

1.3 Reference Documents

[RD1] IROWG BUFR discussion paper

[RD2] CF Conventions

1.4 Document Structure

The document is structured as follows:

Chapter 1:	Introduction (this chapter)
Chapter 2:	Overview on the organisation of RO data formats
Chapter 3:	NetCDF-based data granule format for individual occultations
Chapter 4:	EPS wrapped RO level 1 data product format
Appendix A:	Meta data in EPS RO products and netCDF RO level 1 granules
Appendix B:	Unpacking EPS wrapped RO level 1 products
Appendix C:	Meta data in netCDF RO level 1 granules and WMO RO BUFR messages

2 RO LEVEL 1 DATA FORMAT OVERVIEW

RO observations are measurements of opportunity – they can be taken whenever one of the GNSS satellites, as seen from the observing spacecraft, sets or rises behind the Earth's horizon. Typically, a single occultation covering the neutral atmosphere lasts less than a few minutes, during which the line of sight between the two satellites moves from heigh altitudes into the troposphere (for setting occultations; vice versa for rising ones), scanning nearly vertically through the atmosphere. The location of the occultation (which is associated with the tangent point of a dedicated ray travelling from the GNSS transmitter to the RO receiver and touching the Earth's surface) depends on the orbit geometry of the satellites being involved in the measurement; it will typically be located about about 3000 km away from the sub-satellite point of the RO receiver. Individual occultations, when being processed to level 1b, therefore consist of vertical bending angle profiles which are more or less randomly distributed over the globe.

2.1 RO Level 1 Profile Granules

Individual bending angle profiles as described above provide a natural packing unit or "granule" for RO data. RO level 1b data produced by EUMETSAT is indeed organised in individual occultation granules; the native output of EUMETSAT's RO processors are netCDF v4 binary data files, each one containing the data of a single occultation. When dealing with such individual netCDF granules, the following naming convention applies:

```
<inst>_1B_<sat>_<start_time>Z_<stop_time>Z_<p>_<d>_<create_time>Z_<Gxx>_<ff>.nc
```

where:

`<inst>`	4-character instrument ID (e.g., `GRAS` for the GRAS instrument)
`<sat>`	3-character satellite ID (e.g., `M02` for Metop-A)
`<start_time>`	14-digit sensing start time (e.g., `20120914050023` for 05:00:23 UTC on 14 September 2012)
`<end_time>`	14-digit timestamp characterising sensing end time
`<p>`	1-character processing mode for Nominal (`N`), Backlog (`B`), Reprocessing (`R`), or Validation (`V`)
`<d>`	1-character disposition mode for Testing (`T`), Operational (`O`), or Commissioning (`C`)
`<create_time>`	14-digit timestamp characterising product creation time
`<Gxx>`	3-character satellite ID of occulting GNSS satellite (e.g., `G23` for PRN 23 of the GPS constellation)
`<ff>`	2-character flag field indicating nominal (`N`) or degraded (`D`) instrument and processing (e.g., `ND` for nominal instrument data, but degraded processing)

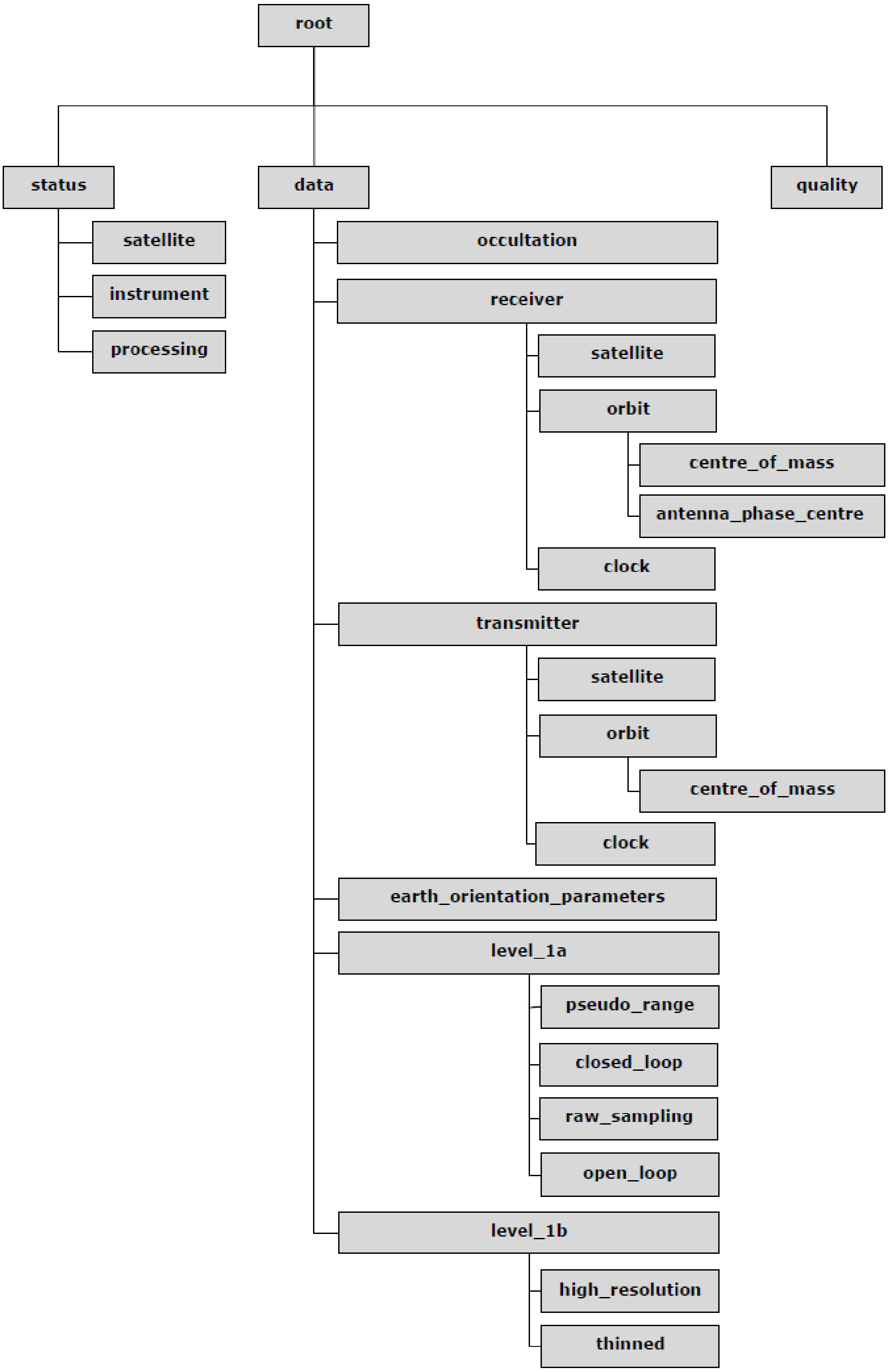

Figure 2.1: Overall netCDF data group structure of an RO level 1 granule.

For example, a nominal GRAS level 1b granule for a Metop-A occultation exploiting signals from PRN 32, with measurements starting at 07:37:14 UTC on 6 June 2015, with both instrument and processing being in a nominal state, and being produced in near-real time in a test environment would have the filename

```
GRAS_1B_M02_20150624073714Z_20150624074008Z_N_T_20160323172956Z_G32_NN.nc
```

Each RO data granule exploits netCDF's data group feature in order to structure its data contents as shown in Fig. 2.1. In particular, it consists of a root (`/`) group, holding global attributes as well as `status`, `data` and `quality` sub-groups. The detailed contents and structure of each data group are described in more detail in chapter 3.

2.2 EPS Data Wrapping

The organisation of radio occultation measurements in terms of individual occultations or granules is straightforward, but may lead to a large number of data files. This has disadvantages especially when disseminating large amounts of data, or for the long-term archival of the data. EUMETSAT therefore combines multiple RO granules into larger level 1 products. In Near-Real-Time (NRT) processing of RO data, such products cover a period of (typically) 15 – 20 minutes; EUMETSAT's data archive organises RO data in products covering a full orbit.

Technically, the "wrapping" of individual granules (or occultations) exploits the EPS native file format described in [AD2]. At a conceptual level, the wrapping can be understood as using the EPS data format as data container, similar to `.tar` or `.zip` data archives well known from Linux or Unix environments. EPS RO data formats also follow the EPS naming conventions, i.e. individual RO level 1 products are named like

```
<inst>_xxx_1B_<sat>_<start_time>Z_<stop_time>Z_<p>_<d>_<create_time>Z
```

where:

- <inst> — 4-character instrument ID (e.g., GRAS for the GRAS instrument)
- <sat> — 3-character satellite ID (e.g., M02 for Metop-A)
- <start_time> — 14-digit sensing start time (e.g., 20120914050023 for 05:00:23 UTC on 14 September 2012)
- <end_time> — 14-digit timestamp characterising sensing end time
- <p> — 1-character processing mode for Nominal (N), Backlog (B), Reprocessing (R), or Validation (V)
- <d> — 1-character disposition mode for Testing (T), Operational (O), or Commissioning (C)
- <create_time> — 14-digit timestamp characterising product creation time

An example file name for an EPS product containing about 14 minutes of GRAS data from Metop-B beginning at 08:50:46 UTC on 5 April 2016 is

```
GRAS_xxx_1B_M01_20160405085046Z_20160405090424Z_N_C_20160405100319Z
```

which was taken from a nominal commissioning (or validation) processing environment.

Details of the EPS wrapping are described in chapter 4. The relation of meta data contained in the Main Product Header (MPHR) of EPS products and netCDF attributes contained in individual level 1 granules is documented in appendix A.

We note that EUMETSAT offers a `tar`-like tool for extracting individual netCDF occultation granules named `epsar`[1]. Examples for its use are also given in chapter 4. More details and installation instructions can be found in appendix B.

2.3 BUFR and other Output Formats

Level 1 data generated by EUMETSAT are further converted to other formats like WMO's Binary Universal Form for the Representation of meteorological data (BUFR), a data format widely adopted in operational NWP. In the future, EUMETSAT's data archive might offer additional data format options for RO products.

In each case, a one-to-one correspondence between data granules/occultations and derived data products will be maintained. For example, in case of BUFR data, individual BUFR messages will contain the data from single occultations, although several BUFR messages might have been combined into a single combined product in order to simplify the dissemination of the data. The mapping between data contained in RO level 1 data granules and WMO BUFR messages is described in Appendix C.

The formal specification of file naming conventions for, e.g., BUFR data as operationally disseminated by EUMETSAT is beyond the scope of this document. For illustration purposes, we note that a BUFR products containing the occultations from the GRAS/Metop-B sample product given in the previous section would be

```
W_XX-EUMETSAT-Darmstadt,SOUNDING+SATELLITE,METOPB+GRAS_C_EUMP_20160405085046_
↪  18408_eps_t_l1.bin
```

Note that the file name in the above text box wraps into the next line due to its length.

[1] The most recent version of the `epsar` software can be downloaded from https://github.com/leonid-butenko/epsar.

3 RO LEVEL 1 PROFILE GRANULE DETAILS

3.1 Overall Conventions

The RO level 1b data format is implemented using the netCDF-4 standard. In contrast to the older netCDF-3 data format specification, netCDF-4 provides hierarchical group structures for organizing sets of variables, adds a number of additional native data types (64-bit wide and unsigned integer data types, along with a string data type), and provides transparent variable-wise data compression. These features of netCDF-4 are used in the RO data format, while other improvements like compound and variable length arrays are not exploited.

The structure of RO level 1a and 1b data in terms of groups and subgroups follows from the characteristics of the various data subsets. In particular, individual subgroups contain data which has common time stamps, or is aligned on the same vertical grid; they thus share one dimension.

Meta data handling is mostly based on the Climate and Forecast (CF) conventions. As the latter mainly provide 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, and conventions on representing times and missing data are described in sections 3.1.2, 3.1.3 and 3.1.4, respectively. In some cases, this and other adaptations of the CF conventions required due to EUMETSAT ground segment needs lead to deviations from the original CF text which are described in section 3.1.5.

3.1.1 Dimensions

Because RO soundings are measurements of opportunity, the lengths of individual variables varies between occultations. In addition, the amount of measurement data obtained for different measurement modes (like open vs. closed loop measurements at the various GNSS frequencies) or of the instrument span different, sometimes overlapping time periods and thus contain a different number of points. Similarly, high resolution bending angle profiles are retrieved on different impact parameter grids for different occultations, and hence exhibit other variable lengths. As a consequence, dimensions are typically defined within individual groups and subgroups of a level 1b product, and not inherited from their parent groups.

The level 1b RO data format contains scalar, one-dimensional and two-dimensional variables. Examples for 1d variables are time series of GNSS observables like amplitude, SNR and carrier phase measurements, or retrieval results like bending angle profiles which are ultimately height referenced. Spatial vectors, e.g. the position of the antenna phase centre with respect to the spacecraft's centre of mass, or the centre of curvature of an occultation sounding are examples of 1d variables with a size of 3 (the x, y and z coordinates). Yet another example are lists of (input) files, where the dimension varies with the number of data files being ingested during the processing. Time series of satellite positions or velocities are 2d variables with a size of $(n, 3)$ (an n-element time series of spatial vectors).

As the number of dimension types is limited, the RO data format uses standard dimension names in all groups; they are listed in Table 3.1. Within a given group, dimensions are always of fixed length (i.e., not unlimited); the actual length of a dimension varies from group to group, and

Name	Description	Length
xyz	Spatial coordinates (x, y, z)	3
t	Time coordinates	variable†
z	Height or impact parameter coordinates	variable†
files	List of files	variable†

† between data groups

Table 3.1: Standard dimension names and their meaning.

also from occultation to occultation. In the tables describing the contents of the various data groups in the following sections, the shape of array variables is given in terms these coordinate names. For example, a variable with a shape of `(t)` denotes a 1d variable dependent on time, with a length defined by the dimension `t` of the data group in which this variable is contained. Similarly, a shape of `(t,xyz)` describes a 2d variable with size $(n, 3)$, where n is the number of epochs in the time series, and the second dimension is used to represent the three spatial coordinates. Scalar variables are represented by a '-', i.e. by no shape.

