EPS-SG RO Level 1B Product Format Specification

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Document Change Record

Version	Date of Version	Document Change Request (DCR) Number	Description of Changes
v1A	15.12.2014	—	Initial version
v1B	27.02.2015	—	Internal pre-PRD Review
v1C	15.09.2015	—	Sec. 1.3 and 1.4: • Updated Applicable and Reference Document lists. Sec. 2.3 and 3.2: • Updated product file naming conventions. Sec. 3.5 – 3.8: • Updated data and attribute tables to be consistent with the most recent version of the RO Reference Processor. • Also updated the .xml/.ncml representation of the data format. Sec. 3.7.2 and 3.7.3: • Clarified the calculation of precise velocity components from POD positions. App. B (RO Level 1 Product Format and BUFR) was newly added.
v1D	15.12.2015	DCR-116	GS PDAP ITT
			Internal pre-GS PDAP ITT Review: • Title changed. • Removed old Sec. 2 "Overview of the Instrument: RO-SG". Sec.1.3 and 1.4: • Updated lists of documents. Sec.1: • Removed old RO-O-3 (Glonass, COMPASS/Beidou not in the baseline). • Closed new RO-O-2 (Content and format of RSN products) Sec. 2.2, Sec. 2.3, Sec. 3.2: • Updated Product-ID. Sec. 3.2: • Updated product description and size. Sec. 5: • Changed product format version control number. Annex A: • Removed sizes estimations related data/products not included in the EPS-SG RO baseline. • Updated the estimated Level1B product size/orbit to take into account of some margin.

Version	Date of Version	Document Change Request (DCR) Number	Description of Changes
			Other Changes: • New section 3.7.2.4 on diagnostic POD parameters. • Updated .xml/.ncml representation of the data format contents.
v2	10.10.2016	—	GS PDAP KO
			Sec. 2: • Cleanup, fixing of typos, layout improvements.
			Sec. 3: • Filled remaining subsections (level 1b, quality flags) with content. • For each data group, combined separate attribute and variable tables into a single one. Annex A: • Cleanup, fixing of typos, layout improvements. Other changes: • Moved open issues etc. to a dedicated appendix. • Removed the .xml/.ncml representation of the RO level 1 data format and replaced it with an attached .xml file. Sec. 3.4: • Clarified the use of dimensions for scalar scalar variables. Sec. 3.6: • Clarified contents of the `instrument_mode` attribute. Sec. 5: • Clarified contents of the `/data/quality` group, in particular with respect to data gaps.
v2A	13.12.2016	DCR-503	GS PDAP KO – Internal review
			Sec. 5: • Reference version of PFS and GPFS corrected. Annex with open issues etc.: • Removed RO-O-5. Other changes: • Various editorial changes; • Updated the attached `.xml` description of the data format.

Version	**Date of Version**	**Document Change Request (DCR) Number**	**Description of Changes**
v3	19.09.2017		Internal update
			Sec. 3.6: • Updated descriptions of the `source` attribute (in the `/status/processing` data group) and the `overall_-quality_flag` variable in the `/quality` data group. Sec. 3.8: • Various editorial updates. Annex B.3: • Added an estimate of the BUFR file size. Annex with open issues: • Closure dates of open issues/assumptions moved to RO-L1B-PFS v4, because missing specifications from industry. • Added an open point (RO-O-4) on the definition of thinned levels and on the vertical range
v3A	06.03.2018	DCR-827	Internal update
			Tab. 3.6: • Removed maneouvre related variables (in the `/status/satellite` data group). • Updated description of the `processor_name` attribute (in the `/status/processing` data group). Tab. 3.29: • Updated description of `overall_quality_flag`. Sec. 5: • Updated references to PFS and GPFS versions. Tab. 3.8: Annex B.3: • Estimate of BUFR product size. Annex C • Removed superfluous contents of the attached `.xml` file.
v3B	27.09.2018		Internal update

Version	Date of Version	Document Change Request (DCR) Number	Description of Changes
			Section 1 • Signature table updated • Applicable and Reference document tables updated Fig 3.1: • Overall level 1b data format structure updated Section 3.6 and 3.7: • Updates to variable names. Section 3.7.5: • Rephrased the overall explanation of the contents and structure of /data/level_1a. • Added a table (currently Tab. 3.20) explaining the variable postfix names based on GNSS code / Rinex 3, with a few adaptations in the corresponding text. Section 3.7.6.5: • Updated the sentence, making reference to the provision of high resolution profiles on a vertical grid of impact parameters (altitude or height) of fixed size. Annex containing the product size • The annex has been removed from this version. It will be restored when a consolidated example of RO-L1B product will be available. Annex containing the xml file • The annex has been removed from this version. It will be restored when a consolidated example of RO-L1B product will be available. Annex with open issues: • Removed RO-O-1 and RO-O-3, and added RO-O-5 and RO-O-6.
v3C	12.04.2019	DCR-1188	

Version	*Date of Version*	*Document Change Request (DCR) Number*	*Description of Changes*
			Updates for • Signature table; • Product format version control (section 5). Clarifications on data types used for: • String attributes and variables (new section 3.4.3); • Simple times (new section 3.4.5); • Boolean variables and flags (new section 3.4.7). Other: • Removed discussion on GRAS-related product sizes (appendix A). • All content is now fully based on the EPS-SG RO level PGS, and does not refer to GRAS any more (affects all sections). • Added a description for reprocessed level 1 data products. • Closed all open issues.
v3D	15.11.2019	DCR-1480	
			Updates for • Signature table; • Product format version control (section 5); • Size of the products (annex A). The product size estimate is not anymore based on EPS-GRAS related products. It is now defined considering the test data generated in accordance with the specifications provided in the RO-L1B-PGS v3D. • Removed reference to the use of a GRAS reprocessed file for generating the xml description (annex C). Changes to some of the variables (description, shape names, types) due to the finalization of the in-house prototype. The content of the L1b product is now aligned with the L1b files included in the test data set v1.0.
v4A	11.10.2021	DCR-2118	
			Changes agreed with the RO PS V4 PSCM (see PSCM-16 MoM, PFS section). • Sec. 3.7.5.7: Removed reference to level_1a subgroups belonging to the GRAS product (PSCM-16, point d.1.3).

Version	Date of Version	Document Change Request (DCR) Number	Description of Changes
			• Sec. 3.7.5.8, Tab. 3.22 and 3.23: Added data_component_available in the `/data/level_1a/` subgroups (PSCM-16, point b.1, entire algorithm was descoped in V3D because no data from the RO Enginnering model have been made available). • Sec. 3.7.5.8, Tab. 3.22 and 3.23: Replaced `navbits_esternal` variable with `navbits` in the `/data/level_1a/` subgroups (PSCM-16, point d.1.1). • Sec. 3.8, Tab. 3.29: Added quality control parameters for the ionospheric retrieval (PSCM-16, point a.1 and PSCM-16 PGS section, point a.2. See also https://jira.eumetsat.int/browse/IFCT-4516). • Tab. 3.20: Corrected typos in the carrier frequencies definition (PSCM-16, ADS section, point d.1). **Further changes approved with PSCM-34.** • Sec. 3.4.4, Tab. 3.3: Added a new abbreviation for the units associated to "seconds since 00:00:00", to be different from the one associated to "seconds since 2000... • Sec. 3.7.1 and B.2, Tab. 3.9 and B.2: Added `velocity_rec_fixed_bfr` and `velocity_gns_fixed_bfr` for WMO BUFR data. • Sec. 3.7.2.1 and 3.7.3.1, Tab. 3.10 and 3.15: Added `satellite_id_nssdc` attribute. • Sec. 3.7.7.3, Tab. 3.27: Splitted the variable `frequencies` that was including the two GNSS carrier frequencies into two single variables `frequency_l1` and `frequency_l5`. • Tab. 3.8: Removed generating_facility attribute from the attribute list of the status/processing group, because not requested by EPS_SG (left over from past releases). **Changes introduced after internal review.** • JIRA IFCT-5921. Document Change Record: added references to JIRA issues and Anomaly Reports to the changes approved by current PSCMs. • updated version from v4 to v4.1 and delivery date. • Sec 2.3 annd Sec 3.2: updated product filename accordingly to new specs, see JIRA IFCT-5938. • Sect. B.1: Added a sentence addressing the packaging needed for sending BUFR products through GTS.

Version	***Date of Version***	***Document Change Request (DCR) Number***	***Description of Changes***
			Changes introduced for the processing of Beidou occultations. • Sec. 3.2 and Annex A: Product sizes have been updated to take into account the processing of Beidou occultations. • Sec. 3.7.5.5, Tab. 3.20: Added Beidou codes and related postfixs. • Sec. 3.7.5.8: Added `level_1a` subgroups names for Beidou signals. • Added open points related the implementation of the Beidou occultation processing.
v4B	11.04.2022	DCR-2315	
			Changes agreed with PSCM-37. • Sec. 3.7.3.1: Added the `satellite_prn` format description (see item #1, PFS section, PSCM MoM). • Annex C: updated xml description to be in line with the products included in the TDS v2.1. • Updated EPS-SG Programme Scientist in the document signature table.