3.1.2 Attributes

Recommendations of the CF conventions regarding global attributes are applied for individual data groups as far as that makes sense. For example, each group has a `title` attribute describing the content of the respective group. Global attributes referring to the entire data set are however not repeated in individual data groups.

In the RO level 1b data format, 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 attributes.

In order to simplify the listing of data units in the tables of the following sections, abbreviations are used to represent long unit strings for angle, longitude, latitude, and time variables. These are consistent with the CF convention guidelines for these units, and listed Tab. 3.2. See section 3.1.3 for details on time representation.

3.1.3 Time

Low level GNSS data requires precise time stamping, with accuracy required in the order of a few picoseconds or less. In order not to have numerical round-off errors affecting the precise storage of observation times, times are stored as a logical compound which is made up of an `integer` variable carrying the days since a reference date, and a `double` variable carrying the seconds elapsed since midnight, i.e. since the start of the day. The two components of the logical time compound are consistently named `*_absdate` (for the number of days since the reference date) and `*_abstime` (for the number of seconds since the beginning of the day) throughout the data format.

The RO level 1b data format provides times in both the UTC and GPS time scale, to facilitate easy conversion between the reference time systems. The corresponding variable names are `utc_absdate` and `utc_abstime` as well as `gps_absdate` and `gps_abstime`, respectively. Some variations of this pattern exist; for example, the time for which the nominal single point geolocation of

Unit	Abbr.	Comments
degrees	<deg>	angles if not expressed n rad
degrees_east	<degE>	geographical longitudes
degrees_west	<degW>	
degrees_north	<degN>	geographical latitudes
degrees_south	<degS>	
days since 2000-01-01†	<days>	compound times; see section 3.1.3
seconds since 00:00:00.00	<time>	

† actual reference date might differ depending on context

Table 3.2: Abbreviations for unit strings used in the Tables 3.5 – 3.25.

a given occultation is determined, is described by the variables `utc_georef_absdate` and `utc_georef_abstime` for the UTC time scale, as well as `gps_georef_absdate` and `gps_georef_abstime` for the GPS time system.

Note that in the case of leap seconds, UTC time stamps may contain an additional 60^{th} second in the last minute of the day, caused by the introduction of the leap second.

Finally, all measurement epochs are referenced to a common (UTC or GPS) time scale for both receiver and transmitter. Thus all instrument measurement times have been corrected by applying the clock bias estimates obtained from the Precise Orbit Determination (POD) processing. The clock bias estimates provided as part of the receiver and transmitter data (see sections 3.4.2 and 3.4.3, respectively) can be used to recover the raw instrument measurement times.

3.1.4 Missing Data

"Missing data" is data not present in a data set or measurement. For example, carrier phase and amplitude measurements of an RO receiver are typically available at two frequencies; but while the tracking on the primary frequency might still have delivered valid data, the tracking on the secondary frequency might have failed, with no further measurement data being provided. In this case, the respective netCDF variables will have the same lengths, but the secondary frequency data will contain a missing value indicator for those measurement epochs where no data was available. Missing data indicator values are identical across all variables in the RO data format, and only depend on the data type of the variable. Their values are shown in Table 3.3.

Note that boolean variables like quality flags are not natively supported by the netCDF data format. In the RO level 1b data format, quality flags are stored as `byte` variables, with values $= 0$ and $\neq 0$ representing False and True, respectively. Thus, boolean variables can be read as integer data and directly coerced to boolean variables, unless they are missing.

3.1.5 Deviations from the CF Conventions

The RO level 1b is not consistent with the CF convention in the following points:

- Some low level instrument data (noise and signal power densities) are provided in logarithmic units ("dB").

Type	Missing value	Comments
single	NaN	IEEE 954 Not-a-Number (float)
double	NaN	IEEE 954 Not-a-Number (double)
byte	-128	Minimum representable value
int	-2^{31}	Minimum representable value
int64	-2^{63}	Minimum representable value
uint	$2^{32}-1$	Maximum representable value
uint64	$2^{64}-1$	Maximum representable value
string	”	Empty string
char	”	Empty string

Table 3.3: Standard missing value indicators.

- Precision time variables are stored a (logical) compound data types consisting on an integer number of days since a reference days, and a (double) number of seconds since midnight; see section 3.1.3.

3.2 `/` (Root) Group

The `/` (root) group of the RO L1 data format contains no variables, but several global attributes as listed in Table 3.4. These attributes provide high level information on the measurement type and spacecraft being involved, as well as generic processing information and the start and end times as well as orbit numbers having provided data to the current product. This information is generic for all EUMETSAT products. Some of the information is used to fill the Main Product Header Record (MPHR) in EUMETSAT's native EPS products (see Appendix A).

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	–
`title`	Short description of the data set or group contents	–	string	–
`summary`	Short description of the data set or group contents	–	string	–
`keywords`	The RO Level 1 data format currently does not set any keywords	–	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	–
`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	–

Table 3.4: Attributes in the `/` group.

Name	**Description**	**Shape**	**Type**	**Units**
`disposition_mode`	One of "Test", "Commissioning", or "Operational"	–	string	–
`sensing_start`	UTC time of the start of sensing data	–	string	–
`sensing_end`	UTC time of the end of sensing data	–	string	–
`environment`	One of "Operational", "Validation", "Development", "Offline", "Integration & verification", and "Support"	–	string	–
`references`	URL of the data provider	–	string	–
`orbit_start`	Orbit number at sensing_start	–	int	–
`orbit_end`	Orbit number at sensing_end	–	int	–
`receive_start`	UTC time of the start of data reception	–	string	–
`receive_end`	UTC time of the end of data reception	–	string	–
`subsetting`	Subsetting applied to the data	–	string	–
`receiving_ground_station`	Receiving ground station identifier	–	string	–

Table 3.4: Attributes in the `/` group.

3.3 Status Group

The status group characterises the status of the satellite, the instrument and the on-ground processing. In EPS, the information is used to construct the majority of the content of the MPHR in the wrapped data products. The information is distributed over the three subgroups `status/satellite`, `status/instrument` and `status/processing`, respectively.

3.3.1 Satellite Status

The list of variables in the Satellite Status group (named `status/satellite` in the RO data format) is described in Table 3.5.

Note that the position and velocity information 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. It therefore does not provide sufficient accuracy for RO data processing. Instead, the position and velocity data provided by the Precise Orbit Determination (POD) carried out as part of the on-ground data processing for the RO instrument should be used in all cases. This data is available as part of the main `data` group, described in section 3.4.2.2.

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>

Table 3.5: Variables in the `/status/satellite` group.

Name	Description	Shape	Type	Units
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>
leap_second_utc	UTC time of occurrence of a leap second in this product (no leap second results in 0)	-	double	<time>
leap_second	Value of leap second in product (1, 0, or -1)	-	byte	s

Table 3.5: Variables in the `/status/satellite` group.

3.3.2 Instrument Status

Instrument status is described by attributes only. For RO, the instrument measurement mode and the onboard software version number are provided; see Tab. 3.6.

Name	Description	Shape	Type	Units
Attributes				
instrument_mode	Measurement mode of the instrument. One of “Occultation” or “Navigation”	–	string	–
onboard_sw_version	Instrument onboard software version number	–	string	–

Table 3.6: Attributes in the `/status/instrument` group.

3.3.3 Processing Status

Processing status is also described by attributes only. In case of the RO L1 data format, various version numbers along with information on the generating facility as well as the version of the RO IDB are available in this data group (Tab. 3.7).

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

Table 3.7: Attributes in the `/status/processing` group.

3.4 Data Group

The `data` group contains all science data from both the RO instrument and the on-ground processing, along with auxiliary data required or used during product generation, like precise positions and velocities of all satellites participating in the occultation. This data is organised in a number of subgroups (which may contain further subgroups themselves):

`data/occultation`: meta data for the occultation, like a single-point geolocation and time;

`data/receiver`: data characterizing the receiver (like antenna positions with respect to the space-craft's centre of mass) along POD data;

`data/transmitter`: as for `data/receiver`, but for the transmitting GNSS satellite;

`data/earth_orientation_parameters`: Earth Orientation Parameters (EOP) covering the occultation, required for precise transformations between Earth fixed and inertial coordinate systems carried out, and used for the georeferencing of the retrieval;

`data/level_1a`: excess and total carrier phase data measured during the occultation, along with pseudorange, amplitude, and SNR data;

`data/level_1b`: bending angle and impact parameter retrievals in high and thinned resolution, together with diagnostic data.

The contents of these data groups are described in more detail in the following sections.

3.4.1 Occultation Meta Data

The occultation data group (`data/occultation`) contains meta data about the occultation gathered during the processing, including the location of the occultation. This nominal georeferencing is based on a simplified (straight-line) propagation model for signal propagation, and is typically representative for the tangent point location in the upper troposphere.

The nominal location of the occultation is calculated neglecting the bending of the signal's ray path, and valid for the moment in time when the straight line connecting transmitter and receiver touches the Earth's ellipsoid (i.e. for SLTA = 0). This is a nominal georeferencing which is useful when interpreting an occultation as a vertical profile. It does neither represent the bending nor the actual motion of the tangential point during the occultation. If the knowledge of the latter is required, the precise geolocation information contained in the `data/level_1b/high_resolution` and `data/level_1b/thinned` data groups should be used instead.

In addition to the occultation's geolocation, the occultation data group also contains the positions of all satellites at the same moment in time in Earth fixed coordinates, as well as the azimuth and elevation angle with respect to the antenna boresight. The complete lists of attributes and variables are given in Tab. 3.8. Note that more precise georeferencing information for individual elements of the retrieved bending angle profile are available in the `data/level_1b` group (see section 3.4.6).

Name	Description	Shape	Type	Units
Attributes				
`occultation_type`	One of "rising" or "setting"	–	string	–
`pod_method`	POD method applied during the processing	–	string	–
`phase_method`	Phase calibration method applied during the processing	–	string	–
`idb_info`	Information characterising which Instrument Data Base version was used	–	string	–
`title`	Short description of the data set or group contents	–	string	–
`retrieval_method`	Retrieval method applied during the processing	–	string	–
Variables				
`prn`	PRN number of the occulting GNSS satellite	-	int	–
`channel`	GRAS channel on which the occultation was measured	-	int	–
`utc_georef_absdate`	Reference UTC time for georeferencing (for SLTA = 0)	-	int	<days>
`utc_georef_abstime`	Reference UTC time for georeferencing (for SLTA = 0)	-	double	<time>
`gps_georef_absdate`	Reference GPS time for georeferencing (for SLTA = 0)	-	int	<days>
`gps_georef_abstime`	Reference GPS time for georeferencing (for SLTA = 0)	-	double	<time>
`longitude`	Longitude of reference location (for SLTA = 0)	-	double	<degE>
`latitude`	Latitude of reference location (for SLTA = 0)	-	double	<degN>
`azimuth_north`	Ray azimuth angle at reference location (for SLTA = 0, clockwise against North)	-	double	<deg>

Table 3.8: Attributes and variables in the `/data/occultation` group.

Name	Description	Shape	Type	Units
`r_curve`	Radius of curvature (for SLTA = 0)	-	double	m
`r_curve_centre`	Centre of curvature position in Earth centred inertial coordinates (J2000, for SLTA = 0)	(xyz)	double	m
`r_curve_centre_fixed`	Centre of curvature position in Earth fixed coordinates (for SLTA = 0)	(xyz)	double	m
`undulation`	EGM96 undulation at reference location	-	double	m
`longitude_rec`	Receiver longitude (for SLTA = 0)	-	double	<degE>
`latitude_rec`	Receiver latitude (for SLTA = 0)	-	double	<degN>
`altitude_rec`	Receiver altitude (for SLTA = 0, above ellipsoid)	-	double	m
`position_rec`	Receiver antenna position in Earth centred inertial coordinates (J2000, for SLTA = 0)	(xyz)	double	m
`position_rec_fixed`	Receiver antenna position in Earth fixed coordinates (for SLTA = 0)	(xyz)	double	m
`velocity_rec`	Receiver antenna velocity in Earth centred inertial coordinates (J2000, for SLTA = 0)	(xyz)	double	m/s
`longitude_gns`	GNSS longitude (for SLTA = 0)	-	double	<degE>
`latitude_gns`	GNSS latitude (for SLTA = 0)	-	double	<degN>
`altitude_gns`	GNSS altitude (for SLTA = 0, above ellipsoid)	-	double	m
`position_gns`	GNSS transmitter position in Earth centred inertial coordinates (J2000, for SLTA = 0)	(xyz)	double	m
`position_gns_fixed`	GNSS transmitter position in Earth fixed coordinates (for SLTA = 0)	(xyz)	double	m
`velocity_gns`	GNSS transmitter velocity in Earth centred inertial coordinates (J2000, for SLTA = 0)	(xyz)	double	m/s
`azimuth_antenna`	Antenna azimuth angle (for SLTA = 0)	-	double	<deg>
`zenith_antenna`	Antenna zenith angle (for SLTA = 0)	-	double	<deg>
`n_analogue_gc`	Number of analogue gain changes during the occultation	-	int	–
`n_digital_gc`	Number of digital gain changes during the occultation	-	int	–

Table 3.8: Attributes and variables in the `/data/occultation` group.

3.4.2 Receiver Data

The receiver data group (`data/receiver`) collects data from the Low Earth Orbit (LEO) satellite carrying the RO receiver. A satellite meta data group provides antenna offset and orientation data allowing to calculate the position and orientation of the occultation antenna with respect to the LEO's centre of mass, and also various commonly used spacecraft IDs. Other subgroups contain POD solution data for the satellite carrying the RO receiver:

`data/receiver/satellite`: satellite meta data like spacecraft IDs and antenna positions and orientations;

`data/receiver/orbit`: parent group for POD reference point dependent results;

`data/receiver/orbit/centre_of_mass`: precise positions and velocities for the centre of mass of the satellite;

`data/receiver/orbit/antenna_phase_centre`: precise positions and velocities for the (occultation) antenna phase centre of the satellite. This takes into account the displacement of the antenna phase centre with respect to the satellite's centre of mass, and ideally also all contributions from attitude changes of the satellite during the occultation;

data/receiver/clock: clock bias estimates.