Table of Contents

1 INTRODUCTION

1.1 Purpose and Scope

This document is the Format Specification for EUMETSAT Polar System - Second Generation (EPS-SG) Radio Occultation (RO) Level 1 (L1) products generated centrally by the EPS-SG Ground Segment at the EUMETSAT Headquarters. It specifies the detailed format of the RO Level 1products in agreement with the format and naming conventions set out in the Generic Product Format Specification (GPFS) applicable to all EPS-SG products. The instrument specific Product Format Specification (PFS) contains all the instrument specific netCDF details, including specific metadata. The common groups and metadata are defined in the GPFS.

This document addresses the native format of the products generated in the EPS-SG Ground Segment, which is netCDF-4 as specified in GPFS. Other user formats will be specified elsewhere.

1.2 Relation to other documents

The EPS-SG Radio Occultation Level 1B Product Format Specification (RO-L1B-PFS) is a System document in the EPS-SG System Specification Tree. It is called up in System Requirements Document (SRD), Overall Ground Segment Requirements Document (OGSRD), Radio Occultation Level 1B Product Generation Specification (RO-L1B-PGS), and EPS-SG System and Ground Segment documents including Interface Control Documents (ICDs)/Interface Requirement Documents (IRDs) wishing to convey information about the RO L1 products format and content.

The Level 0 products are described in [L0-PFS]. The RO Level 1 Auxiliary Data files are described in [RO-L1B-ADS].

This document is derived from and compliant to [GPFS] for generic product format and naming conventions applicable to all EPS-SG products.

1.3 Applicable Documents

ID	Title	Reference Number
[GPFS]	Generic Product Format Specification, v3B,	EUM/LEO-EPSSG/SPE/13/702108
[MCSD]	EPS-SG Mission Conventions and Standards Document	EUM/LEO-EPSSG/STD/14/745221
[DEV]	Development Logic for EPS-SG L0-L1-L2 Processing Specifications	EUM/LEO-EPSSG/TEN/14/763159
[RO-BUFR]	ROM SAF, CDOP-2, WMO FM94 (BUFR) Specification For Radio Occultation Data, Issue 2.4, 1. December 2016	SAF/ROM/METO/FMT/BUFR/001

1.4 Reference Documents

ID	Title	Reference Number
[OGSRD]	EPS-SG Overall Ground Segment Requirements Document	EUM/LEO-EPSSG/REQ/13/725156
[RO-IDTD]	Instrument Design and Technical Description	MOS-DD-RSE-RO-0209, version 4, 29/08/2014
[RO-IRS]	RO Instrument Requirements Specification For the Radio Occultation (RO) Instrument	MOS-RS-ESA-RO-0431, version 1.1, 18/07/2014
[L0-PFS]	EPS-SG L0 Product Format Specification	EUM/LEO-EPSSG/SPE/13/703928
[RO-L1B-PGS]	EPS-SG RO L1B Product Generation Specification	EUM/LEO-EPSSG/SPE/14/776622
[RO-L1B-ADS]	EPS-SG RO L1B Auxiliary Data Specification	EUM/LEO-EPSSG/SPE/14/776624
[RO-L1B-ATBD]	EPS-SG RO Level 1B Algorithm Theoretical Baseline Document	EUM/LEO-EPSSG/SPE/14/743399
[RO-ICCDB]	Instrument Characterisation Database Specification	MOS-RS-RSE-RO-0683
[IROWG-BUFR]	Recommendations of the IROWG-4 action group on the homogeneization and evolution of the BUFR file specification for GNSS Radio Occultation http://irowg.org/workshops/irowg-4/bufr-discussions-at-and-following-irowg-4/IROWG4-BUFR_action_group_20150603_summary_final.doc	IROWG/MM/2015
[RINEX3]	RINEX - The Receiver Independent Exchange Format, version 3.03	`ftp://igs.org/pub/data/format/rinex303.pdf`
[SP3-d]	The Extended Standard Product 3 Orbit Format (SP3-d)	`ftp://igscb.jpl.nasa.gov/igscb/data/format/sp3d.pdf`

1.5 Acronyms

The definition of conventions, terms and abbreviations applicable to the EPS-SG Programme can be found in [MCSD]. The following table lists abbreviations specific to this document.

BUFR	Binary Universal Form for the Representation of meteorological data
CF	Climate and Forecast
EOP	Earth Orientation Parameters
EPS-SG	EUMETSAT Polar System - Second Generation
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GNSS	Global Navigation Satellite System
GPFS	Generic Product Format Specification
GPS	Global Positioning System
ICDs	Interface Control Documents
IDB	Instrument Data Base
IRDs	Interface Requirement Documents
L0-PFS	Level 0 Product Format Specification
L1	Level 1
LEO	Low Earth Orbit
MCSD	Mission Conventions and Standards Document
NCO	Numerically Controlled Oscillator
OGSRD	Overall Ground Segment Requirements Document
PFS	Product Format Specification
PLL	Phase-Locked-Loop
POD	Precise Orbit Determination

RO	Radio Occultation
RO-L1B-PGF	Radio Occultation Level 1B Product Generation Function
RO-L1B-ADS	Radio Occultation Level 1B Auxiliary Data Specification
RO-L1B-PGS	Radio Occultation Level 1B Product Generation Specification
RO-L1B-PFS	Radio Occultation Level 1B Product Format Specification
SNR	Signal-to-Noise Ratio
SRD	System Requirements Document
UTC	Coordinated Universal Time

1.6 Conventions and Terminology

Generic conventions and terminology used in this document for EPS-SG products are those described in the [GPFS]. Generic terms and definitions applicable to the EPS-SG Programme can be found in [MCSD].

1.7 Document Structure

Section	Title	Content
1	Introduction	The Scope and Purpose of the PFS document is described in this section, along with Open Issues, Assumptions, Applicable and Reference documents.
2	EPS-SG RO Level 1 Products Overview	A high-level overview on the RO Level 1 Product structure is presented in this section. The Product Tree and the Product Naming convention are also specified here.
3	EPS-SG RO Level 1 Product Detailed Format	The format of each RO Level 1 Product (detailed description of the NetCDF Data Files of each product) is described in this section.
5	Product Format Version Control	This section is aimed to describe the product format version control number for each product described in this document.
B	RO level 1 Format and BUFR	Mapping of PFS netCDF variables to variables provided in the WMO RO BUFR format.

2 EPS-SG RO LEVEL 1 PRODUCT OVERVIEW

2.1 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, and can extend to more than 10 minutes if ionospheric observations are also made. During the occultation, 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 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.

Individual bending angle profiles as described above provide a natural packing unit or "granule" for RO data. Thus, RO level 1b data produced by EUMETSAT is therefore indeed organised in individual occultation granules; each native output of the RO Level 1 processor is a netCDF v4 binary data file containing the data of a single occultation. For convenience, RO level 1b data products also contain all level 1a data, so that there are no seperate level 1a data products for the RO instrument.

Note that a thinned version of the main level 1b content (bending angle profiles as function of impact parameter) are provided in an additional BUFR formatted product, which will be generated by a separate function outside the Radio Occultation Level 1B Product Generation Function (RO-L1B-PGF). Please refer to Appendix B for more information on the exact mapping between BUFR and netCDF variables.

2.2 Product List

Product ID	Product Description	Usage
RO_-1B-BND	EPS-SG RO Level 1B Product	Disseminated to end users

2.3 Naming Convention

The naming convention of EPS-SG products complies with the naming convention specified in [GPFS] for all EPS-SG Ground Segment products generated in native format. An example RO level 1 product name is:

```
W_XX-EUMETSAT-Darmstadt,SAT,SGA1-RO_-1B-BND_C_EUMT_20220101121212_G_O_
↪  20220101103000_20220101104000_C_N_G20
```

referring to a global bending angle L1b (`1B-BND`) product containing data from a single occultation. According to the file name, this product was generated in the context of the EPS-SG Global mission, for the RO (`RO_`) instrument embarked on the Metop-SG/A1 satellite (`SGA1`). The `RO_-1B-BND` string signifies the Product ID and is more generally written for RO L1B products as `RO_-1B-BND`. The global mission type is signified by `G`, regional products use a `R`. The GNSS satellite used for the occultation is encoded in the last 3 digits, in this case it is GPS satellite with PRN 20 (`G20`). Other GNSS systems would be marked with the letter `E` for Galileo, `R` for GLONASS, and `C` for COMPASS.

The product was created on the 01 January 2022 at 12:12:12 UTC, with a sensing start date of 01 January 2022 at 10:30:00 UTC, and a sensing end date of 01 January 2022 at 10:40:00 UTC. It stems from the operational ground segment (`O`) environment, and was generated during commissioning (`C`) in NRT (`N`) processing mode.

3 EPS-SG RO LEVEL 1 PRODUCT DETAILED FORMAT

3.1 Overall Structure of EPS-SG Products

All EPS-SG product types generated by the EPS-SG Ground Segment are NetCDF-4 files complying with the generic structure and data model set out in the [GPFS]. Their high-level structure consists of a root group holding global attributes defined in the [GPFS] and the following netCDF sub-groups: `/status`, `/data` and `/quality`.

In the following sections, the composition of the RO L1B product is specified.

3.2 Product Summary Sheet

The filename entry in the table below is for illustrative purpose only, it assumes a certain occultation, as outlined in Section 2.3. For further information on the product ID entry, please also refer to that section.

Filename	W_XX-EUMETSAT-Darmstadt,SAT,SGA1-RO_-1B-BND_ C_EUMT_20220101121212_G_O_20220101103000_ 20220101104000_C_N_G20
Product ID	RO_-1B-BND
Product Description	Bending angle profiles of the atmosphere, up to 500 km
Format	netCDF-4
Size (per orbit)	3.2 GB (GPS+Gal+Bei), see Annex A
Duration	Duration of an occultation (up to several minutes, see [RO-L1B-PGS])

3.3 Overall Group Structure

EPS-SG RO L1 products generated by the EPS-SG Ground Segment are NetCDF-4 files complying with the generic structure and data model set out in the [GPFS]. Their high-level structure is presented in Fig. 3.1 and consists of a `root` group, holding global attributes defined in the [GPFS] and the following sub-groups: `status`, `data` and `quality`. We note that some of the level 1a data groups (denoted by grey name entries in Fig. 3.1) are optional in the sense that they may not by default be included in operational products

3.4 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 organising 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.

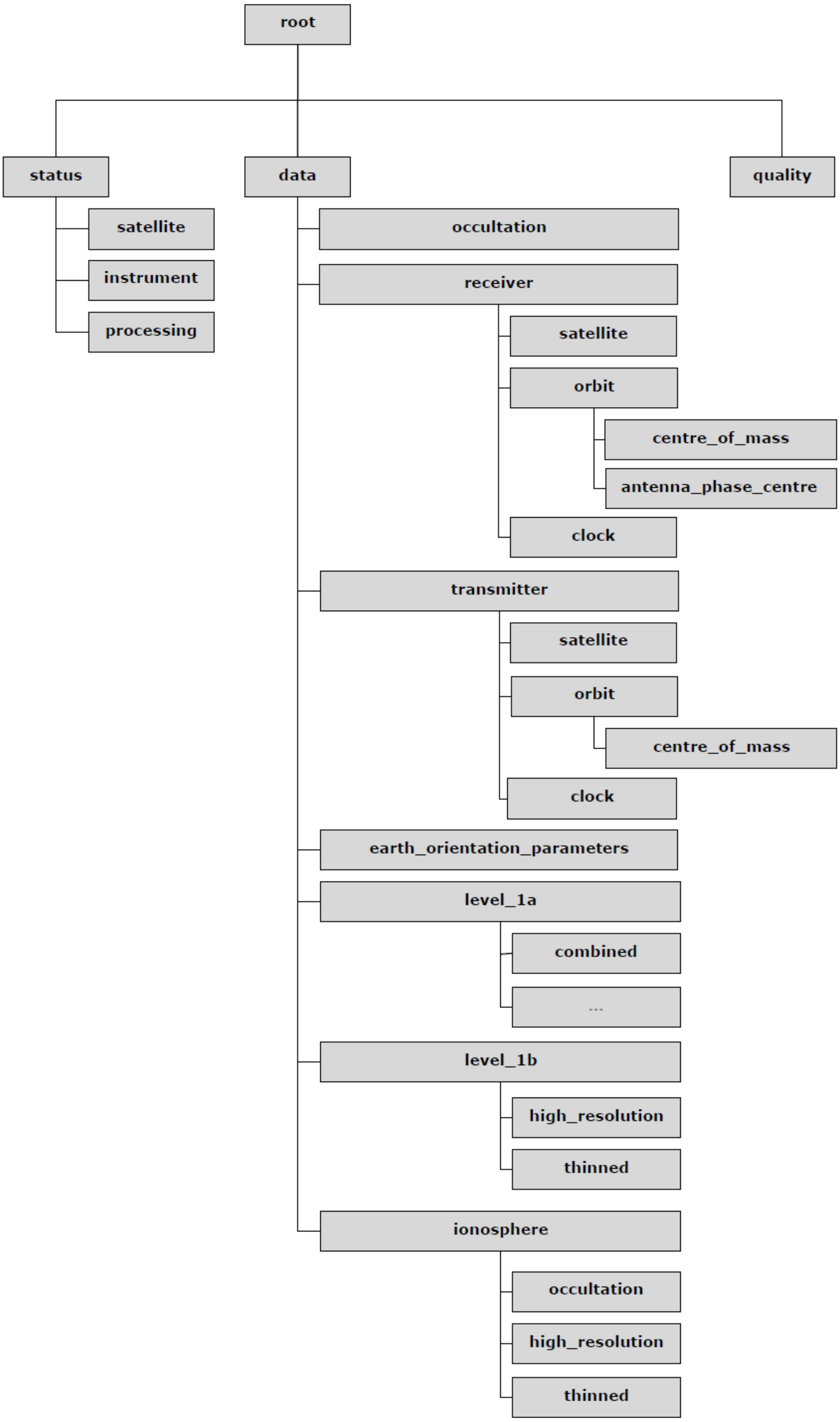

Fig. 3.1: Overall Structure of EPS-SG RO L1 Products.

Name	Description	Length
-	Scalar variables	1
`xyz`	Spatial coordinates (x, y, z)	3
`t`	Time coordinates	variable†
`z`	Height or impact parameter coordinates	variable†
`files`	List of files	variable†
`signals`	List of tracked GNSS signals	2
`codes`	List of tracked GNSS signal codes	variable††

† between data groups
†† between different RO-L1B products

Tab. 3.2: Standard dimension names and their meaning.

The structure of RO level 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 3.4.2, 3.4.4 and 3.4.6, respectively. In some cases, this and other adaptations of the CF conventions are required due to EUMETSAT ground segment needs, and lead to deviations from the original CF text which are described in section 3.4.8.

3.4.1 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) of the same occultation is typically different, sometimes exhibiting overlapping time periods. Therefore, the respective variables contain different numbers of data 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 3.2. 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 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 of these dimension 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 '-', i.e. by no shape, and consist of single values.

3.4.2 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.

Note that 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 in Tab. 3.3. See sections 3.4.4 and 3.4.5 for details on time representation.

3.4.3 Strings

All attributes containing strings as well as all string variables used in the RO level 1 data format are based on the netCDF variable length string (`NC_STRING`) data type.

Some programming languages and scientific computation environments – in particular Matlab – do not yet support the reading and writing of variable length string data, at least at the time of writing this document. In this case, users need to access the respective data through HDF5 APIs.

3.4.4 Compound Times

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_north	<degN>	geographical latitudes
days since 2000-01-01†	<days>	compound times; see section 3.4.4
seconds since 00:00:00.00†	<day_secs>	simple times; see section 3.4.5
seconds since 2000-01-01 00:00:00.00†	<time>	simple times; see section 3.4.5

† actual reference date might differ depending on context

Tab. 3.3: Abbreviations for unit strings used in the Tables 3.6 – 3.29.

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 on 30th June or 31st December may contain an additional 60th second in the last minute of the day.

Finally, in level 1 data, all measurement epochs are referenced to a common 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 3.7.2 and 3.7.3, respectively) can be used to recover the raw instrument measurement times.

3.4.5 Simple Times

For consistency with products from other EPS-SG instruments, a small number of variables in the various status groups (see section 3.6) represent epochs as double precision floating point numbers. The values of these variables are given in units of seconds since a reference epoch, and are supposed to be used with POSIX compliant C system functions such as gmtime(). The latter converts a time in seconds since the UNIX epoch[1] into a broken-down time (consisting of year, month, day, hour, minute, and second), expressed as Coordinated Universal Time (UTC).

Note that POSIX times ignore leap seconds. The difference between two simple times therefore does not equal the number of physically elapsed seconds between the corresponding epochs in case a leap second occurred in between.

3.4.6 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 3.4.

[1] The POSIX standard references all times to 1 January 1970 00:00:00 UTC.

Type	Missing value	Comments
float	NaN	IEEE 954 Not-a-Number (float)
double	NaN	IEEE 954 Not-a-Number (double)
byte	-128	Minimum representable value
short	-2^{15}	Minimum representable value
int	-2^{31}	Minimum representable value
int64	-2^{63}	Minimum representable value
ubyte	255	Maximum representable value
ushort	$2^{16}-1$	Maximum representable value
uint	$2^{32}-1$	Maximum representable value
uint64	$2^{64}-1$	Maximum representable value
string	”	Empty string
char	”	Empty string

Tab. 3.4: Standard missing value indicators.

3.4.7 Booleans and Flags

Boolean variables such as quality flags are not natively supported by the netCDF data format. In the RO level 1b data format, quality flags are stored as unsigned `ubyte` 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.

3.4.8 Deviations from the CF Conventions

The RO level 1b data format 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”).
- Precision time variables are stored in 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 3.4.4.

3.5 `/` (Root) Group

The `/` (root) group of the RO L1 data format contains no variables, but several global attributes as listed in Table 3.5. 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 the orbit numbers having provided data to the current product. This information is generic for all EUMETSAT products.

Name	Description	Shape	Type	Units
Attributes				
`Conventions`	Name of the conventions followed by the data-set	–	string	–

Tab. 3.5: Attributes in the `/` group.