The detailed contents of these data groups are given in Tables 3.9 – 3.12.

Note that orbit data in the data/receiver/orbit and clock groups is stored in the temporal resolution used by the POD processing. These POD solutions are trimmed to a period covering the respective occultation duration, still providing enough data points to allow an 8^{th}-order polynomial interpolation of position and velocity data to arbitrary epochs during the occultation. Similarly, clock bias data allows for linear interpolation of the clock bias estimates to all measurement epochs of the raw occultation data.

When interpolating POD data to new intermediate epochs, we strongly recommend to interpolate the original POD contained in the data/receiver/orbit and clock groups, rather than re-interpolating the position and velocity arrays provided together with the measurement data in the data/level_1a data group (see section 3.4.5).

3.4.2.1 Receiver Satellite Data

The group data/receiver/satellite provides various spacecraft IDs for the satellite carrying the receiver, and also geometrical data on the location of the antenna phase centre(s) with respect to the centre of mass of the spacecraft (see Tab. 3.9). The data is used in order to convert from the centre-of-mass POD solution to the antenna-specific precise orbit; see the following section for details.

Name	Description	Shape	Type	Units
Attributes				
satellite	Satellite name	–	string	–
satellite_id_eum	EUMETSAT Satellite identifier	–	string	–
satellite_id_sp3	SP3 satellite identifier	–	string	–
satellite_id_norad	NORAD satellite identifier	–	string	–
Variables				
centre_of_mass	Centre of mass (in S/C coordinates)	(xyz)	double	m
antenna_phase_centre	Antenna phase centre (in S/C coordinates)	(xyz)	double	m
antenna_orientation	Antenna orientation (unit vector perpendicular to antenna plane in S/C coordinates)	(xyz)	double	m

Table 3.9: Attributes and variables in the /data/receiver/satellite group.

3.4.2.2 Receiver Orbit Data

By convention, a POD provides the positions and velocities of the spacecraft's centre of mass. The original POD results for the spacecraft carrying the RO receiver are contained in the data/receiver/orbit/centre_of_mass group (Tab. 3.10), together with additional information about the coordinate system in which the orbit data is provided ("J2000" for Earth-centered Inertial (ECI), and IGS08 for Earth-centered and Fixed (ECF) coordinates). Other information, e.g. about the expected accuracy of the orbit solution as well as about the occurrence of manoeuvres are also available. Note that in EUMETSAT's level 1 RO products, POD data is usually provided in an inertial reference frame; the conversion between inertial and Earth-fixed reference frames makes use of Earth Orientation Parameters contained in the `data/earth_orientation_-parameters` group (see section 3.4.4).

We note that the meta data stored in POD data groups resembles (on purpose) the full header of SP3 files. An individual level 1 granule will also contain POD data at the original temporal resolution with sufficiently many data points to allow 8^{th}-order polynomial interpolation of positions and velocities for the entire duration of the occultation contained in this granule. However, rather than (re-) interpolating velocity data from the POD solution, we recommend to calculate satellite velocities by interpolating precise positions and calculating the derivative with respect to time analytically using the interpolating polynomial, as this approach usually provides higher accuracy and better reproducibility.

Name	**Description**	**Shape**	**Type**	**Units**
Attributes				
`title`	Short description of the data set or group contents	–	string	–
`institution`	Name of the institution where the data was produced	–	string	–
`filename`	File name of the original GSN/RSN auxiliary product	–	string	–
`coordinate_system`	Coordinate system in which the orbit data is provided	–	string	–
`orbit_type`	One of FIT (fitted), EXT (extrapolated or predicted), or BCT (broadcast); others are possible	–	string	–
`std_base_pv_sp3`	Floating point base for position / velocity standard deviation (in mm or 10**-4 mm/sec)	–	string	–
`std_base_clock_sp3`	Floating point base for clock / clock rate standard deviation (in psec or 10**-4 psec/sec)	–	string	–
`comments_1_sp3`	Comment lines of the original SP3 auxiliary data product	–	string	–
`comments_2_sp3`	(as above)	–	string	–
`comments_3_sp3`	(as above)	–	string	–
`comments_4_sp3`	(as above)	–	string	–
`satellite_id_sp3`	SP3 satellite identifier	–	string	–
`accuracy_exponent_sp3`	SP3 accuracy exponent; the estimated one-sigma orbit error is 2**exp mm	–	string	–
Variables				
`utc_absdate`	Epochs (full days) in UTC	`(t)`	int	<days>
`utc_abstime`	Epochs (seconds since last midnight) in UTC	`(t)`	double	<time>
`position`	Satellite position in J2000 reference frame	`(t,xyz)`	double	m
`velocity`	Satellite velocity in J2000 reference frame	`(t,xyz)`	double	m/s
`orbit_predicted`	True if orbits are predicted (instead of estimated)	`(t)`	byte	–
`manoeuvre`	True if satellite undergoes a manoeuvre	`(t)`	byte	–

Table 3.10: Attributes and variables in the `/data/receiver/orbit/centre_of_mass` group.

For the satellite carrying the RO receiver, the antenna offset with respect to the centre of mass can provide a significant contribution to the motion of the antenna phase centre, especially for large satellites like Metop. Changes in the attitude of the spacecraft may cause further deviations of the actual antenna positions with respect to the satellite's centre of mass. The "orbit" of the occultation antenna phase centre is therefore also provided in the `data/receiver/orbit/antenna_-phase_centre` group (Tab. 3.11), taking both the position of the antenna phase centre with respect to the spacecraft's centre of mass and the satellite's attitude into account.

Name	**Description**	**Shape**	**Type**	**Units**
Attributes				
`title`	Short description of the data set or group contents	–	string	–
`institution`	Name of the institution where the data was produced	–	string	–
`filename`	File name of the original GSN/RSN auxiliary product	–	string	–
`coordinate_system`	Coordinate system in which the orbit data is provided	–	string	–
`orbit_type`	One of FIT (fitted), EXT (extrapolated or predicted), or BCT (broadcast); others are possible	–	string	–
`std_base_pv_sp3`	Floating point base for position / velocity standard deviation (in mm or 10**-4 mm/sec)	–	string	–
`std_base_clock_sp3`	Floating point base for clock / clock rate standard deviation (in psec or 10**-4 psec/sec)	–	string	–
`comments_1_sp3`	Comment lines of the original SP3 auxiliary data product	–	string	–
`comments_2_sp3`	(as above)	–	string	–
`comments_3_sp3`	(as above)	–	string	–
`comments_4_sp3`	(as above)	–	string	–
`satellite_id_sp3`	SP3 satellite identifier	–	string	–
`accuracy_exponent_sp3`	SP3 accuracy exponent; the estimated one-sigma orbit error is 2**exp mm	–	string	–
Variables				
`utc_absdate`	Epochs (full days) in UTC	`(t)`	int	<days>
`utc_abstime`	Epochs (seconds since last midnight) in UTC	`(t)`	double	<time>
`position`	Satellite position in J2000 reference frame	`(t,xyz)`	double	m
`velocity`	Satellite velocity in J2000 reference frame	`(t,xyz)`	double	m/s
`orbit_predicted`	True if orbits are predicted (instead of estimated)	`(t)`	byte	–
`manoeuvre`	True if satellite undergoes a manoeuvre	`(t)`	byte	–

Table 3.11: Attributes and variables in the `/data/receiver/orbit/antenna_phase_centre` group.

For completeness, we note that the complete SP3 header information is also provided for the antenna phase centre orbit, and the above remarks concerning coverage and interpolation approaches are valid for these orbits as well. Also note that the antenna phase centre orbit is specific for the antenna taking the occultation observations, being different for rising and setting occultations, respectively.

3.4.2.3 Receiver Clock Data

The second result of the POD processing – estimated clock biases of the receiver clock – are of course independent of the antenna position, and contained in a single group named `data/receiver/clock` (Tab. 3.12). Similar to the orbit data groups, this group contains somewhat redundant meta data in order to simplify the conversion of this data into standard GNSS data format for clock data.

A widely used convention in the GNSS community is to provide clock offsets with relativistic corrections reflecting the *average* orbit height, thus ignoring relativistic corrections caused by periodic height variations the spacecraft may experience due to the eccentricity of the orbit. In EUMETSAT'S RO level 1 product granules, these periodic relativistic corrections to the receiver clock are usually applied, and thus contained in the clock bias data; a dedicated flag is used to keep track of this processing step.

Name	Description	Shape	Type	Units
Attributes				
`title`	Short description of the data set or group contents	–	string	–
`institution`	Name of the institution where the data was produced	–	string	–
`periodic_relativistic_-correction`	"Yes" is the periodic relativistic correction has been applied, "No" otherwise	–	string	–
`transponder_id`	Transponder identifier; usually equals SP3 satellite identifier	–	string	–
`satellite_id`	EUMETSAT satellite identifier as used in the POD processing	–	string	–
Variables				
`filelist`	List of files that were used to generate this file	`(files)`	string	–
`utc_absdate`	Epochs (full days) in UTC	`(t)`	int	<days>
`utc_abstime`	Epochs (seconds since last midnight) in UTC	`(t)`	double	<time>
`bias`	Satellite/receiver/transmitter clock bias	`(t)`	double	s
`rate`	Satellite/receiver/transmitter clock drift	`(t)`	double	s/s
`type`	Clock error type: o(bserved), p(ropagated), e(stimated), i(nterpolated) or n(o obs)	`(t)`	char	–

Table 3.12: Attributes and variables in the `/data/receiver/clock` group.

In contrast to position data, it is strongly recommended to use linear interpolation for clock offsets. We note that clock bias data is often provided in different (and typically much higher) sampling rates than the precise positions and velocities.

3.4.3 Transmitter Data

Similar to the receiver data group described in the previous section, the transmitter data group contains meta data characterising the GNSS satellite used for the occultation measurements as well as POD data for this satellite.

In contrast to the receiver's POD data, positions and velocities are currently only provided for the centre of mass of the GNSS satellite, as the impact of antenna position and attitude effects on RO data quality is smaller than for the LEO satellite. This may change in the future. Otherwise, the structure of the transmitter data group and its subgroups is more or less identical to those in the receiver data group:

`data/transmitter/satellite`: satellite meta data like spacecraft IDs, block and clock type;

`data/transmitter/orbit`: parent group for POD results;

`data/transmitter/orbit/centre_of_mass`: precise positions and velocities for the centre of mass of the occulting GNSS satellite;

`data/receiver/clock`: clock bias estimates.

3.4.3.1 Transmitter Satellite Data

Meta data for the occultating GNSS satellite is provided in a similar way as for the spacecraft carrying the receiver. In addition to the various satellite IDs, information on the GNSS block and atomic clock are also available.

We note that at present, geometrical data on the transmitters antenna phase centres are not provided in the EUMETSAT RO processing, and are therefore set to missing values. This may change in the future.

Name	Description	Shape	Type	Units
Attributes				
`satellite`	Satellite name	–	string	–
`satellite_block`	GNSS satellite block type	–	string	–
`satellite_clock`	GNSS satellite clock type	–	string	–
`satellite_prn`	GNSS satellite PRN	–	string	–
`satellite_id_sp3`	SP3 satellite identifier	–	string	–
`satellite_id_norad`	NORAD satellite identifier	–	string	–
Variables				
`centre_of_mass`	Centre of mass (in S/C coordinates)	`(xyz)`	double	m
`antenna_phase_centre`	Antenna phase centre (in S/C coordinates)	`(xyz)`	double	m
`antenna_orientation`	Antenna orientation (unit vector perpendicular to antenna plane in S/C coordinates)	`(xyz)`	double	m
`satellite_in_eclipse`	True if GNSS satellite is in eclipse during the occultation	-	byte	–

Table 3.13: Attributes and variables in the `/data/transmitter/satellite` group.

3.4.3.2 Transmitter Orbit Data

As for the satellite carrying the receiver, transmitter (that is: GNSS satellite) orbits are provided in the original temporal resolution as used in the processing. They are also trimmed to a period covering the respective occultation duration; in particular, the interpolation of precise orbit data using an 8^{th}-order polynomial is ensured for the entire occultation contained in any given RO level 1 granule.

Similar to the receiver orbits, meta data allow for the reconstruction of POD data in an SP3 format. The EUMETSAT data processing currently does not apply antenna phase centre corrections for the GNSS satellites. Therefore, only centre of mass orbits are provided the current level 1 data format (in the `data/transmitter/orbit/centre_of_mass` data group). Additional orbit data for antenna phase centres might be provided in the future.

Name	Description	Shape	Type	Units
Attributes				
`title`	Short description of the data set or group contents	–	string	–
`institution`	Name of the institution where the data was produced	–	string	–
`filename`	File name of the original GSN/RSN auxiliary product	–	string	–
`coordinate_system`	Coordinate system in which the orbit data is provided	–	string	–
`orbit_type`	One of FIT (fitted), EXT (extrapolated or predicted), or BCT (broadcast); others are possible	–	string	–
`std_base_pv_sp3`	Floating point base for position / velocity standard deviation (in mm or 10**-4 mm/sec)	–	string	–
`std_base_clock_sp3`	Floating point base for clock / clock rate standard deviation (in psec or 10**-4 psec/sec)	–	string	–
`comments_1_sp3`	Comment lines of the original SP3 auxiliary data product	–	string	–
`comments_2_sp3`	(as above)	–	string	–
`comments_3_sp3`	(as above)	–	string	–
`comments_4_sp3`	(as above)	–	string	–
`satellite_id_sp3`	SP3 satellite identifier	–	string	–
`accuracy_exponent_sp3`	SP3 accuracy exponent; the estimated one-sigma orbit error is 2**exp mm	–	string	–
Variables				
`utc_absdate`	Epochs (full days) in UTC	`(t)`	int	<days>
`utc_abstime`	Epochs (seconds since last midnight) in UTC	`(t)`	double	<time>
`position`	Satellite position in J2000 reference frame	`(t,xyz)`	double	m
`orbit_predicted`	True if orbits are predicted (instead of estimated)	`(t)`	byte	–
`manoeuvre`	True if satellite undergoes a manoeuvre	`(t)`	byte	–

Table 3.14: Attributes and variables in the `/data/transmitter/orbit/centre_of_mass` group.