Name	Description	Shape	Type	Units
metadata_conventions	Name of the meta data conventions followed by the dataset	–	string	–
product_name	Product name	–	string	–
title	Short description of the data set or group contents	–	string	–
summary	Short description of the data set or group contents	–	string	–
history	One of “original generated product”, “aggregated product”, or “sub-setted product”	–	string	–
institution	Name of the institution where the data was produced	–	string	–
references	URL of the data provider	–	string	–
environment	One of “Operational”, “Validation”, “Integration & Verification”, “Development”, or “Engineering”	–	string	–
keywords	The RO Level 1 data format currently does not set any keywords	–	string	–
spacecraft	Satellite identifier (“SGA[1-3]” or “SGB[1-3]”)	–	string	–
instrument	Instrument or product identifier (“RO_”)	–	string	–
product_level	Product processing level (“1B”)	–	string	–
type	Type of product	–	string	–
mission_type	One of “Global” or “Regional”	–	string	–
disposition_mode	One of “Test”, “Commissioning”, “Operational”, or “Validation”	–	string	–
sensing_start_time_utc	UTC time of the start of sensing data	–	string	–
sensing_end_time_utc	UTC time of the end of sensing data	–	string	–
orbit_start	Absolute orbit number at sensing_start_time_utc	–	uint	–
orbit_end	Absolute orbit number at sensing_end_time_utc	–	uint	–

Tab. 3.5: Attributes in the `/` group.

3.6 Status Group

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

3.6.1 Satellite Status

The list of variables in the Satellite Status group (named `status/satellite` in the RO data format) is described in Table 3.6.

Note that the position and velocity data provided in this data group is either obtained from the GNSS navigation receiver onboard the spacecraft, or from a Flight Dynamics estimate of the spacecraft’s orbit. This data usually does not have 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 these cases. This data is available as part of the main `data` group, described in section 3.7.2.2.

Name	Description	Shape	Type	Units
Variables				
`epoch_time_utc`	Epoch time in UTC of the orbital elements	-	double	<time>
`semi_major_axis`	Semi major axis of the orbit at epoch time [TOD]	-	double	m
`eccentricity`	Eccentricity of the orbit at epoch time [TOD]	-	double	–
`inclination`	Inclination of the orbit at epoch time [TOD]	-	double	<deg>
`perigee_argument`	Argument of perigee of the orbit at epoch time [TOD]	-	double	<deg>
`right_ascension`	Right ascension of the orbit at epoch time [TOD]	-	double	<deg>
`mean_anomaly`	Mean anomaly of the orbit at epoch time [TOD]	-	double	<deg>
`state_vector_time_utc`	Epoch time in UTC of the state vector and attitude items	-	double	<time>
`x_position`	X position of the orbital state vector [EARTH+FIXED]	-	double	m
`y_position`	Y position of the orbital state vector [EARTH+FIXED]	-	double	m
`z_position`	Z position of the orbital state vector [EARTH+FIXED]	-	double	m
`x_velocity`	X velocity of the orbital state vector [EARTH+FIXED]	-	double	m/s
`y_velocity`	Y velocity of the orbital state vector [EARTH+FIXED]	-	double	m/s
`z_velocity`	Z velocity of the orbital state vector [EARTH+FIXED]	-	double	m/s
`earth_sun_distance_ratio`	Ratio of current Earth-Sun distance to Mean Earth-Sun distance	-	double	–
`yaw_error`	Yaw attitude error	-	double	<deg>
`roll_error`	Roll attitude error	-	double	<deg>
`pitch_error`	Pitch attitude error	-	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_time_utc`	UTC time of occurrence of a leap second in this product (0: no leap second)	-	double	<time>
`leap_second_value`	Value of leap second in product (1, 0, or -1)	-	short	s

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

3.6.2 Instrument Status

Instrument status is described by attributes only. For RO, the onboard software version number is provided; see Tab. 3.7. Note that RO level 1 occultation data products will only be available if the instrument is in "Occultation" mode; in particular, it will never change during a single occultation.

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

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

3.6.3 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 Instrument Data Base (IDB) are available in this data group (Tab. 3.8).

The `source` attribute lists the level 0 input file containing the data of the occultation.

In contrast to other EPS-SG instruments, the source attribute does not contain a list of auxiliary data files. As an individual occultation is implicitely affected by all data that went into the precise orbit determination (which entails hours of level 0 and auxiliary data), the full list would be excessive, though not provide value to users.

Name	Description	Shape	Type	Units
Attributes				
`processor_name`	Name of the product processor (“RO_L1B” in case of the operational RO level 1b processor)	–	string	–
`processor_version`	Processor version number	–	string	–
`processing_mode`	One of “NRT” or ”Reprocessing”	–	string	–
`format_version`	Product format version control number	–	string	–
`source`	The method of production of the original data; see text for details	–	string	–
`idb_version`	Version of the Instrument Data Base being used in the processing	–	string	–
`pgs_reference_and_version`	Reference and version of the PGS	–	string	–
`pfs_reference_and_version`	Reference and version of the PFS	–	string	–
`atbd_reference_and_version`	Reference and version of the ATBD	–	string	–
Variables				
`creation_time_utc`	Start time of product creation in UTC	-	double	<time>

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

3.7 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 the single-point geolocation and time;

`/data/receiver`: data characterizing the receiver (e.g., antenna positions with respect to the spacecraft'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 for the neutral atmosphere as well as the ionosphere, together with diagnostic data.

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

3.7.1 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 nominal georeferencing is useful when the occultation is interpreted as a vertical profile. If more precise knowledge of the location of each tangential point 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 (see section 3.7.6).

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. 3.9.

Name	Description	Shape	Type	Units
Attributes				
`title`	Short description of the data set or group contents	–	string	–
Variables				
`occultation_prn`	PRN of the occulting GNSS satellite	-	string	–
`occultation_type`	Occultation type (rising or setting)	-	string	–
`gnss_system`	GNSS system (one of GPS, Galileo, Glonass, Beidou, or QZSS)	-	string	–

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

Name	Description	Shape	Type	Units
`occultation_id`	Occultation ID	-	int	–
`complete`	If True, data for this occultation is complete	-	ubyte	–
`slta_georef`	Reference SLTA for georeferencing	-	double	m
`utc_georef_absdate`	Reference UTC time for georeferencing (for SLTA = 0 km)	-	int	<days>
`utc_georef_abstime`	Reference UTC time for georeferencing (for SLTA = 0 km)	-	double	<day_secs>
`gps_georef_absdate`	Reference GPS time for georeferencing (for SLTA = 0 km)	-	int	<days>
`gps_georef_abstime`	Reference GPS time for georeferencing (for SLTA = 0 km)	-	double	<day_secs>
`longitude`	Longitude of reference location	-	double	<degE>
`latitude`	Latitude of reference location	-	double	<degN>
`azimuth_north`	GNSS -> LEO line of sight azimuth angle at reference location (clockwise against True North)	-	double	<deg>
`r_curve`	Radius of curvature for reference location	-	double	m
`r_curve_centre`	Centre of curvature position in Earth centred inertial coordinates for reference location	`(xyz)`	double	m
`r_curve_centre_fixed`	Centre of curvature position in Earth fixed coordinates for reference location	`(xyz)`	double	m
`undulation`	EGM96 undulation at reference location	-	double	m
`longitude_rec`	Receiver longitude for reference location	-	double	<degE>
`latitude_rec`	Receiver latitude for reference location	-	double	<degN>
`altitude_rec`	Receiver altitude for reference location (above ellipsoid)	-	double	m
`position_rec`	Receiver antenna position in Earth centred inertial coordinates for reference location	`(xyz)`	double	m
`velocity_rec`	Receiver antenna velocity in Earth centred inertial coordinates for reference location	`(xyz)`	double	m/s
`position_rec_fixed`	Receiver antenna position in Earth fixed coordinates for reference location	`(xyz)`	double	m
`velocity_rec_fixed`	Receiver antenna velocity in Earth fixed coordinates for reference location	`(xyz)`	double	m/s
`velocity_rec_fixed_bfr`	Receiver antenna inertial velocity in Earth fixed coordinates for reference location (for WMO BUFR)	`(xyz)`	double	m/s
`longitude_gns`	GNSS longitude for reference location	-	double	<degE>
`latitude_gns`	GNSS latitude for reference location	-	double	<degN>
`altitude_gns`	GNSS altitude for reference location (above ellipsoid)	-	double	m
`position_gns`	GNSS transmitter position in Earth centred inertial coordinates for reference location)	`(xyz)`	double	m
`velocity_gns`	GNSS transmitter velocity in Earth centred inertial coordinates for reference location	`(xyz)`	double	m/s
`position_gns_fixed`	GNSS transmitter position in Earth fixed coordinates for reference location	`(xyz)`	double	m
`velocity_gns_fixed`	GNSS transmitter velocity in Earth fixed coordinates for reference location	`(xyz)`	double	m/s
`velocity_gns_fixed_bfr`	GNSS transmitter inertial velocity in Earth fixed coordinates for reference location (for WMO BUFR)	`(xyz)`	double	m/s
`azimuth_antenna`	Antenna azimuth angle for reference location (in S/C coordinates)	-	double	<deg>
`zenith_antenna`	Antenna zenith angle for reference location (in S/C coordinates)	-	double	<deg>
`pod_method`	Method used to perform Precise Orbit Determination (POD)	-	string	–

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

Name	Description	Shape	Type	Units
phase_method	Method used to perform carrier phase differencing	-	string	–
retrieval_method	Method used to perform level 1b (bending angle) retrieval	-	string	–

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

3.7.2 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 includes 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 with respect to the satellite's centre of mass as well as the satellite's attitude;

/data/receiver/clock: clock bias estimates;

/data/receiver/orbit_diagnostics: diagnostics of the precise orbit determination performed for this occultation.

The detailed contents of these data groups are given in Tables 3.10 – 3.14.