3.4.3.3 Transmitter Clock Data

Precise bias estimates for the transmitter clocks are contained in the `/data/transmitter/clock` group; the remarks made for receiver clock biases (see section 3.4.2.3) on sampling rates, relativistic corrections and interpolation approaches are also valid for transmitter clocks.

Name	Description	Shape	Type	Units
Attributes				
`title`	Short description of the data set or group contents	–	string	–
`institution`	Name of the institution where the data was produced	–	string	–
`periodic_relativistic_-correction`	"Yes" is the periodic relativistic correction has been applied, "No" otherwise	–	string	–
`transponder_id`	Transponder identifier; usually equals SP3 satellite identifier	–	string	–
`satellite_id`	EUMETSAT satellite identifier as used in the POD processing	–	string	–
Variables				
`filelist`	List of files that were used to generate this file	`(files)`	string	–
`utc_absdate`	Epochs (full days) in UTC	`(t)`	int	<days>
`utc_abstime`	Epochs (seconds since last midnight) in UTC	`(t)`	double	<time>
`bias`	Satellite/receiver/transmitter clock bias	`(t)`	double	s
`rate`	Satellite/receiver/transmitter clock drift	`(t)`	double	s/s
`type`	Clock error type: o(bserved), p(ropagated), e(stimated), i(nterpolated) or n(o obs)	`(t)`	char	–

Table 3.15: Attributes and variables in the `/data/transmitter/clock` group.

3.4.4 Earth Orientation Parameters

Earth Orientation Parameters (EOP) are used to perform precise conversions between an Earth-centered inertial coordinate system (in which the RO retrieval is carried out) and the Earth-fixed coordinate system which is used to calculate the geolocation of the level 1b data. Similar to orbit data, EOPs are provided in the original temporal resolution (EOPs are a by-product of the POD), and are trimmed to the occultation duration. It is usually sufficient to interpolate EOPs linearly in time.

Name	Description	Shape	Type	Units
Attributes				
`title`	Short description of the data set or group contents	–	string	–
`model`	Earth Orientation Parameter model applied	–	string	–
`filename`	File name of the original GSN/RSN auxiliary product	–	string	–
Variables				
`utc_absdate`	Epochs (full days) in UTC	`(t)`	int	<days>
`utc_abstime`	Epochs (seconds since last midnight) in UTC	`(t)`	double	<time>
`xp`	x component of polar motion	`(t)`	double	rad
`yp`	y component of polar motion	`(t)`	double	rad
`ut1_utc`	Difference between Universal Time (UT1) and Coordinated Universal Time (UTC)	`(t)`	double	s
`dX`	dX wrt IAU2000A Nutation, Free Core Nutation NOT Removed	`(t)`	double	rad

Table 3.16: Attributes and variables in the `/data/earth_orientation_parameters` group.

Name	Description	Shape	Type	Units
`dY`	dY wrt IAU2000A Nutation, Free Core Nutation NOT Removed	`(t)`	double	rad
`flag_predicted`	Estimated (0) or Predicted (1) flag for polar motion values	`(t)`	byte	–
`LOD`	Length of Day (difference between the astronomically determined duration of the day and 86400)	`(t)`	double	ms

Table 3.16: Attributes and variables in the `/data/earth_orientation_parameters` group.

3.4.5 Level 1a Data

Level 1a RO data generally consists of pseudo range, carrier phase and amplitude as measured by the RO instrument in its various measurements modes (e.g., closed loop and high-rate raw sampling carrier phase tracking in case of the GRAS instrument). If high-rate carrier phase and amplitude data is available from the instrument, a coherently integrated 50 Hz carrier phase and amplitude data set known as "open loop" data is also provided. The `data/level_1a` data group thus has the following structure:

`data/level_1a`: Parent group of the level 1a data; contains a common reference time for all time referencing;

`data/level_1a/pseudo_range`: Pseudo-range data;

`data/level_1a/closed_loop`: 50 Hz closed loop carrier phase and amplitude data;

`data/level_1a/raw_sampling`: High-rate (e.g., 1 kHz in case of GRAS) raw sampling carrier phase and amplitude data;

`data/level_1a/open_loop`: 50 Hz open loop carrier phase and amplitude data calculated from the raw sampling data by coherently integrating and dumping between navigation bit boundaries.

In the following sections, the representation of GNSS measurements is discussed, along with the navigation bit handling, carrier phase differencing, and excess phase calculation being applied during the level 1a processing. We also caution against the use of interpolated position and velocity data as contained in the level 1a data group, before discussing the detailed content of the various measurement data subgroups.

3.4.5.1 Carrier Phase and Amplitude Representation

The physical electromagnetic signal measured by an RO receiver is usually modelled as

$$S_i(t) = A_i(t)\, e^{2\pi j \phi_i(t)} \tag{3.1}$$

where $S_i(t)$ is the complex valued electromagnetic signal, $A_i(t)$ a real valued amplitude, and ϕ_i a real valued (total) phase. j denotes the usual $j = \sqrt{-1}$, while the index i refers to the carrier frequency, e.g. $i = 1$ for measurements taken in the L1 frequency band.

Another, mathematically equivalent way to write the same measurement $S_i(t)$ is

$$S_i(t) = (I_i(t) + jQ_i(t))\, e^{2\pi i \phi_{\text{nco},i}(t)} \tag{3.2}$$

where $I_i(t)$ and $Q_i(t)$ represent the real and imaginary parts of a complex amplitude, with $\phi_{\mathrm{nco},i}$ being a (again real valued) phase which is however slightly differing from the total phase ϕ_i introduced in (3.1). The two representations can be converted into each other using

$$A_i(t) = \sqrt{I_i^2(t) + Q_i^2(t)} \tag{3.3a}$$

and

$$\phi_i(t) = \phi_{\mathrm{nco},i}(t) + \Delta\phi_i(t) \quad \text{with} \quad \Delta\phi_i(t) = \arctan\left(I_i(t), Q_i(t)\right) \tag{3.3b}$$

An advantage of (3.2) is that it mimics the receiver's measurement approach, especially in open loop mode: The instrument provides a reference or "Numerically Controlled Oscillator" (NCO) driven phase ($\phi_{\mathrm{nco},i}$), and measures – through correlating the signal with the known GNSS code – by how much the actual signal differs from this reference phase. The deviation is expressed through the correlator's Is and Qs, which in turn can be mapped back to the physical amplitude of the signal measured by the antenna.

The RO level 1 data format therefore provides measured GNSS data primarily in form (3.2), i.e. through the variables I_i, Q_i, and $\phi_{\mathrm{nco},i}$. In closed loop tracking modes, $\phi_{\mathrm{nco},i}$ represents the output of the receiver's tracking loop; the values of I and Q then allow analysis of the quality of the closed loop tracking[1]. In open loop tracking modes, $\phi_{\mathrm{nco},i}$ represents the receiver's phase model for the occultation, which is usually obtained from some doppler model implemented in the receiver. Both I and Q will then carry significant information about the measured signal (and its deviation from the receiver's phase model).

For convenience, real-valued amplitude A and total phase data ϕ_i derived from the I/Q representation are provided, but only limited attempts have been made

Note that none of the two representations provides a unique representation of the measured signal. In particular, phase is only unique up to multiples of 2π due to the periodicity of the complex e function. In the I/Q representation, and for continuous data segments, the NCO phase $\phi_{\mathrm{nco},i}$ generated by the receiver's tracking loop or doppler model will not exhibit cycle slips by construction, but large jumps can be expected across data gaps and between data from different measurement modes. In contrast, total phase ϕ, while having been subject to some form of unwrapping during the level 1a processing, may have cycle slips.

Users preferring to interpret (total) carrier phase as a proxy of geometrical range should take great care to implement proper phase unwrapping and cycle slip detection algorithms before using (total) phase data as-is.

3.4.5.2 Navigation Bits

The I/Q phase representation (3.2) is also beneficial when it comes to the handling of the navigation bit data handling, as the data navigation affects the signs of both I and Q, but has no impact on ϕ_{nco}. Note that for GPS, the navigation bit data modulation is only present on L1 C/A data. The RO level 1 data format provides an internal estimate o the navigation bit sequence from the observed I and Q data, interpolated to measurement epochs; external navigation bit data originally provided by the RSN is also provided if available, or set to "missing" otherwise. Finnally, the `level1_a` data group contains I and Q data both in their raw form (i.e.,

[1] If the receiver's carrier phase Phase-Locked-Loop (PLL) works well, all energy should be contained in I, while Q just contains random noise.

with the navigation bit modulation still present; variables `i_ca_uncorr` and `q_ca_uncorr`) as well as with the navigation bit solution removed (variables `i_ca` and `q_ca`). The `quality` data group (see section 3.5 contains a flag for each type of carrier phase measurement mode which indicates whether external navigation bits were available (and applied) during the processing, or if internal navigation bits had to be used for removing the navigation bit data sequence from the I and Q components of the carrier phase data.

3.4.5.3 Zero-Differencing

All carrier phase data has been corrected for receiver and transmitter clock biases by applying the clock biases obtained from the POD processing; the clock data is available in the `data/receiver/clock` and `data/transmitter/clock` groups of the RO level 1 data format (see sections 3.4.2 and 3.4.3).

3.4.5.4 Excess Carrier Phases

Along with (total) NCO phase ϕ_{nco} and total phase ϕ, the `data/level_1a` data group also contains excess NCO phase and phase. They are are calculated as, e.g.,

$$\Delta\phi_{\text{nco}} = \phi_{\text{nco}} - \left|\vec{r}_{\text{GNSS, retarded}} - \vec{r}_{\text{LEO, antenna}}\right| \tag{3.4}$$

and are normalised to zero at the top of the occultation. Here, $\vec{r}_{\text{GNSS, retarded}}$ and $\vec{r}_{\text{LEO, antenna}}$ denote are the precise positions of the transmitter (retarded) and receiver antennas, respectively. Note that eq. (3.4) makes use of the convenience that carrier phase data are stored in units of meters.

3.4.5.5 Precise Orbit Data

The precise orbit data for both transmitter and receiver (originally available in the data groups `data/receiver` and `data/transmitter` is available in the `data/level_1a` data group, interpolated to the measurement epochs. For the transmitter, "retarded" positions taking into account the travel time of the GNSS signals between transmitter and receiver is taken into account.

While the availability of POD data at measurement epochs is convenient, we highly recommend to avoid re-interpolation of the position and velocity data contained in the `data/level_1a` data group. Instead, the original POD data as contained in the groups `data/receiver` and `data/transmitter` (see sections 3.4.2 and 3.4.3) should be interpolated directly for all calculations.

3.4.5.6 Time Representation

Within each level 1a data subgroup (`level_1a/pseudo_range`, `level_1a/closed_loop`, `level_1a/raw_-sampling`, and `level_1a/open_loop`), all data is available at identical measurement epochs. Time stamps are provided via the variable `dtime`, denoting the time passed since the start (reference) time of the occultation given in the `level_1a` parent group (see Tab. 3.17). Note that, in order to comply with the CF conventions, the `units` attribute of `dtime` also refers to the (same) reference time. As time stamps in the CF unit conventions cannot be more accurate than to hundredths of a second, the reference time has been rounded to accordingly.

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>

Table 3.17: Attributes and variables in the `/data/level_1a` group.

Start (reference) times given in the `data/level_1a` parent group are *not* related to the nominal reference time of the occultation provided in the `data/occultation` group (see section 3.4.1). Instead, they refer to the (approximate) beginning of measurements for this particular occultation.

3.4.5.7 Data Subgroups

Pseudorange and closed loop carrier phase measurements are available in the data groups `data/level_1a/pseudorange` and `data/level_1a/closed_loop`, respectively; Tables 3.18 and 3.19 contain the detailed lists and short descriptions for these data subgroups. Each subgroup contains data for all GNSS frequencies (L1 and L2) and codes (C/A and P on L1, P on L2). While both pseudo range and closed loop carrier phase data exhibit dual frequency measurements, periods may exist where only single frequency measurements (L1 C/A) are available; the data from the L1 and L2 P-code tracking channels is then filled with missing data indicators (see section 3.1.4). The relation of a variable with a frequency and code can be inferred from its variable name. For example, the excess carrier phase as reconstructed from the L1 C/A or L2/P code tracking are named `exphase_ca` and `exphase_p2`, respectively.

Apart from containing the measurements themselves, each subgroup also provides Straight Line Tangent Altitude (SLTA) as well as interpolated orbit, velocity and clock bias data for each measurement epoch. Elevation and azimuth with respect to the antenna borehole are based on a straight line approximation. Additional diagnostic data like upper level noise figures and (for pseudoranges) systematic offsets between pseudorange and carrier phase data are also available.

Raw sampling data provided by GRAS instruments at a 1 kHz sampling rate is available in the `data/level_1a/raw_sampling` data group (see Table 3.20); the downsampled (to 50 Hz) version of the same data as used in the level 1b retrievals is contained in the group `data/level_1a/open_loop` (Table 3.21). In this measurement mode, only single frequency (L1 C/A) data is available; otherwise, the contents of the respective data groups are similar to those of pseudorange and closed loop carrier phase measurements.

Data from different measurement modes may overlap in time; combining them into a single time series of unique measurements is part of the level 1b processing. Further note that level 1a data from both closed and open loop/raw sampling measurement modes may contain data gaps. The latter can be identified by analysing the time differences between successive measurement epochs.

Finally, all level 1a data groups contain zero differenced total as well as excess carrier phases (or pseudoranges). Differencing (see section 3.4.5.3) has been applied to all carrier phase data contained the various level 1a data subgroups using the precise clock bias data as contained in the same data group. Similarly, the calculation of excess phases and ranges (see section 3.4.5.4) is based on the interpolated POD data provided in the same data group.

Calculating excess phases from orbit solutions other than the one provided by EUMETSAT will require undoing the differencing and excess phase calculation first.

Name	Description	Shape	Type	Units
Attributes				
`title`	Short description of the data set or group contents	–	string	–
Variables				
`dtime`	Measurement epoch	`(t)`	double	<time>
`slta`	Straight line tangent altitude	`(t)`	double	m
`samplerate`	Measurement sample rate	-	double	Hz
`tracking_state`	Tracking states	`(t)`	int	–
`pseudorange_ca`	C/A pseudorange	`(t)`	double	m
`pseudorange_p1`	P1 pseudorange	`(t)`	double	m
`pseudorange_p2`	P2 pseudorange	`(t)`	double	m
`expseudorange_ca`	C/A excess (pseudo-) range	`(t)`	double	m
`expseudorange_p1`	P1 excess (pseudo-) range	`(t)`	double	m
`expseudorange_p2`	P2 excess (pseudo-) range	`(t)`	double	m
`r_receiver`	Receiver position in Earth centred inertial coordinates (J2000)	`(t,xyz)`	double	m
`v_receiver`	Receiver velocity in Earth centred inertial coordinates (J2000)	`(t,xyz)`	double	m/s
`r_transmitter`	Transmitter position (retarded) in Earth centred inertial coordinates (J2000)	`(t,xyz)`	double	m
`v_transmitter`	Transmitter velocity (retarded) in Earth centred inertial coordinates (J2000)	`(t,xyz)`	double	m/s
`zenith_antenna`	Straight line ray antenna zenith angle (in S/C coordinates)	`(t)`	double	<deg>
`azimuth_antenna`	Straight line ray antenna azimuth angle (in S/C coordinates)	`(t)`	double	<deg>
`pseudorange_ca_noise`	Mean C/A pseudorange noise (SLTA > 60 km)	-	double	m
`pseudorange_p1_noise`	Mean P1 pseudorange noise (SLTA > 60 km)	-	double	m
`pseudorange_p2_noise`	Mean P2 pseudorange noise (SLTA > 60 km)	-	double	m
`pseudorange_ca_offset`	Mean C/A pseudorange (vs. phase) offset (SLTA > 60 km)	-	double	m
`pseudorange_p1_offset`	Mean P1 pseudorange (vs. phase) offset (SLTA > 60 km)	-	double	m
`pseudorange_p2_offset`	Mean P2 pseudorange (vs. phase) offset (SLTA > 60 km)	-	double	m
`slta_ca_min_all`	Minimum overall SLTA of C/A pseudorange data	-	double	m
`slta_ca_max_all`	Maximum overall SLTA of C/A pseudorange data	-	double	m

Table 3.18: Attributes and variables in the `/data/level_1a/pseudo_range` group.

Name	Description	Shape	Type	Units
slta_p1_min_all	Minimum overall SLTA of P1 pseudorange data	-	double	m
slta_p1_max_all	Maximum overall SLTA of P1 pseudorange data	-	double	m
slta_p2_min_all	Minimum overall SLTA of P2 pseudorange data	-	double	m
slta_p2_max_all	Maximum overall SLTA of P2 pseudorange data	-	double	m
slta_ca_min_main	Minimum SLTA of main (longest) C/A pseudorange data segment	-	double	m
slta_ca_max_main	Maximum SLTA of main (longest) C/A pseudorange data segment	-	double	m
slta_p1_min_main	Minimum SLTA of main (longest) P1 pseudorange data segment	-	double	m
slta_p1_max_main	Maximum SLTA of main (longest) P1 pseudorange data segment	-	double	m
slta_p2_min_main	Minimum SLTA of main (longest) P2 pseudorange data segment	-	double	m
slta_p2_max_main	Maximum SLTA of main (longest) P2 pseudorange data segment	-	double	m
slta_ca_min_select	Minimum SLTA of C/A pseudorange data selected for processing	-	double	m
slta_ca_max_select	Maximum SLTA of C/A pseudorange data selected for processing	-	double	m
slta_p1_min_select	Minimum SLTA of P1 pseudorange data selected for processing	-	double	m
slta_p1_max_select	Maximum SLTA of P1 pseudorange data selected for processing	-	double	m
slta_p2_min_select	Minimum SLTA of P2 pseudorange data selected for processing	-	double	m
slta_p2_max_select	Maximum SLTA of P2 pseudorange data selected for processing	-	double	m

Table 3.18: Attributes and variables in the /data/level_1a/pseudo_range group.

Name	Description	Shape	Type	Units
Attributes				
title	Short description of the data set or group contents	–	string	–
Variables				
dtime	Measurement epoch	(t)	double	<time>
slta	Straight line tangent altitude	(t)	double	m
samplerate	Measurement sample rate	-	double	Hz
tracking_state	Tracking states	(t)	int	–
phase_l1_nco	L1 carrier NCO phase	(t)	double	m
phase_l2_nco	L2 carrier NCO phase	(t)	double	m
phase_ca	C/A carrier phase including I/Q contributions	(t)	double	m
phase_p1	P1 carrier phase including I/Q contributions	(t)	double	m
phase_p2	P2 carrier phase including I/Q contributions	(t)	double	m
exphase_l1_nco	L1 carrier NCO excess phase	(t)	double	m
exphase_l2_nco	L2 carrier NCO excess phase	(t)	double	m

Table 3.19: Attributes and variables in the /data/level_1a/closed_loop group.

Name	Description	Shape	Type	Units
exphase_ca	C/A carrier excess phase including I/Q contributions	(t)	double	m
exphase_p1	P1 carrier excess phase including I/Q contributions	(t)	double	m
exphase_p2	P2 carrier excess phase including I/Q contributions	(t)	double	m
i_ca_uncorr	In-phase component I of C/A carrier phase measurements, normalized to antenna port	(t)	double	V
i_ca	In-phase component I of C/A carrier phase measurements, navigation bits demodulated, normalized to antenna port	(t)	double	V
i_p1	In-phase component I of P1 carrier phase measurements, normalized to antenna port	(t)	double	V
i_p2	In-phase component I of P2 carrier phase measurements, normalized to antenna port	(t)	double	V
q_ca_uncorr	Quadrature component Q of C/A carrier phase measurements, normalized to antenna port	(t)	double	V
q_ca	Quadrature component Q of C/A carrier phase measurements, navigation bits demodulated, normalized to antenna port	(t)	double	V
q_p1	Quadrature component Q of P1 carrier phase measurements, normalized to antenna port	(t)	double	V
q_p2	Quadrature component Q of P2 carrier phase measurements, normalized to antenna port	(t)	double	V
amplitude_ca	Amplitude of C/A carrier phase measurements, normalized to antenna port	(t)	double	V
amplitude_p1	Amplitude of P1 carrier phase measurements, normalized to antenna port	(t)	double	V
amplitude_p2	Amplitude of P2 carrier phase measurements, normalized to antenna port	(t)	double	V
snr_ca	Signal-to-Noise-Ratio of C/A carrier phase measurements	(t)	double	V/V
snr_p1	Signal-to-Noise-Ratio of P1 carrier phase measurements	(t)	double	V/V
snr_p2	Signal-to-Noise-Ratio of P2 carrier phase measurements	(t)	double	V/V
navbits_external	External navigation data bits if available	(t)	double	–
navbits_internal	Internal navigation data bits	(t)	double	–
r_receiver	Receiver position in Earth centred inertial coordinates (J2000)	(t,xyz)	double	m
v_receiver	Receiver velocity in Earth centred inertial coordinates (J2000)	(t,xyz)	double	m/s
r_transmitter	Transmitter position (retarded) in Earth centred inertial coordinates (J2000)	(t,xyz)	double	m
v_transmitter	Transmitter velocity (retarded) in Earth centred inertial coordinates (J2000)	(t,xyz)	double	m/s
zenith_antenna	Straight line ray antenna zenith angle (in S/C coordinates)	(t)	double	<deg>
azimuth_antenna	Straight line ray antenna azimuth angle (in S/C coordinates)	(t)	double	<deg>
snr_ca_mean	Mean Signal-to-Noise-Ratio (amplitude) of C/A carrier phase measurements (SLTA > 60 km)	-	double	V/V
snr_p1_mean	Mean Signal-to-Noise-Ratio (amplitude) of P1 carrier phase measurements (SLTA > 60 km)	-	double	V/V

Table 3.19: Attributes and variables in the /data/level_1a/closed_loop group.

Name	Description	Shape	Type	Units
snr_p2_mean	Mean Signal-to-Noise-Ratio (amplitude) of P2 carrier phase measurements (SLTA > 60 km)	-	double	V/V
cn0_ca_mean	Mean Signal-to-Noise-Ratio (C/No) of C/A carrier phase measurements (SLTA > 60 km)	-	double	dB Hz
cn0_p1_mean	Mean Signal-to-Noise-Ratio (C/No) of P1 carrier phase measurements (SLTA > 60 km)	-	double	dB Hz
cn0_p2_mean	Mean Signal-to-Noise-Ratio (C/No) of P2 carrier phase measurements (SLTA > 60 km)	-	double	db Hz
signal_power_ca_mean	Mean signal power for C/A carrier phase measurements (SLTA > 60 km)	-	double	db
signal_power_p1_mean	Mean signal power for P1 carrier phase measurements (SLTA > 60 km)	-	double	db
signal_power_p2_mean	Mean signal power for P2 carrier phase measurements (SLTA > 60 km)	-	double	db
noise_power_l1_mean	Mean noise power spectral density for L1 carrier phase measurements	-	double	db/Hz
noise_power_l2_mean	Mean noise power spectral density for L2 carrier phase measurements	-	double	db/Hz
exphase_ca_noise	Mean phase noise of C/A carrier excess phase measurements (SLTA > 60 km)	-	double	m
exphase_p1_noise	Mean phase noise of P1 carrier excess phase measurements (SLTA > 60 km)	-	double	m
exphase_p2_noise	Mean phase noise of P2 carrier excess phase measurements (SLTA > 60 km)	-	double	m
slta_ca_min_all	Minimum overall SLTA of C/A carrier phase data	-	double	m
slta_ca_max_all	Maximum overall SLTA of C/A carrier phase data	-	double	m
slta_p1_min_all	Minimum overall SLTA of P1 carrier phase data	-	double	m
slta_p1_max_all	Maximum overall SLTA of P1 carrier phase data	-	double	m
slta_p2_min_all	Minimum overall SLTA of P2 carrier phase data	-	double	m
slta_p2_max_all	Maximum overall SLTA of P2 carrier phase data	-	double	m
slta_ca_min_main	Minimum SLTA of main (longest) C/A carrier phase data segment	-	double	m
slta_ca_max_main	Maximum SLTA of main (longest) C/A carrier phase data segment	-	double	m
slta_p1_min_main	Minimum SLTA of main (longest) P1 carrier phase data segment	-	double	m
slta_p1_max_main	Maximum SLTA of main (longest) P1 carrier phase data segment	-	double	m
slta_p2_min_main	Minimum SLTA of main (longest) P2 carrier phase data segment	-	double	m
slta_p2_max_main	Maximum SLTA of main (longest) P2 carrier phase data segment	-	double	m
slta_ca_min_select	Minimum SLTA of C/A carrier phase data selected for processing	-	double	m
slta_ca_max_select	Maximum SLTA of C/A carrier phase data selected for processing	-	double	m
slta_p1_min_select	Minimum SLTA of P1 carrier phase data selected for processing	-	double	m
slta_p1_max_select	Maximum SLTA of P1 carrier phase data selected for processing	-	double	m

Table 3.19: Attributes and variables in the `/data/level_1a/closed_loop` group.

Name	Description	Shape	Type	Units
slta_p2_min_select	Minimum SLTA of P2 carrier phase data selected for processing	-	double	m
slta_p2_max_select	Maximum SLTA of P2 carrier phase data selected for processing	-	double	m

Table 3.19: Attributes and variables in the `/data/level_1a/closed_loop` group.

Name	Description	Shape	Type	Units
Attributes				
title	Short description of the data set or group contents	–	string	–
Variables				
dtime	Measurement epoch	(t)	double	<time>
slta	Straight line tangent altitude	(t)	double	m
samplerate	Measurement sample rate	-	double	Hz
tracking_state	Tracking states	(t)	int	–
phase_l1_nco	L1 carrier NCO phase	(t)	double	m
phase_ca	C/A carrier phase including I/Q contributions	(t)	double	m
exphase_l1_nco	L1 carrier NCO excess phase	(t)	double	m
exphase_ca	C/A carrier excess phase including I/Q contributions	(t)	double	m
i_ca_uncorr	In-phase component I of C/A carrier phase measurements, normalized to antenna port	(t)	double	V
q_ca_uncorr	Quadrature component Q of C/A carrier phase measurements, normalized to antenna port	(t)	double	V
i_ca	In-phase component I of C/A carrier phase measurements, navigation bits demodulated, normalized to antenna port	(t)	double	V
q_ca	Quadrature component Q of C/A carrier phase measurements, navigation bits demodulated, normalized to antenna port	(t)	double	V
amplitude_ca	Amplitude of C/A carrier phase measurements, normalized to antenna port	(t)	double	V
snr_ca	Signal-to-Noise-Ratio of C/A carrier phase measurements	(t)	double	V/V
navbits_external	External navigation data bits if available	(t)	double	–
navbits_internal	Internal navigation data bits	(t)	double	–
r_receiver	Receiver position in Earth centred inertial coordinates (J2000)	(t,xyz)	double	m
v_receiver	Receiver velocity in Earth centred inertial coordinates (J2000)	(t,xyz)	double	m/s
r_transmitter	Transmitter position (retarded) in Earth centred inertial coordinates (J2000)	(t,xyz)	double	m
v_transmitter	Transmitter velocity (retarded) in Earth centred inertial coordinates (J2000)	(t,xyz)	double	m/s
zenith_antenna	Straight line ray antenna zenith angle (in S/C coordinates)	(t)	double	<deg>
azimuth_antenna	Straight line ray antenna azimuth angle (in S/C coordinates)	(t)	double	<deg>
noise_power_l1_mean	Mean noise power spectral density for L1 phase measurements	-	double	db/Hz

Table 3.20: Attributes and variables in the `/data/level_1a/raw_sampling` group.