Note that orbit data in the /data/receiver/orbit and /data/receiver/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 3.7.5).

3.7.2.1 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. 3.10). 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_nssdc`	NSSDC 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

Tab. 3.10: Attributes and variables in the `/data/receiver/satellite` group.

3.7.2.2 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. 3.11), together with additional information about the coordinate system in which the orbit data is provided (e.g. "J2000" or "TOD" for Earth-centered Inertial (ECI) systems, 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 POD data is 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 3.7.4).

We note that the meta data stored in POD data groups resembles (on purpose) the full header of SP3 files [SP3-d]. An individual level 1 granule will also contain POD data at the original temporal resolution with sufficiently many data points to allow 8th-order polynomial interpolation of positions and velocities for the entire duration of the occultation contained in this granule.

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 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)	–	float	–
`std_base_clock_sp3`	Floating point base for clock / clock rate standard deviation (in psec or 10**-4 psec/sec)	–	float	–
`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	–	int	–
Variables				
`utc_absdate`	Epochs (full days) in UTC	`(t)`	int	<days>
`utc_abstime`	Epochs (seconds since last midnight) in UTC	`(t)`	double	<day_secs>
`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)`	ubyte	–
`manoeuvre`	True if satellite undergoes a manoeuvre	`(t)`	ubyte	–

Tab. 3.11: 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-SG. 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. 3.12), 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	–

Tab. 3.12: Attributes and variables in the `/data/receiver/orbit/antenna_phase_centre` group.

Name	Description	Shape	Type	Units
`institution`	Name of the institution where the data was produced	–	string	–
`filename`	File name of the original 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)	–	float	–
`std_base_clock_sp3`	Floating point base for clock / clock rate standard deviation (in psec or 10**-4 psec/sec)	–	float	–
`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	–	int	–
Variables				
`utc_absdate`	Epochs (full days) in UTC	`(t)`	int	<days>
`utc_abstime`	Epochs (seconds since last midnight) in UTC	`(t)`	double	<day_secs>
`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)`	ubyte	–
`manoeuvre`	True if satellite undergoes a manoeuvre	`(t)`	ubyte	–

Tab. 3.12: 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.

3.7.2.3 Receiver Clock Data

Estimated clock biases of the receiver clock are contained in the `/data/receiver/clock` group (Tab. 3.13). Similar to the orbit data groups, this group contains somewhat redundant meta data in order to simplify the conversion of this data into the data format of clock data used in the RO processing.

In many GNSS products, clock offsets are provided with relativistic corrections reflecting the *average* orbit height, thus ignoring relativistic corrections caused by the eccentricity of the orbit. In RO level 1 product granules, these periodic relativistic corrections to the receiver clock may be applied; a dedicated flag is used to keep track of this processing step.

In contrast to position data, it is strongly recommended to use linear interpolation for clock offsets. We note that clock bias data may be provided with a different (often higher) sampling rate than the precise positions and velocities.

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	–
`filename`	File name of the original auxiliary product	–	string	–
`transponder_id`	Transponder identifier; usually equals SP3 satellite identifier	–	string	–
`satellite_id`	EUMETSAT satellite identifier as used in the POD processing	–	string	–
Variables				
`utc_absdate`	Epochs (full days) in UTC	`(t)`	int	<days>
`utc_abstime`	Epochs (seconds since last midnight) in UTC	`(t)`	double	<day_secs>
`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)`	string	–

Tab. 3.13: Attributes and variables in the `/data/receiver/clock` group.

3.7.2.4 Receiver Orbit Diagnostics

EUMETSAT's POD processing is based on a batch processing, i.e. the orbit and clock estimates for the spacecraft's GNSS receiver are obtained by fitting the orbit and clock solution to zenith antenna carrier phase and pseudorange measurements over a long (typically between several hours up to a full day) period. The nominal length of this estimation arc is configurable, although certain operational conditions such as manoeuvres or gaps in the level 0 or auxiliary data may cause shorter estimation arcs. In general, orbit and clock estimates will become more accurate with longer estimation arcs.

The receiver data group provides a number of useful diagnostics obtained from the POD processing in its `diagnostics` subgroup (see Table 3.14). Apart from the start and end times of the POD estimation arc, this group also contains information on the total number of observations (for the combined set of pseudorange and carrier phase measurements) being used (or rejected) by the POD processing, as well as mean and RMS statistics of the pseudorange and carrier phase residuals, which are common diagnostic parameters for the performance of a POD.

Note that while the POD diagnostics will typically be derived from several hours of data, the processing of an individual occultation requires only a short time span from the estimated orbit and clock bias solutions of the POD. Under operational processing conditions, this short time span will be at the end of the orbit estimation arc, while under reprocessing or backlog processing conditions occultations might also benefit from the higher orbit accuracy in the centre of the estimation arc.

Name	Description	Shape	Type	Units
Attributes				
`title`	Short description of the data set or group contents	–	string	–
Variables				
`utc_pod_start_absdate`	Start UTC time for POD estimation arc / date	-	int	<days>
`utc_pod_start_abstime`	Start UTC time for POD estimation arc / time	-	double	<day_secs>
`gps_pod_start_absdate`	Start GPS time for POD estimation arc / date	-	int	<days>
`gps_pod_start_abstime`	Start GPS time for POD estimation arc / time	-	double	<day_secs>
`utc_pod_end_absdate`	End UTC time for POD estimation arc / date	-	int	<days>
`utc_pod_end_abstime`	End UTC time for POD estimation arc / time	-	double	<day_secs>
`gps_pod_end_absdate`	End GPS time for POD estimation arc / date	-	int	<days>
`gps_pod_end_abstime`	End GPS time for POD estimation arc / time	-	double	<day_secs>
`n_obs_available`	Number of observations (pseudorange & carrier phase) available from the instrument	-	int	–
`n_obs_used`	Number of observations (pseudorange & carrier phase) used by the POD	-	int	–
`n_obs_rejected`	Number of observations (pseudorange & carrier phase) rejected by the POD	-	int	–
`pseudorange_residual_rms`	Pseudorange (ionospheric corrected) residuals - RMS	-	double	m
`pseudorange_residual_mean`	Pseudorange (ionospheric corrected) residuals - mean	-	double	m
`phase_residual_rms`	Carrier phase (ionospheric corrected) residuals - RMS	-	double	m
`phase_residual_mean`	Carrier phase (ionospheric corrected) residuals - mean	-	double	m

Tab. 3.14: Attributes and variables in the `/data/receiver/orbit/diagnostics` group.

3.7.3 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. 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/transmitter/orbit/antenna_phase_centre:` precise positions and velocities for the antenna phase centre of the occulting GNSS satellite. This takes into account the displacement of the antenna with respect to the satellite's centre of mass as well as the satellite's attitude;

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

3.7.3.1 Transmitter Satellite Data

Meta data for the GNSS satellite taking part in the occultation 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 provided.

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_nssdc	NSSDC 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	-	ubyte	–

Tab. 3.15: Attributes and variables in the /data/transmitter/satellite group.

The satellite_prn attribute stores the GNSS satellite PRN as a Xnn string, where X is the Satellite System Identifier (G/E/C for GPS, Galileo and Beidou respectively) and nn is the PRN, as specified in [RINEX3].

3.7.3.2 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. The meta data provided allows for the reconstruction of POD data in the SP3 format.

Name	Description	Shape	Type	Units

Tab. 3.16: Attributes and variables in the /data/transmitter/orbit/centre_of_mass group.

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 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)	–	float	–
`std_base_clock_sp3`	Floating point base for clock / clock rate standard deviation (in psec or 10**-4 psec/sec)	–	float	–
`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	–	int	–
Variables				
`utc_absdate`	Epochs (full days) in UTC	`(t)`	int	<days>
`utc_abstime`	Epochs (seconds since last midnight) in UTC	`(t)`	double	<day_secs>
`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)`	ubyte	–
`manoeuvre`	True if satellite undergoes a manoeuvre	`(t)`	ubyte	–

Tab. 3.16: Attributes and variables in the `/data/transmitter/orbit/centre_of_mass` group.

Similar to the receiver orbits, the positions of the GNSS antenna is calculated from the precise orbit of the GNSS satellite, corrected for antenna offsets and the attitude of the satellite. The "orbit" of the transmitter's / GNSS satellite's antenna phase centre is provided in the `/data/transmitter/orbit/antenna_phase_centre` group (Tab. 3.17).

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 auxiliary product	–	string	–
`coordinate_system`	Coordinate system in which the orbit data is provided	–	string	–

Tab. 3.17: Attributes and variables in the `/data/transmitter/orbit/antenna_phase_centre` group.

Name	Description	Shape	Type	Units
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)	–	float	–
std_base_clock_sp3	Floating point base for clock / clock rate standard deviation (in psec or 10**-4 psec/sec)	–	float	–
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	–	int	–
Variables				
utc_absdate	Epochs (full days) in UTC	(t)	int	<days>
utc_abstime	Epochs (seconds since last midnight) in UTC	(t)	double	<day_secs>
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)	ubyte	–
manoeuvre	True if satellite undergoes a manoeuvre	(t)	ubyte	–

Tab. 3.17: Attributes and variables in the `/data/transmitter/orbit/antenna_phase_centre` group.