Name	Description	Shape	Type	Units
slta_ca_min_all	Minimum overall SLTA of C/A carrier phase data	-	double	m
slta_ca_max_all	Maximum overall SLTA of C/A carrier phase data	-	double	m
slta_ca_min_main	Minimum SLTA of main (longest) C/A carrier phase data segment	-	double	m
slta_ca_max_main	Maximum SLTA of main (longest) C/A carrier phase data segment	-	double	m
slta_ca_min_select	Minimum SLTA of C/A carrier phase data selected for processing	-	double	m
slta_ca_max_select	Maximum SLTA of C/A carrier phase data selected for processing	-	double	m
cl_rs_overlap_period	Period with overlapping closed loop and raw sampling data	-	double	s
cl_rs_phase_shift_mean	Closed loop vs. raw sampling phase shift mean	-	double	rad
cl_rs_phase_shift_sdev	Closed loop vs. raw sampling phase shift standard deviation	-	double	rad
cl_rs_phase_shift_t	Closed loop vs. raw sampling phase shift t-test value	-	double	–
cl_rs_phase_shift_prob	Closed loop vs. raw sampling phase shift t-test probability	-	double	–
cl_rs_amplitude_ratio_mean	Closed loop vs. raw sampling amplitude ratio mean	-	double	–
cl_rs_amplitude_ratio_sdev	Closed loop vs. raw sampling amplitude ratio standard deviation	-	double	–
cl_rs_amplitude_ratio_t	Closed loop vs. raw sampling amplitude ratio t-test value	-	double	–
cl_rs_amplitude_ratio_prob	Closed loop vs. raw sampling amplitude ratio t-test probability	-	double	–

Table 3.20: Attributes and variables in the `/data/level_1a/raw_sampling` group.

Name	Description	Shape	Type	Units
Attributes				
title	Short description of the data set or group contents	–	string	–
Variables				
dtime	Measurement epoch	(t)	double	<time>
slta	Straight line tangent altitude	(t)	double	m
samplerate	Measurement sample rate	-	double	Hz
tracking_state	Tracking states	(t)	int	–
phase_l1_nco	L1 carrier NCO phase	(t)	double	m
phase_ca	C/A carrier phase including I/Q contributions	(t)	double	m
exphase_l1_nco	L1 carrier NCO excess phase	(t)	double	m
exphase_ca	C/A carrier excess phase including I/Q contributions	(t)	double	m
i_ca_uncorr	In-phase component I of C/A carrier phase measurements, normalized to antenna port	(t)	double	V
q_ca_uncorr	Quadrature component Q of C/A carrier phase measurements, normalized to antenna port	(t)	double	V

Table 3.21: Attributes and variables in the `/data/level_1a/open_loop` group.

Name	Description	Shape	Type	Units
i_ca	In-phase component I of C/A carrier phase measurements, navigation bits demodulated, normalized to antenna port	(t)	double	V
q_ca	Quadrature component Q of C/A carrier phase measurements, navigation bits demodulated, normalized to antenna port	(t)	double	V
amplitude_ca	Amplitude of C/A carrier phase measurements, normalized to antenna port	(t)	double	V
snr_ca	Signal-to-Noise-Ratio of C/A carrier phase measurements	(t)	double	V/V
navbits_external	External navigation data bits if available	(t)	double	–
navbits_internal	Internal navigation data bits	(t)	double	–
r_receiver	Receiver position in Earth centred inertial coordinates (J2000)	(t,xyz)	double	m
v_receiver	Receiver velocity in Earth centred inertial coordinates (J2000)	(t,xyz)	double	m/s
r_transmitter	Transmitter position (retarded) in Earth centred inertial coordinates (J2000)	(t,xyz)	double	m
v_transmitter	Transmitter velocity (retarded) in Earth centred inertial coordinates (J2000)	(t,xyz)	double	m/s
zenith_antenna	Straight line ray antenna zenith angle (in S/C coordinates)	(t)	double	<deg>
azimuth_antenna	Straight line ray antenna azimuth angle (in S/C coordinates)	(t)	double	<deg>
noise_power_l1_mean	Mean noise power spectral density for L1 phase measurements	-	double	db/Hz
slta_ca_min_all	Minimum overall SLTA of C/A carrier phase data	-	double	m
slta_ca_max_all	Maximum overall SLTA of C/A carrier phase data	-	double	m
slta_ca_min_main	Minimum SLTA of main (longest) C/A carrier phase data segment	-	double	m
slta_ca_max_main	Maximum SLTA of main (longest) C/A carrier phase data segment	-	double	m
slta_ca_min_select	Minimum SLTA of C/A carrier phase data selected for processing	-	double	m
slta_ca_max_select	Maximum SLTA of C/A carrier phase data selected for processing	-	double	m

Table 3.21: Attributes and variables in the `/data/level_1a/open_loop` group.

3.4.6 Level 1b Data

The primary content of level 1b RO data are vertical bending angle profiles provided as function of the impact parameter, along with georeferencing and some diagnostic data. EUMETSAT provides both a high resolution as well as a thinned bending angle profile. The structure of the `data/level_1b` data group is as follows:

`data/level_1b`: Parent group of the level 1b data; contains a common reference time for all time referencing;

`data/level_1b/high_resolution`: High resolution bending angle profile;

`data/level_1b/thinned`: Thinned bending angle profile.

The following sections discuss retrieval types, interpretation issues with time stamping and geolocation of bending angle data as well as the contents of the high resolution and thinned bending angle data groups.

3.4.6.1 Retrieval Types

EUMETSAT's RO processing suites are capable of producing both advanced (often referred to as "wave optics") as well as traditional ("geometrical optics") retrievals. Starting in 2016, the default retrieval methodology is a wave optics method based on the Full Spectrum Inversion (FSI). By default, the FSI is applied over the entire profile[2]. Geometrical optics retrievals are only produced if the FSI processing fails for some reason, or if the the processing system is configured to perform geometrical optics retrievals only. The processing algorithm applied to a particular occultation can be inferred in textual form from the `retrieval_method` attribute of the `/data/occultation` group.

3.4.6.2 Time Stamping and Georeferencing

In the traditional (or "geometrical optics") retrieval, assigning specific measurement epochs to (excess) doppler and bending angle/impact parameter values is straightforward as the latter are essentially derived by simple time differentiation of the raw phase measurements. Refractivity structures causing atmospheric multipath are however characterised by sharp peaks in the bending angle when seen as function of impact parameter. Due to the large bending around the peak's maximum, rays originating from regions around the peak's maximum (i.e., from the multipath region) will be observed significantly later (in case of a setting occultation; or much earlier in case of a rising occultation) than for surrounding impact parameter regions above or below the bending angle peak. Such bending angle structures are thus characterised by a wide spread of measurement epochs. Wave optics based retrieval methods therefore don't process the measurements in the time domain, but instead transform the signal to the doppler frequency or even impact parameter domain.

As a consequence, there is no one-to-one correspondence of observation times and retrieved bending angle/impact parameter values in the vicinity of multipath regions. In EUMETSAT's processing, an averaged time stamp is instead calculated over a window consistent with the smoothing applied during the retrieval. This averaged epoch is then used to calculate the geolocation of each bending angle/impact parameter value.

3.4.6.3 High Resolution Profiles

In geometrical optics retrievals, high resolution retrievals consist of bending angle/impact parameter pairs calculated at the 50 Hz measurement rate common to most RO instruments. For wave optics retrievals, an equidistant 1 Hz grid covering the doppler bandwidth of the observed L1 C/A carrier phase measurements is exploited during the retrieval; this choice (typcally) provides a number of data points similar to the original 50 Hz measurement time series.

At present, bending angle error estimates are not yet available. This will change in a future version of EUMETSAT's radio occultation processor.

[2]Note in particular that there is no merging between indpendent tropospheric and stratospheric retrieval results.

3.4.6.4 Thinned Bending Profiles

The structure of the /data/level_1b/thinned data group is identical to the one for high resolution bending angle retrievals. Bending angle profiles have however been thinned (and smoothed) to a set of 247 standard impact altitude levels. The same limitations as listed for the high resolution bending angle data also apply to the thinned retrievals. Note that the contents of the /data/level_1b/thinned data group are also available as BUFR products (see appendix C).

3.4.6.5 Time representation

Similar to the level 1a data measurement group, the nominal time stamps of individual bending angle/impact parameter values (within the limitations discussed in section 3.4.6.2) are given as time passed since a reference time, using a variable named dtime. As in the level 1a data group, reference times are provided in the root group for the level 1b data in both UTC and GPS time (see Tab. 3.22), and are equal to the reference times used in the level 1a data representation. As for level 1a data, the value of the units attribute of each dtime variable can also be used to infere about the reference time.

Similar to the level 1a data, the reference time used for providing time stamps for individual bending angle/impact parameter values is loosely related to the first measurement for the particular occultation, but *not* to the nominal reference time of the entire occultation as provided in the data/occultation group (see section 3.4.1).

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>

Table 3.22: Attributes and variables in the /data/level_1b group.

3.4.6.6 Data Subgroups

The detailed contents of the high resolution and thinned retrievals are given in the Tables 3.23 and 3.24 on the following pages, respectively.

Name	Description	Shape	Type	Units
Attributes				
title	Short description of the data set or group contents	–	string	–
Variables				
impact	Impact parameter	(z)	double	m
impact_height	Impact height (wrt WGS 84 ellipsoid)	(z)	double	m
bangle	Bending angle (ionospheric corrected)	(z)	double	rad
bangle_ca	Bending angle (C/A)	(z)	double	rad
bangle_p1	Bending angle (P1)	(z)	double	rad
bangle_p2	Bending angle (P2)	(z)	double	rad
bangle_ca_p2_diff	Bending angle difference, (L1 / C/A - L2 / P2, extrapolated)	(z)	double	rad
bangle_sdev	Bending angle (ionospheric corrected) estimated standard deviation	(z)	double	rad
bangle_ca_sdev	Bending angle (C/A) estimated standard deviation	(z)	double	rad
bangle_p1_sdev	Bending angle (P1) estimated standard deviation	(z)	double	rad
bangle_p2_sdev	Bending angle (P2) estimated standard deviation	(z)	double	rad
lat_tp	Latitudes for tangent points	(z)	double	<degN>
lon_tp	Longitudes for tangent points	(z)	double	<degE>
azimuth_tp	GNSS->LEO line of sight angles (from True North) for tangent points	(z)	double	<deg>
dtime_mean	Mean measurement epoch (used for georeferencing only)	(z)	double	<time>
doppler_ca_max	Maximum instantaneous Doppler (C/A)	-	double	Hz
doppler_p2_max	Maximum instantaneous Doppler (P2)	-	double	Hz
doppler_rate_ca_max	Maximum instantaneous Doppler rate (C/A)	-	double	Hz/s
doppler_rate_p2_max	Maximum instantaneous Doppler rate (P2)	-	double	Hz/s
doppler_accel_ca_max	Maximum instantaneous Doppler acceleration (C/A)	-	double	Hz/s^2
doppler_accel_p2_max	Maximum instantaneous Doppler acceleration (P2)	-	double	Hz/s^2
exdoppler_ca_max	Maximum instantaneous excess Doppler (C/A)	-	double	Hz
exdoppler_p2_max	Maximum instantaneous excess Doppler (P2)	-	double	Hz
exdoppler_rate_ca_max	Maximum instantaneous excess Doppler rate (C/A)	-	double	Hz/s
exdoppler_rate_p2_max	Maximum instantaneous excess Doppler rate (P2)	-	double	Hz/s
exdoppler_accel_ca_max	Maximum instantaneous excess Doppler acceleration (C/A)	-	double	Hz/s^2
exdoppler_accel_p2_max	Maximum instantaneous excess Doppler acceleration (P2)	-	double	Hz/s^2
bangle_upper_level_mean	Bending angle (ionospheric corrected) - 60-80km mean	-	double	rad
bangle_upper_level_sdev	Bending angle (ionospheric corrected) - 60-80km standard deviation	-	double	rad
bangle_upper_level_mean_robust	Bending angle (ionospheric corrected) - 60-80km robust mean	-	double	rad
bangle_upper_level_sdev_robust	Bending angle (ionospheric corrected) - 60-80km robust standard deviation	-	double	rad
bangle_resid_upper_level_mean	Bending angle (ionospheric corrected) residual - 60-80km mean	-	double	rad

Table 3.23: Attributes and variables in the /data/level_1b/high_resolution group.

Name	Description	Shape	Type	Units
bangle_resid_upper_-level_sdev	Bending angle (ionospheric corrected) residual - 60-80km standard deviation	-	double	rad
bangle_resid_upper_-level_mean_robust	Bending angle (ionospheric corrected) residual - 60-80km robust mean	-	double	rad
bangle_resid_upper_-level_sdev_robust	Bending angle (ionospheric corrected) residual - 60-80km robust standard deviation	-	double	rad
impact_top	Highest impact parameter (ionospheric corrected)	-	double	m
impact_ca_top	Highest impact parameter (L1 / C/A)	-	double	m
impact_p1_top	Highest impact parameter (L1 / P1)	-	double	m
impact_p2_top	Highest impact parameter (L2 / P2)	-	double	m
impact_bot	Lowest impact parameter (ionospheric corrected)	-	double	m
impact_ca_bot	Lowest impact parameter (L1 / C/A)	-	double	m
impact_p1_bot	Lowest impact parameter (L1 / P1)	-	double	m
impact_p2_bot	Lowest impact parameter (L2 / P2)	-	double	m
ic_tec	Total electron content estimated in ionospheric correction	-	double	m^-3
ic_bangle_diff_slope	Bending angle L1-L2 difference fit slope estimated in ionospheric correction	-	double	–
ic_bangle_diff_offset	Bending angle L1-L2 difference fit offset estimated in ionospheric correction	-	double	–
signal_cutoff_slta	Deep occultation signal cut-off SLTA (L1 / C/A)	-	double	m
impact_rate_mesosphere	Mesospheric (> 50 km) neutral impact parameter descent/ascent rate	-	double	m/s
impact_rate_troposphere	Tropospheric (< 5 km) neutral impact parameter descent/ascent rate	-	double	m/s

Table 3.23: Attributes and variables in the `/data/level_1b/high_resolution` group.

Name	Description	Shape	Type	Units
Attributes				
title	Short description of the data set or group contents	–	string	–
thinner_method	Thinning method applied during the processing	–	string	–
Variables				
impact	Impact parameter	(z)	double	m
impact_height	Impact height (wrt WGS 84 ellipsoid)	(z)	double	m
bangle	Bending angle (ionospheric corrected)	(z)	double	rad
bangle_ca	Bending angle (C/A)	(z)	double	rad
bangle_p1	Bending angle (P1)	(z)	double	rad
bangle_p2	Bending angle (P2)	(z)	double	rad
bangle_ca_p2_diff	Bending angle difference, (L1 / C/A - L2 / P2, extrapolated)	(z)	double	rad
bangle_sdev	Bending angle (ionospheric corrected) estimated standard deviation	(z)	double	rad
bangle_ca_sdev	Bending angle (C/A) estimated standard deviation	(z)	double	rad
bangle_p1_sdev	Bending angle (P1) estimated standard deviation	(z)	double	rad

Table 3.24: Attributes and variables in the `/data/level_1b/thinned` group.

Name	Description	Shape	Type	Units
`bangle_p2_sdev`	Bending angle (P2) estimated standard deviation	(z)	double	rad
`lat_tp`	Latitudes for tangent points	(z)	double	<degN>
`lon_tp`	Longitudes for tangent points	(z)	double	<degE>
`azimuth_tp`	GNSS->LEO line of sight angles (from True North) for tangent points	(z)	double	<deg>
`dtime_mean`	Mean measurement epoch (used for georeferencing only)	(z)	double	<time>
`doppler_ca_max`	Maximum instantaneous Doppler (C/A)	-	double	Hz
`doppler_p2_max`	Maximum instantaneous Doppler (P2)	-	double	Hz
`doppler_rate_ca_max`	Maximum instantaneous Doppler rate (C/A)	-	double	Hz/s
`doppler_rate_p2_max`	Maximum instantaneous Doppler rate (P2)	-	double	Hz/s
`doppler_accel_ca_max`	Maximum instantaneous Doppler acceleration (C/A)	-	double	Hz/s^2
`doppler_accel_p2_max`	Maximum instantaneous Doppler acceleration (P2)	-	double	Hz/s^2
`exdoppler_ca_max`	Maximum instantaneous excess Doppler (C/A)	-	double	Hz
`exdoppler_p2_max`	Maximum instantaneous excess Doppler (P2)	-	double	Hz
`exdoppler_rate_ca_max`	Maximum instantaneous excess Doppler rate (C/A)	-	double	Hz/s
`exdoppler_rate_p2_max`	Maximum instantaneous excess Doppler rate (P2)	-	double	Hz/s
`exdoppler_accel_ca_max`	Maximum instantaneous excess Doppler acceleration (C/A)	-	double	Hz/s^2
`exdoppler_accel_p2_max`	Maximum instantaneous excess Doppler acceleration (P2)	-	double	Hz/s^2
`bangle_upper_level_mean`	Bending angle (ionospheric corrected) - 60-80km mean	-	double	rad
`bangle_upper_level_sdev`	Bending angle (ionospheric corrected) - 60-80km standard deviation	-	double	rad
`bangle_upper_level_mean_robust`	Bending angle (ionospheric corrected) - 60-80km robust mean	-	double	rad
`bangle_upper_level_sdev_robust`	Bending angle (ionospheric corrected) - 60-80km robust standard deviation	-	double	rad
`bangle_resid_upper_level_mean`	Bending angle (ionospheric corrected) residual - 60-80km mean	-	double	rad
`bangle_resid_upper_level_sdev`	Bending angle (ionospheric corrected) residual - 60-80km standard deviation	-	double	rad
`bangle_resid_upper_level_mean_robust`	Bending angle (ionospheric corrected) residual - 60-80km robust mean	-	double	rad
`bangle_resid_upper_level_sdev_robust`	Bending angle (ionospheric corrected) residual - 60-80km robust standard deviation	-	double	rad
`impact_top`	Highest impact parameter (ionospheric corrected)	-	double	m
`impact_ca_top`	Highest impact parameter (L1 / C/A)	-	double	m
`impact_p1_top`	Highest impact parameter (L1 / P1)	-	double	m
`impact_p2_top`	Highest impact parameter (L2 / P2)	-	double	m
`impact_bot`	Lowest impact parameter (ionospheric corrected)	-	double	m
`impact_ca_bot`	Lowest impact parameter (L1 / C/A)	-	double	m
`impact_p1_bot`	Lowest impact parameter (L1 / P1)	-	double	m
`impact_p2_bot`	Lowest impact parameter (L2 / P2)	-	double	m
`ic_tec`	Total electron content estimated in ionospheric correction	-	double	m^-3
`ic_bangle_diff_slope`	Bending angle L1-L2 difference fit slope estimated in ionospheric correction	-	double	–

Table 3.24: Attributes and variables in the `/data/level_1b/thinned` group.

Name	Description	Shape	Type	Units
`ic_bangle_diff_offset`	Bending angle L1-L2 difference fit offset estimated in ionospheric correction	-	double	–
`signal_cutoff_slta`	Deep occultation signal cut-off SLTA (L1 / C/A)	-	double	m
`impact_rate_mesosphere`	Mesospheric (> 50 km) neutral impact parameter descent/ascent rate	-	double	m/s
`impact_rate_troposphere`	Tropospheric (< 5 km) neutral impact parameter descent/ascent rate	-	double	m/s

Table 3.24: Attributes and variables in the `/data/level_1b/thinned` group.

3.5 Quality Group

Name	Description	Shape	Type	Units
Attributes				
`title`	Short description of the data set or group contents	–	string	–
Variables				
`cl_data_available`	True if closed loop data is available	-	byte	–
`rs_data_available`	True if raw sampling data is available	-	byte	–
`ol_data_available`	True if open loop data is available	-	byte	–
`pr_data_available`	True if pseudorange data is available	-	byte	–
`cl_rs_data_continuous`	True if closed loop and raw sampling data form continuous time series	-	byte	–
`cl_rs_consistency_ok`	True if closed loop and raw sampling data are consistent in the overlap region	-	byte	–
`cl_snr_ca_ok`	True if upper level (SLTA > 60 km) mean C/A carrier phase SNR > 200 V/V	-	byte	–
`cl_snr_p1_ok`	True if upper level (SLTA > 60 km) mean P1 carrier phase SNR > 50 V/V	-	byte	–
`cl_snr_p2_ok`	True if upper level (SLTA > 60 km) mean P2 carrier phase SNR > 50 V/V	-	byte	–
`rs_snr_ca_ok`	True if raw sampling max C/A carrier phase SNR > 200 V/V	-	byte	–
`ol_snr_ca_ok`	True if open loop max C/A carrier phase SNR > 200 V/V	-	byte	–
`cl_external_navbits_applied`	True if external navigation bit data available and used during closed loop processing	-	byte	–
`rs_external_navbits_applied`	True if external navigation bit data available and used during raw sampling processing	-	byte	–
`ol_external_navbits_applied`	True if external navigation bit data available and used during open loop/downsampled raw sampling processing	-	byte	–
`analogue_gain_changes_ok`	True if occultation is not affected by (analogue) gain changes.	-	byte	–
`gns_orbit_ok`	True if GNSS orbit estimates are available	-	byte	–
`gns_clock_ok`	True if GNSS clock error estimates are available	-	byte	–
`rec_orbit_ok`	True if receiver orbit estimates are available	-	byte	–
`rec_clock_ok`	True if receiver clock error estimates are available	-	byte	–

Table 3.25: Attributes and variables in the `/quality` group.

Name	Description	Shape	Type	Units
rec_clock_estimated	True if receiver clock error has been estimated (False if interpolated due to missing epochs from POD estimation)	-	byte	–
fsi_done	True if full spectrum inversion retrieval has been performed	-	byte	–
go_done	True if geometrical optics retrieval has been performed	-	byte	–
thinned_done	True if thinned retrieval has been performed	-	byte	–
sl_done	True if straight line retrieval has been performed	-	byte	–
fsi_ok	True if full spectrum inversion retrieval is ok	-	byte	–
go_ok	True if geometrical optics retrieval is ok	-	byte	–
sl_ok	True if straight line retrieval is ok	-	byte	–
overall_quality_ok	True if retrieval is ok	-	byte	–
thinned_ok	True if thinned retrieval is ok	-	byte	–
high_resolution_ok	True if high resolution retrieval is ok	-	byte	–
bangle_bias_ok	True if upper level (60 - 80 km) mean bending angle is ok	-	byte	–
bangle_sdev_ok	True if upper level (60 - 80 km) bending angle residual standard deviation is ok	-	byte	–
iono_corr_ok	True if ionospheric correction is ok	-	byte	–
impact_top_ok	True if uppermost impact parameter height is ok	-	byte	–
impact_bot_ok	True if lowermost impact parameter height is ok	-	byte	–
impact_ca_top_ok	True if uppermost C/A impact parameter height is ok	-	byte	–
impact_ca_bot_ok	True if lowermost C/A impact parameter height is ok	-	byte	–
impact_p1_top_ok	True if uppermost L1/P impact parameter height is ok	-	byte	–
impact_p1_bot_ok	True if lowermost L1/P impact parameter height is ok	-	byte	–
impact_p2_top_ok	True if uppermost L2/P impact parameter height is ok	-	byte	–
impact_p2_bot_ok	True if lowermost L2/P impact parameter height is ok	-	byte	–
signal_cutoff_done	True if deep occultation signal cut-off was done.	-	byte	–

Table 3.25: Attributes and variables in the `/quality` group.

4 UNPACKING EPS WRAPPED DATA PRODUCTS

4.1 Overview

Technically, the native EPS Data Format [AD2] consists of a fixed-length ASCII header, followed by one or more data records. Each such data record contains itself a header specifying the record's type, length, and possibly some additional meta data.

EUMETSAT's RO processing suites use the native EPS Data Format as a container for multiple RO granules, similar to a simplified variant of `.tar` or `.zip` archives well known from many computer operating systems. In particular, the EPS Wrapped RO Data Format consists of the standard Main Product Header (MPHR) common to all EPS products, and one or more Measurement Data Records (MDRs). Each MDR, after its header is removed, technically is a netCDF occultation granule.

The contents of the MPHR of each EPS RO product are related to the meta data of the occultation granules contained in the product; the mapping of netCDF attributes and variables to the content of the MPHR are described in detail in appendix A.

Technically, the EPS native Data Format Specification [AD2] allows for additional types of data record, although those are not exploited in RO data products. The only exception in operationally generated EPS products are so-called "dummy MDRs" indicating that during specific periods no observations are available — e.g. during the short intervals between two successive occultations. These dummy MDRs are introduced by some EPS Ground Segment facilities for technical reasons. They contain no data and can usually be ignored. The `epsar` extraction tool described below handles dummy MDRs transparently for the user.

4.2 Unpacking EPS Products with `epsar`

A `tar`-like command line tool named `epsar`[1] is available to allow users to easily unpack the netCDF-based RO granules / occultations from an RO EPS container products. The software is written in plain `perl` which is part of nearly all Linux, Unix, OS-X variants, and also available on Windows. `epsar` has no further dependencies. Appendix B contains installation instructions.

Once installed, the contents of an EPS container product can be obtained with

```
user@linux:~# epsar -t <EPS-product>
```

For example, the command

```
user@linux:~# epsar -t GRAS_xxx_1B_M01_20160405084240Z_20160405085244Z_N_C_20160405095153Z
MDR 0: GRAS_1B_M01_20160405084240Z_20160405084414Z_N_C_20160405095153Z_G24_NN.nc
MDR 1: GRAS_1B_M01_20160405084326Z_20160405084616Z_N_C_20160405095153Z_G05_NN.nc
MDR 2: GRAS_1B_M01_20160405084443Z_20160405084717Z_N_C_20160405095153Z_G09_NN.nc
MDR 3: GRAS_1B_M01_20160405084831Z_20160405085017Z_N_C_20160405095153Z_G12_NN.nc
MDR 4: GRAS_1B_M01_20160405084842Z_20160405085244Z_N_C_20160405095153Z_G01_NN.nc
MDR 5: GRAS_1B_M01_20160405084954Z_20160405085141Z_N_C_20160405095153Z_G30_NN.nc
```

[1] The most recent version of the `epsar` software can be downloaded from https://github.com/leonid-butenko/epsar.

indicats that the EPS file `GRAS_xxx_1B_M01_20160405084240Z...` contains six netCDF granules/occultations of nominal quality. Unpacking these occultation granules can be achieved with

```
user@linux:~# epsar -x GRAS_xxx_1B_M01_20160405084240Z_20160405085244Z_N_C_20160405095153Z
```

or even

```
user@linux:~# epsar -x GRAS_xxx_1B_M01_20160405084240Z_20160405085244Z_N_C_20160405095153Z
```

where the latter variant will list the names of the occultation granules while extracting them from the archive. We note that `epsar` will also create a pure text version of the MPHR for reference; most users will not need this file further and can safely delete it. For example, after running one of the two previous commands, the current directory will hold the following additional files (parts of the file names were replaced with "..." for better readability):

```
user@linux:~# ls -l
total 1336416
-rw-rw-r-- 1 user met 11103858 Apr 13 16:52 GRAS_1B_M01_20160405084240Z_..._G24_NN.nc
-rw-rw-r-- 1 user met     3307 Apr 13 16:52 GRAS_1B_M01_20160405084240Z_....mphr
-rw-rw-r-- 1 user met 14389225 Apr 13 16:52 GRAS_1B_M01_20160405084326Z_..._G05_NN.nc
-rw-rw-r-- 1 user met 12327206 Apr 13 16:52 GRAS_1B_M01_20160405084443Z_..._G09_NN.nc
-rw-rw-r-- 1 user met 10977523 Apr 13 16:52 GRAS_1B_M01_20160405084831Z_..._G12_NN.nc
-rw-rw-r-- 1 user met 15562078 Apr 13 16:52 GRAS_1B_M01_20160405084842Z_..._G01_NN.nc
-rw-rw-r-- 1 user met  5035872 Apr 13 16:52 GRAS_1B_M01_20160405084954Z_..._G30_NN.nc
```

Note the file with the extension `.mphr` which contains the MPHR header as a plain text file.