3.7.3.3 Transmitter Clock Data

Precise estimates for the transmitter clock biases are contained in the `/data/transmitter/clock` group. The remarks made for receiver clock biases (see section 3.7.2.3) on sampling rates, relativistic corrections and interpolation approaches are also valid for transmitter clocks. The same is true for the contents of the meta data provided with the clock data, allowing for reconstruction of the internally used data formats for GNSS clock data handling.

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	–
filename	File name of the original auxiliary product	–	string	–
transponder_id	Transponder identifier; usually equals SP3 satellite identifier	–	string	–
satellite_id	EUMETSAT satellite identifier as used in the POD processing	–	string	–

Tab. 3.18: Attributes and variables in the `/data/transmitter/clock` group.

Name	Description	Shape	Type	Units
Variables				
`utc_absdate`	Epochs (full days) in UTC	`(t)`	int	<days>
`utc_abstime`	Epochs (seconds since last midnight) in UTC	`(t)`	double	<day_secs>
`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)`	string	–

Tab. 3.18: Attributes and variables in the `/data/transmitter/clock` group.

3.7.4 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 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	<day_secs>
`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
`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)`	ubyte	–
`LOD`	Length of Day (difference between the astronomically determined duration of the day and 86400)	`(t)`	double	ms

Tab. 3.19: Attributes and variables in the `/data/earth_orientation_parameters` group.

3.7.5 Level 1a Data

Level 1a RO data generally consists of pseudorange, carrier phase and amplitude (SNR) as measured by the RO instrument in its various measurements modes, with the navigation bit modulation of the carrier phase data having been removed during the processing. Any clock correction ("differencing") has also been applied. The data from different, potentially overlapping measurement modes has further been combined into a single time series of measurement data for each GNSS code being tracked by the instrument, and is contained in a mandatory data group named `/data/level_1a/combined`. Data from individual measurement modes (e.g., measurements from the closed and open loop carrier phase tracking of the R0 instrument) may optionally be contained in additional, correspondingly named data subgroups. The `/data/level_1a` data group thus has the following baseline structure:

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

`/data/level_1a/combined`: Combined closed and open loop carrier phase data with its navigation bit modulation being removed. Note that this group contains individual subgroups for each GNSS frequency being tracked.

The `/data/level_1a` data group may contain additional subgroups containing, e.g., closed and open loop carrier phase measurements in a state prior to the combination into a single time series in the subgroups named `/data/level_1a/closed_loop` and `/data/level_1a/open_loop`, respectively. These optional subgroups have a similar structure as the `/data/level_1a/combined` data group and may, for example, contain multiple instances of carrier phase and amplitude or SNR measurements, e.g. for pilot and data signals being tracked in parallel. Such additional level 1a output is however not foreseen to be used in an operational context, so no further details are provided here.

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 carrier phase measurement data subgroups.

3.7.5.1 Carrier Phase and Amplitude Representation

The physical electromagnetic signal measured by an RO receiver is represented as

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

where $S_i(t)$ is the complex valued electromagnetic signal, $A_i(t)$ a real valued amplitude, and ϕ_i a real valued phase range in units of meters. j denotes the usual $j = \sqrt{-1}$, while the index i refers to the carrier frequency, e.g. the L1 frequency band. λ_i denotes the wave length of the GNSS signal at frequency i,

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

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

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

$$\phi_i(t) = \phi_{\mathrm{nco},i}(t) + \Delta\phi_i(t) \quad \text{with} \quad \Delta\phi_i(t) = \frac{\lambda_i}{2\pi} \arctan\left(I_i(t), Q_i(t)\right) \tag{3.3b}$$

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 modulation – 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. For processed carrier phase data, $\phi_{\mathrm{nco},i}$ may alternatively be a model phase which is used to represent the observations.

The RO level 1 data format therefore provides both measured and processed GNSS data in the 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[2]. 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).

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. For combined closed and open loop data which also has been post-processed, $\phi_{\mathrm{nco},i}$ will represent a fitted or modelled common phase that has been used for providing a joint representation of data from both measurement modes.

Real-valued amplitude A and total phase data ϕ_i can be derived from the I/Q representation via (3.1). Before using such total carrier phase data, e.g. as a proxy for geometrical range, users should take great care to implement proper phase unwrapping and cycle slip detection and fixing.

3.7.5.2 Navigation Bits

The I/Q phase representation (3.2) is also beneficial when it comes to the handling of the navigation bit data modulation, as the latter affects the signs of both I and Q, but has no impact on ϕ_{nco}. Combined carrier phase data provided in RO level 1 data products already has the navigation modulation removed. However, the navigation bit data being used to removed data modulation is also provided, and can be used to reconstruct the original Is and Qs of the signal.

[2] 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.

The `quality` data group (see section 3.8 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.

3.7.5.3 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 3.7.2 and 3.7.3).

3.7.5.4 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.,

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

and are normalised to zero at the top of the occultation. Here, $\vec{r}_{\mathrm{GNSS,\ retarded}}$ and $\vec{r}_{\mathrm{LEO,\ antenna}}$ 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.

As for total carrier phase data, users of excess phase data as provided in RO level 1 data products should take great care to implement proper phase unwrapping and cycle slip detection and fixing.

3.7.5.5 Signals and Codes

Modern GNSS receivers are able to track a multitude of codes modulated on top of a variety of carrier frequencies; the EPS-SG receiver is capable of tracking L1 and L5 GPS, Galileo and Beidou signals, and for these signals is able to perform the measurement tracking for both pilot and data codes. Dependent on the GNSS code being tracked for each carrier phase measurements, variable names of the I, Q and phase components of the measurements as well as their SNR contain a two character postfix identifying the code being tracked; see Tab. 3.20 for a list of postfixes relevant for EPS-SG RO. The postfixes are based on the observation code naming conventions detailed in the RINEX v3 specification (see in particular Tables 4 and 6 in section 5.1 of [RINEX3]). For example, GPS L1C carrier phase measurements obtained by tracking the pilot signal are named `i_1l`, `q_1l` and `phase_1l`, while measurements obtained by combining pilot and data carrier phase measurements are named `i_1x`, `q_1x`, and `phase_1x`, respectively. On the other hand, observations combined from the I and Q components on Galileo's E5a signal would be stored in variables carrying the postfix `_5x`. For SNR data, the same naming convention is followed.

Each level 1a data group contains a list of signals being available in the data group (via the RINEX-based observation code specifiers given in Tab. 3.20, though without the leading variable name and underscore) as well as the corresponding carrier frequencies.

System	Frequency	Channel or Code	Postfix
GPS	L1 / 1575.42 MHz	C/A	`*_1c`
		L1C (Data)	`*_1s`
		L1C (Pilot)	`*_1l`
		L1C (Data + Pilot)	`*_1x`
	L5 / 1176.45 MHz	I	`*_5i`
		Q	`*_5q`
		I + Q	`*_5x`
Galileo	E1 / 1575.42 MHz	B OS data	`*_1b`
		C OS pilot	`*_1c`
		B + C	`*_1x`
	E5a / 1176.45 MHz	I F/NAV OS	`*_5i`
		Q (no data)	`*_5q`
		I + Q	`*_5x`
Beidou	B1C / 1575.42 MHz	Data	`*_1d`
		Pilot	`*_1p`
		Data + Pilot	`*_1x`
	B2a / 1176.45 MHz	Data	`*_5d`
		Pilot	`*_5p`
		Data + Pilot	`*_5x`

Tab. 3.20: GNSS codes and postfix naming conventions for carrier phase, amplitude, and SNR variables in subgroups of the `/data/level_1a` data group.

3.7.5.6 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 and velocities are provided, taking into account the travel time of the GNSS signals between transmitter and receiver.

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 3.7.2 and 3.7.3) should be interpolated directly for all calculations.

3.7.5.7 Time Representation

Within each level 1a data subgroup, 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. 3.21). 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 accordingly.

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 3.7.1). Instead, they refer to the (approximate) beginning of measurements for this particular occultation.

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	<day_secs>
`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	<day_secs>

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

3.7.5.8 Data Subgroups

The prime data group for carrier phase observations is `/data/level_1a/combined` which in turn contains two subgroups: one for each GNSS frequency for which measurements were taken by the instrument. For example, for a GPS-based occultation, the two subgroups will be named `/data/level_1a/combined/L1` and `/data/level_1a/combined/L5`, respectively, the corresponding subgroups for a Galileo-based occultation will be named `/data/level_1a/combined/E1` and `/data/level_1a/combined/E5a`, while the subgroups for a Beidou-based occultation will be named `/data/level_1a/combined/B1C` and `/data/level_1a/combined/B2a`. Tables 3.22 and 3.23 provide examples of these groups for a GPS-based occultation; data groups for Galileo-based occultations will be structured identically apart from different naming of the groups and some of the variables. In any case, each of these groups contains a single time series of combined closed and open loop data for the respective carrier frequency. The navigation bit modulation has been removed from the data.

Name	Description	Shape	Type	Units
Attributes				
`title`	Short description of the data set or group contents	–	string	–
Variables				
`signal`	GNSS signal	-	string	–
`frequency`	GNSS frequency	-	double	Hz
`gps_absdate`	GPS time for all observation epochs / date	`(t)`	int	<days>
`gps_abstime`	GPS time for all observation epochs / time	`(t)`	double	<day_secs>
`dtime`	Measurement epoch	`(t)`	double	<time>
`slta`	Straight line tangent altitude	`(t)`	double	m
`samplerate`	Measurement sample rate	-	double	Hz
`navbits`	Navigation data bits	`(t)`	byte	–

Tab. 3.22: Attributes and variables in the `/data/level_1a/combined/L1` group.