The files with an extension `.nc` generated by the above command(s) are ordinary netCDF data files following the RO level 1 data format as described in chapter 3. They can be further read and processed with the usual netCDF tools and APIs available for various programming languages.

A EPS MPHR AND NETCDF GRANULE ATTRIBUTES

Meta data in the Main Product Header Record (MPHR) of the EPS data containers are (mostly) based on attributes in the `/status/satellite` or `/status/processing` groups of the netCDF-based RO data granules contained in the respective EPS product. Table A.1 lists the mapping between MPHR fields and global or group attributes used in the generation of EPS wrapped data products from Yaros.

The following specific considerations and limitations apply:

- Level 0 product(s) covering the sensing start and end time of the EPS container product are listed as parent product(s).
- Some of the MPHR information required for, e.g., instrument characterisation (ID and model) or the processor major and minor version numbers are combined into fewer netCDF attributes. The respective information is extracted from the relevant attributes before being placed in the respective MPHR fields.
- In EPS, there is no product type defined for RO soundings. Thus, the `PRODUCT_TYPE` field in EPS MPHRs is set to `xxx`, although the corresponding attribute in RO granules might carry useful information.
- Theoretical start and end sensing times make have no meaning for RO soundings and are set to the actual start and end sensing times.
- Processing start and end times are based on the earliest and latest creation time of the RO granules being combined into a single EPS container.
- Product duration is calculated from the earliest start and the latest end sensing time of all granules combined into the EPS container product.
- An MDR containing an RO netCDF granule is degraded if the `/quality/overall_quality_ok` attribute is set to `False` (or 0). In addition, the granule names contains the degraded flag (see sec. 2 for naming conventions).
- All state vector variables are copied from the applicable level 0 data files; they are unrelated to the Precise Orbit Determination results obtained in the RO data processing.
- The number of, e.g., MPHRs is set based on the content of the RO EPS product.
- The number of data record types not exploited in RO EPS products (e.g. SPHRs, IPRs, GEADRs, GIADRs, VIADRs, and VIADRs) are always zero; the corresponding fields nevertheless have to be present in the MPHR in order to be compliant with the EPS native product format specification.

MPHR Field	NetCDF Attribute
PRODUCT_NAME	*(dynamic)*[a]
PARENT_PRODUCT_NAME_1	*(dynamic)*[a]
PARENT_PRODUCT_NAME_2	*(dynamic)*[a]
PARENT_PRODUCT_NAME_3	*(dynamic)*[a]
PARENT_PRODUCT_NAME_4	*(dynamic)*[a]
INSTRUMENT_ID	/instrument[b]
INSTRUMENT_MODEL	/instrument[b]
PRODUCT_TYPE	/type[c]
PROCESSING_LEVEL	/product_level
SPACECRAFT_ID	/spacecraft
SENSING_START	/sensing_start
SENSING_END	/sensing_end
SENSING_START_THEORETICAL	/sensing_start[c]
SENSING_END_THEORETICAL	/sensing_end[c]
PROCESSING_CENTRE	/status/processing/processing_centre
PROCESSOR_MAJOR_VERSION	/status/processing/processor_version[b]
PROCESSOR_MINOR_VERSION	/status/processing/processor_version[b]
PROCESSING_TIME_START	*(dynamic)*[a,c]
PROCESSING_TIME_END	*(dynamic)*[a,c]
PROCESSNG_MODE	/status/processing/processing_mode
DISPOSITION_MODE	/disposition_mode
RECEIVING_GROUND_STATION	/receiving_ground_station
RECEIVE_TIME_START	/receive_start
RECEIVE_TIME_END	/receive_end
ORBIT_START	/orbit_start
ORBIT_END	/orbit_end
ACTUAL_PRODUCT_SIZE	*(dynamic)*[a]
STATE_VECTOR_TIME	/status/satellite/epoch_time_utc
SEMI_MAJOR_AXIS	/status/satellite/semi_major_axis
ECCENTRICITY	/status/satellite/eccentricity
INCLINATION	/status/satellite/inclination
PERIGEE_ARGUMENT	/status/satellite/perigee_argument
RIGHT_ASCENSION	/status_satellite/right_ascension
MEAN_ANOMALY	/status/satellite/mean_anomaly
X_POSITION	/status/satellite/x_position
Y_POSITION	/status/satellite/y_position
Z_POSITION	/status/satellite/z_position
X_VELOCITY	/status/satellite/x_velocity
Y_VELOCITY	/status/satellite/y_velocity
Z_VELOCITY	/status/satellite/z_velocity
EARTH_SUN_DISTANCE_RATIO	/status/satellite/earth_sun_distance_ratio
LOCATION_TOLERANCE_RADIAL	/status/satellite/location_tolerance_radial
LOCATION_TOLERANCE_CROSSTRACK	/status/satellite/location_tolerance_crosstrack
LOCATION_TOLERANCE_ALONGTRACK	/status/satellite/location_tolerance_alongtrack
YAW_ERROR	/status/satellite/yaw_error
ROLL_ERROR	/status/satellite/roll_error
PITCH_ERROR	/status/satellite/pitch_error
SUBSAT_LATITUDE_START	/status/satellite/subsat_latitude_start
SUBSAT_LONGITUDE_START	/status/satellite/subsat_longitude_start
SUBSAT_LATITUDE_END	/status/satellite/subsat_latitude_end
SUBSAT_LONGITUDE_END	/status/satellite/subsat_longitude_end
LEAP_SECOND	/status/satellite/leap_second
LEAP_SECOND_UTC	/status/satellite/leap_second_utc
TOTAL_RECORDS	*(dynamic)*[a]

[a] Determined when packing multiple granules into a single EPS native product.
[b] Implemented by parsing the respective attribute and extracting the required information.
[c] Workaround; see text for details.

Table A.1: Mapping between EPS MPHR field names and RO Level 1 netCDF granule attributes.

MPHR Field	NetCDF Attribute
TOTAL_MPHR	*(dynamic)*[a]
TOTAL_SPHR	*(dynamic)*[a]
TOTAL_IPR	*(dynamic)*[a]
TOTAL_GEADR	*(dynamic)*[a]
TOTAL_GIADR	*(dynamic)*[a]
TOTAL_VEADR	*(dynamic)*[a]
TOTAL_VIADR	*(dynamic)*[a]
TOTAL_MDR	*(dynamic)*[a]
COUNT_DEGRADED_INST_MDR	*(dynamic)*[a]
COUNT_DEGRADED_PROC_MDR	*(dynamic)*[a]
COUNT_DEGRADED_INST_MDR_BLOCKS	*(dynamic)*[a]
COUNT_DEGRADED_PROC_MDR_BLOCKS	*(dynamic)*[a]
DURATION_OF_PRODUCT	*(dynamic)*[a]
MILLISECONDS_OF_DATA_PRESENT	*(dynamic)*[a]
MILLISECONDS_OF_DATA_MISSING	*(dynamic)*[a]
SUBSETTED_PRODUCT	/subsetting

[a] Determined when packing multiple granules into a single EPS native product.
[b] Implemented by parsing the respective attribute and extracting the required information.
[c] Workaround; see text for details.

Table A.1: Mapping between EPS MPHR field names and RO Level 1 netCDF granule attributes.

B INSTALLING EPSAR

The `epsar` software can be downloaded as a `.zip` archive from

```
https://github.com/leonid-butenko/epsar
```

by clicking on the `Download ZIP` button in the upper right of the GitHub project page.

B.1 Simple Installation

After unpacking the archive file (and having made sure that the system's `perl` software is properly installed), change into the directory of the unpacked `epsar` software and run the following two commands:

```
user@linux:~# perl Makefile.PL
user@linux:~# make install
```

The first command will prepare a `Makefile` which is then used for installing the software by the second command. On Linux, Unix and OS-X platforms, the default installation path is `/usr/local/bin`, which is where a single perl script will be copied to. The installation directory must be in the user's `PATH` environment variable in order for `epsar` to function properly.

B.2 Advanced Installation

If a different installation path is desired, the following command

```
user@linux:~# perl Makefile.PL [INSTALL_BASE=<path-to-install>]
user@linux:~# make install
```

can be used instead, where `<path-to-install>` points to the exact directory of where the script shall be installed. Yet another otion is to use

```
user@linux:~# perl Makefile.PL [PREFIX=<prefix>]
user@linux:~# make install
```

where `<prefix>` points to an installation root directory; the executable script will then be installed in the directory `<prefix>/bin`.

As before, the installation directory must be part of the user's `PATH` environment variable.

C WMO BUFR

This Appendix describes the mapping between variables in the EPS-SG RO Level 1 data format and WMO's Binary Universal Form for the Representation of meteorological data (BUFR) format for RO measurements. The full description of the RO BUFR format is outside the scope of this document; it is assumed that the reader is familiar with the details of the RO BUFR format as defined in [AD3]. The recommendations of IROWG (see [RD1]) were taken into account, assuming they will be implemented in the foreseeable future.

C.1 BUFR Sections 1 (Identification) and 3 (Data Description)

BUFR sections 1 is filled with meta data as described in the BUFR specification ([AD3]) using Edition 4 messages. The time information "most typical for [the] BUFR message content" contained in octet numbers 16-17 (year) and 18–22 (month, day, hour, minute and second) are derived from the georeferencing time, i.e. from the variables `utc_georef_absdate` and `utc_georef_absdate` in the `/data/occultation` group.

Section 3 is to be set dynamically from the number of profiles (usually 1 in a single BUFR message) and the message size. Note that there is no Section 2 (Optional Data) in RO BUFR products.

C.2 BUFR Section 4 (Data Template)

Quality information is stored in a single 16-bit data field (octet number 13), where the detailed meaning of each flag is defined in Table 8 of [AD3]. The mapping between BUFR and RO Level 1 product quality flags is described in Tab. C.1 below.

Note that values stored in BUFR products will be matching BUFR conventions, in some cases requiring a translation from the logical values used in the netCDF granules as described in section 3.1. For example, in case on Bit 1, the global attribute `environment` may exhibit values of "Operational", "Validation", "Development", "Offline","Integration & Verification", and "Support"

Bit	Description	Variable
1	Nominal / non-nominal quality	`/quality/overall_quality`
2	NRT / Offline product	`/environment`
3	Descending / ascending occultation	`/data/occultation/occultation_type`
4	Excess phase processing (non-) nominal	`/quality/cl_snr_[ca|p1|p2]_ok`
5	Bending angle processing (non-) nominal	`/quality/thinned_ok`
6	Refractivity processing (non-) nominal	*Unused*
7	Meteorological processing (non-) nominal	*Unused*
8	Closed / open loop data only / included	`/quality/ol_data_available`
9	(No) Surface reflections detected	*Unused*
10	L2P / L2C GPS signals used	*TBD*
11-13	Reserved	*Unused*
14	Background profile (non-) nominal	*Unused*
15	Retrieved / background profile	*Unused*

Table C.1: Mapping between BUFR Section 4 quality flags for RO and EPS-SG RO L1 data format quality flags.

(see section 3.2). Values of "Operational" and "Validation" will be mapped to "NRT product", while the remaining ones will be mapped to "Offline product". On the other hand, the excess phase processing flag is calculated as the logical `and` of the `quality_snr_ca_ok`, `quality_snr_p1_ok`, and `quality_snr_p2_ok` flags in the netCDF granule.

Tab. C.2 links data fields as used in BUFR Section 4 entries (see Table 5 of [AD3]) to the corresponding variables in the netCDF granule data format. We finally note that BUFR products generated by EUMETSAT do not contain any "Step 2a", "Level2a" or "Level2b" data.

Octet	Variable(s)	Remarks
Nominal Reporting Time		
7-12	/data/occultation/utc_georef_absdate /data/occultation/utc_georef_abstime	Assumes [RD1] is implemented
RO Summary Quality Information		
13	*various*	see Tab. C.1
14	/quality/overall_quality_ok	100% if True, 0% otherwise
LEO & GNSS POD – Location of Platform		
15-17	/data/occultation/position_rec_fixed	Antenna phase centre positions...
18-20	/data/occultation/velocity_rec	...and velocities at georeferencing time
21	/data/occultation/prn	First letter, e.g. G01 → 401 (for GPS)
22	/data/occultation/prn	Integer part, e.g. G01 → 1 (for PRN 01)
23-25	/data/occultation/position_gns_fixed	Positions...
26-28	/data/occultation/velocity_gns	...and velocities at georeferencing time
Local Earth Parameters		
29	*always zero*	Assumes [RD1] is implemented
30	/data/occultation/latitude	Valid at georeferencing time
31	/data/occultation/longitude	*ditto*
32-34	/data/occultation/r_curve_centre_fixed	*ditto*
35	/data/occultation/r_curve	*ditto*
36	/data/occultation/azimuth_north	*ditto*
37	/data/occultation/undulation	*ditto*
RO Step 1b Data		
38	len(/data/level_1b/thinned/impact)	Fixed number of levels; same for all products
39	/data/level_1b/thinned/lat_tp	
40	/data/level_1b/thinned/lon_tp	
41	/data/level_1b/thinned/azimuth_tp	
42	3	for ionospheric corrected, L1, and L2 data
43	0 or nominal carrier frequencies	0 for ionospheric corrected bending angles
44	/data/level_1b/thinned/impact	
45	/data/level_1b/thinned/bangle /data/level_1b/thinned/bangle_ca /data/level_1b/thinned/bangle_p2	
46-48	*Currently unused*	

Table C.2: Mapping between BUFR Section 4 data fields and EPS-SG RO Level 1 data format variables.