Name	Description	Shape	Type	Units
r_receiver	Receiver position in Earth centred inertial co-ordinates	(t,xyz)	double	m
v_receiver	Receiver velocity in Earth centred inertial co-ordinates	(t,xyz)	double	m/s
r_transmitter	Tansmitter position (retarded) in Earth centred inertial co-ordinates	(t,xyz)	double	m
v_transmitter	Transmitter velocity (retarded) in Earth centred inertial co-ordinates	(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>
i_1x	In-phase component I of l1 carrier phase, navigation bits demodulated	(t)	double	–
q_1x	Quadrature component Q of l1 carrier phase, navigation bits demodulated	(t)	double	–
phase_nco_1x	l1 NCO carrier phase measurements	(t)	double	m
exphase_nco_1x	l1 NCO carrier excess phase measurements	(t)	double	m
phase_1x	l1 carrier phase including I/Q contributions	(t)	double	m
exphase_1x	l1 carrier excess phase including I/Q contributions	(t)	double	m
snr_1x	Signal-to-Noise-Ratio of l1 carrier phase measurements	(t)	double	V/V
pseudorange_1x	l1 pseudorange measurements	(t)	double	m
expseudorange_1x	l1 excess pseudorange measurements	(t)	double	m
snr_1x_mean	Mean Signal-to-Noise-Ratio (amplitude) of l1 carrier phase measurements (60.0 km < SLTA < 80.0 km)	-	double	V/V
exphase_1x_noise	Mean phase noise of l1 carrier excess phase measurements (60.0 km < SLTA < 80.0 km)	-	double	m
slta_1x_min	Minimum overall SLTA of l1 carrier phase data	-	double	m
slta_1x_max	Maximum overall SLTA of l1 carrier phase data	-	double	m
slta_1x_continuous	Lowest SLTA without gaps(SNR drops) of l1 carrier phase data	-	double	m
data_component_available	Signal data component available flag (1 = available, 0 = not available)	(t)	byte	–
open_loop	1 = open loop data used, 0 = closed loop data used	(t)	byte	–

Tab. 3.22: Attributes and variables in the /data/level_1a/combined/L1 group.

Name	Description	Shape	Type	Units
Attributes				
title	Short description of the data set or group contents	–	string	–
Variables				
signal	GNSS signal	-	string	–
frequency	GNSS frequency	-	double	Hz

Tab. 3.23: Attributes and variables in the /data/level_1a/combined/L5 group.

Name	Description	Shape	Type	Units
`gps_absdate`	GPS time for all observation epochs / date	`(t)`	int	<days>
`gps_abstime`	GPS time for all observation epochs / time	`(t)`	double	<day_secs>
`dtime`	Measurement epoch	`(t)`	double	<time>
`slta`	Straight line tangent altitude	`(t)`	double	m
`samplerate`	Measurement sample rate	-	double	Hz
`navbits`	Navigation data bits	`(t)`	byte	–
`r_receiver`	Receiver position in Earth centred inertial co-ordinates	`(t,xyz)`	double	m
`v_receiver`	Receiver velocity in Earth centred inertial co-ordinates	`(t,xyz)`	double	m/s
`r_transmitter`	Tansmitter position (retarded) in Earth centred inertial co-ordinates	`(t,xyz)`	double	m
`v_transmitter`	Transmitter velocity (retarded) in Earth centred inertial co-ordinates	`(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>
`i_5x`	In-phase component I of l5 carrier phase, navigation bits demodulated	`(t)`	double	–
`q_5x`	Quadrature component Q of l5 carrier phase, navigation bits demodulated	`(t)`	double	–
`phase_nco_5x`	l5 NCO carrier phase measurements	`(t)`	double	m
`exphase_nco_5x`	l5 NCO carrier excess phase measurements	`(t)`	double	m
`phase_5x`	l5 carrier phase including I/Q contributions	`(t)`	double	m
`exphase_5x`	l5 carrier excess phase including I/Q contributions	`(t)`	double	m
`snr_5x`	Signal-to-Noise-Ratio of l5 carrier phase measurements	`(t)`	double	V/V
`pseudorange_5x`	l5 pseudorange measurements	`(t)`	double	m
`expseudorange_5x`	l5 excess pseudorange measurements	`(t)`	double	m
`snr_5x_mean`	Mean Signal-to-Noise-Ratio (amplitude) of l5 carrier phase measurements (60.0 km $<$ SLTA $<$ 80.0 km)	-	double	V/V
`exphase_5x_noise`	Mean phase noise of l5 carrier excess phase measurements (60.0 km $<$ SLTA $<$ 80.0 km)	-	double	m
`slta_5x_min`	Minimum overall SLTA of l5 carrier phase data	-	double	m
`slta_5x_max`	Maximum overall SLTA of l5 carrier phase data	-	double	m
`slta_5x_continuous`	Lowest SLTA without gaps(SNR drops) of l5 carrier phase data	-	double	m
`data_component_available`	Signal data component available flag (1 = available, 0 = not available)	`(t)`	byte	–
`open_loop`	1 = open loop data used, 0 = closed loop data used	`(t)`	byte	–

Tab. 3.23: Attributes and variables in the `/data/level_1a/combined/L5` group.

The `/data/level_1a` group may contain additional data groups containing carrier phase data at intermediate processing steps (e.g., individual closed and open loop carrier phase data in data groups `/data/closed_loop` and `/data/open_loop`, respectively). These data groups are similar in structure to the `/data/level_1a/combined` data group (apart from different postfixes to some variable names); as they are not foreseen to be contained in operational products, no examples of their detailed structure are provided in this document.

Apart from containing the measurements themselves, each data subgroup also provides Straight Line Tangent Altitude (SLTA) as well as interpolated orbit, velocity and clock bias data for each measurement epoch. In addition, elevation and azimuth with respect to the antenna borehole are provided, as are additional diagnostic data like upper level noise figures and SNR values averaged over an upper altitude range (typically between 60 and km).

Data from different measurement modes may overlap in time; combining them into a single time series of unique measurements as contained in the `/data/level_1a/combined` group is part of the level 1a processing. Further note that level 1a data from both closed and open loop (or combined) measurement modes may contain data gaps. The latter can be identified by analysing the time differences between successive measurement epochs.

Finally, the calculation of excess phases and ranges (see section 3.7.5.4) is based on the interpolated POD data provided in the same data group. We note that calculating excess phases from orbit solutions other than the one provided by EUMETSAT will require undoing the differencing and excess phase calculation first.

3.7.6 Level 1b Data

The primary content of level 1b RO data are vertical bending angle profiles in the neutral atmosphere 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; 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. Note that in particular the georeferencing of the occultation is different for neutral atmospheric and ionospheric retrievals.

3.7.6.1 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. The default retrieval methodology for neutral atmosphere bending angle retrievals is a wave optics method based on the Phase Transform method. By default, the wave optics retrieval is applied over the entire profile[3]. 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] Note in particular that there is no merging between independent tropospheric and stratospheric retrieval results.

3.7.6.2 Signals and Frequencies

EPS-SG RO data is based on measurements in the GNSS L1 and L5 frequency bands. Variables containing bending angle profiles retrieved from single frequency measurements carry a postfix of `_l1` and `_l5` in their name, e.g. `bangle_l1` and `bangle_l5`, while neutral atmospheric bending angle profiles do not carry this postfix in their names (e.g., `bangle`). We note that all bending angle profiles are referred to the same vertical impact parameter values (as contained in the variable `impact`). The signal names and corresponding carrier frequencies can be obtained from the variables `signals` and `frequencies`, respectively, and as said previously, follows the Rinex conventions [RINEX3]. Similar naming conventions are adopted for frequency specific diagnostic data.

During the level 1b processing, the neutral atmospheric (or "ionospheric corrected") bending angle profile is obtained by extrapolating the geometry-free combination of the L1 and L5 bending angle profiles. The geometry-free combination of bending angles – in its extrapolated form – is also provided as `bangle_l4`.

3.7.6.3 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 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.

3.7.6.4 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 3.7.6.3) 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. 3.24), 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. The latter is provided in the `/data/occultation` group (see section 3.7.1).

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	<day_secs>
`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	<day_secs>

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

3.7.6.5 High Resolution Profiles (Neutral Atmosphere)

Neutral atmospheric high resolution profiles are given on a fixed vertical grid in impact parameter (height or altitude) with a vertical spacing. The contents of the corresponding data group is shown in Table 3.25. Note that the actual profiles are accompanied by various diagnostic information, including estimates of the bending angle uncertainty as well as the potential occurrence of impact multipath (Rènyi entropy).

Name	Description	Shape	Type	Units
Attributes				
`title`	Short description of the data set or group contents	–	string	–
Variables				
`signals`	GNSS signals being used	`(signals)`	string	–
`frequency_l1`	Frequency of L1 signal being tracked	-	double	Hz
`frequency_l5`	Frequency of L5 signal being tracked	-	double	Hz
`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_l1`	Bending angle (L1)	`(z)`	double	rad
`bangle_l5`	Bending angle (L5)	`(z)`	double	rad
`bangle_l4`	Bending angle (L4 = L1 - L5, extrapolated)	`(z)`	double	rad

Tab. 3.25: Attributes and variables in the `/data/level_1b/high_resolution` group.

Name	Description	Shape	Type	Units
`bangle_sdev`	Bending angle (ionospheric corrected) estimated standard deviation	(z)	double	rad
`bangle_l1_sdev`	Bending angle (L1) estimated standard deviation	(z)	double	rad
`bangle_l5_sdev`	Bending angle (L5) estimated standard deviation	(z)	double	rad
`bangle_l1_renyi_entropy`	Bending angle (L1) local Renyi entropy	(z)	double	rad
`bangle_l5_renyi_entropy`	Bending angle (L5) local Renyi entropy	(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 azimuth angles at tangent points (clockwise against True North)	(z)	double	<deg>
`dtime_mean`	Mean measurement epoch (used for georeferencing only)	(z)	double	<time>
`doppler_l1_max`	Maximum instantaneous Doppler (L1)	-	double	Hz
`doppler_rate_l1_max`	Maximum instantaneous Doppler rate (L1)	-	double	Hz/s
`doppler_accel_l1_max`	Maximum instantaneous Doppler acceleration (L1)	-	double	Hz/s^2
`exdoppler_l1_max`	Maximum instantaneous excess Doppler (L1)	-	double	Hz
`exdoppler_rate_l1_max`	Maximum instantaneous excess Doppler rate (L1)	-	double	Hz/s
`exdoppler_accel_l1_max`	Maximum instantaneous excess Doppler acceleration (L1)	-	double	Hz/s^2
`doppler_l5_max`	Maximum instantaneous Doppler (L5)	-	double	Hz
`doppler_rate_l5_max`	Maximum instantaneous Doppler rate (L5)	-	double	Hz/s
`doppler_accel_l5_max`	Maximum instantaneous Doppler acceleration (L5)	-	double	Hz/s^2
`exdoppler_l5_max`	Maximum instantaneous excess Doppler (L5)	-	double	Hz
`exdoppler_rate_l5_max`	Maximum instantaneous excess Doppler rate (L5)	-	double	Hz/s
`exdoppler_accel_l5_max`	Maximum instantaneous excess Doppler acceleration (L5)	-	double	Hz/s^2
`bangle_upper_mean`	Bending angle (ionospheric corrected) 60-80km robust mean	-	double	rad
`bangle_upper_resid_sdev`	Bending angle (ionospheric corrected) 60-80km robust residual standard deviation	-	double	rad
`impact_top`	Highest impact parameter (ionospheric corrected)	-	double	m
`impact_l1_top`	Highest impact parameter (L1)	-	double	m
`impact_l5_top`	Highest impact parameter (L5)	-	double	m
`impact_bot`	Lowest impact parameter (ionospheric corrected)	-	double	m
`impact_l1_bot`	Lowest impact parameter (L1)	-	double	m
`impact_l5_bot`	Lowest impact parameter (L5)	-	double	m
`ic_tec`	Total electron content estimated in ionospheric correction	-	double	m^-3
`ic_bangle_diff_slope`	Bending angle difference fit slope estimated in ionospheric correction	-	double	–
`ic_bangle_diff_offset`	Bending angle difference fit offset estimated in ionospheric correction	-	double	–
`signal_cutoff_l1_slta`	L1a postprocessing signal cut-off SLTA (L1)	-	double	m
`signal_cutoff_l5_slta`	L1a postprocessing signal cut-off SLTA (L5)	-	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

Tab. 3.25: Attributes and variables in the `/data/level_1b/high_resolution` group.

3.7.6.6 Thinned Profiles (Neutral Atmosphere)

The structure of the `/data/level_1b/thinned` data group is identical to the one for high resolution bending angle retrievals (and thus not shown). Bending angle profiles have however been thinned (and smoothed) on a fixed grid of fewer impact (height or altitude) levels. The latter are identical to those being provided as BUFR product (see appendix B).

3.7.7 Ionospheric Data

The content of ionospheric level 1b RO data are vertical bending angle profiles as well as S4 scintillation indices. As for neutral atmospheric retrievals, both high resolution and thinned variants are provided. The structure of the `/data/ionosphere` data group is as follows:

`/data/ionosphere`: parent group; contains a common reference time for all time referencing;

`/data/ionosphere/occultation`: georeferencing information for the ionospheric data;

`/data/ionosphere/high_resolution`: high resolution ionospheric data;

`/data/ionosphere/thinned`: thinned ionospheric data.

The following sections discuss the retrieval types and organisation of the ionospheric data in more detail.

3.7.7.1 Georeferencing

In contrast to neutral atmospheric occultations, the georeferencing for ionospheric measurements is carried out at (typically) 250 km SLTA; correspondingly, the geolocation of the ionospheric profile is slightly different from that of the neutral atmospheric one. Therefore the `/data/level_1b/ionosphere/occultation` group (see Table 3.26) provides the corresponding information for the ionospheric data.

Name	Description	Shape	Type	Units
Attributes				
`title`	Short description of the data set or group contents	–	string	–
Variables				
`occultation_prn`	PRN of the occulting GNSS satellite	-	string	–
`occultation_type`	Occultation type (rising or setting)	-	string	–
`gnss_system`	GNSS system (one of GPS, Galileo, Glonass, Beidou, or QZSS)	-	string	–
`occultation_id`	Occultation ID	-	int	–

Tab. 3.26: Attributes and variables in the `/data/ionosphere/occultation` group.

Name	Description	Shape	Type	Units
complete	If True, data for this occultation is complete (1=True, 0=False)	-	ubyte	–
slta_georef	Reference SLTA for georeferencing	-	double	m
utc_georef_absdate	Reference UTC time for georeferencing (for SLTA = 250 km)	-	int	<days>
utc_georef_abstime	Reference UTC time for georeferencing (for SLTA = 250 km)	-	double	<day_secs>
gps_georef_absdate	Reference GPS time for georeferencing (for SLTA = 250 km)	-	int	<days>
gps_georef_abstime	Reference GPS time for georeferencing (for SLTA = 250 km)	-	double	<day_secs>
longitude	Longitude of reference location	-	double	<degE>
latitude	Latitude of reference location	-	double	<degN>
azimuth_north	GNSS -> LEO line of sight azimuth angle at reference location (clockwise against True North)	-	double	<deg>
r_curve	Radius of curvature for reference location	-	double	m
r_curve_centre	Centre of curvature position in Earth centred inertial coordinates for reference location	(xyz)	double	m
r_curve_centre_fixed	Centre of curvature position in Earth fixed coordinates for reference location	(xyz)	double	m
undulation	EGM96 undulation at reference location	-	double	m
longitude_rec	Receiver longitude for reference location	-	double	<degE>
latitude_rec	Receiver latitude for reference location	-	double	<degN>
altitude_rec	Receiver altitude for reference location (above ellipsoid)	-	double	m
position_rec	Receiver antenna position in Earth centred inertial coordinates for reference location	(xyz)	double	m
velocity_rec	Receiver antenna velocity in Earth centred inertial coordinates for reference location	(xyz)	double	m/s
position_rec_fixed	Receiver antenna position in Earth fixed coordinates for reference location	(xyz)	double	m
velocity_rec_fixed	Receiver antenna velocity in Earth fixed coordinates for reference location	(xyz)	double	m/s
longitude_gns	GNSS longitude for reference location	-	double	<degE>
latitude_gns	GNSS latitude for reference location	-	double	<degN>
altitude_gns	GNSS altitude for reference location (above ellipsoid)	-	double	m
position_gns	GNSS transmitter position in Earth centred inertial coordinates for reference location)	(xyz)	double	m
velocity_gns	GNSS transmitter velocity in Earth centred inertial coordinates for reference location	(xyz)	double	m/s
position_gns_fixed	GNSS transmitter position in Earth fixed coordinates for reference location	(xyz)	double	m
velocity_gns_fixed	GNSS transmitter velocity in Earth fixed coordinates for reference location	(xyz)	double	m/s
azimuth_antenna	Antenna azimuth angle for reference location	-	double	<deg>
zenith_antenna	Antenna zenith angle for reference location	-	double	<deg>
pod_method	Method used to perform Precise Orbit Determination (POD)	-	string	–
phase_method	Method used to perform carrier phase differencing	-	string	–
retrieval_method	Method used to perform level 1b (bending angle) retrieval	-	string	–

Tab. 3.26: Attributes and variables in the `/data/ionosphere/occultation` group.

3.7.7.2 Retrieval Types

EUMETSAT's ionospheric bending angle retrievals are ba default based on a geometrical optics retrieval methodology. The actual used one is available from the `/data/ionosphere/occultation` group by checking its `retrieval_method` attribute. In addition, ionospheric data contains S4 scintillation indices based on both amplitude and phase measurements. They are provided separately for both GNSS frequencies.

3.7.7.3 High Resolution and Thinned Profiles

Similarly to neutral atmospheric retrievals, ionospheric data is available in a high resolution (`/data/level_1b/ionosphere/high_resolution`) variant which is accompanied by a thinned version (in the group `/data/level_1b/ionosphere/thinned`). The contents of these groups (which are identical apart from the group's name and the number of vertical levels) are shown in Table 3.27.

Name	Description	Shape	Type	Units
Attributes				
`title`	Short description of the data set or group contents	–	string	–
Variables				
`signals`	GNSS signals being used	`(signals)`	string	–
`frequency_l1`	Frequency of L1 signal being tracked	-	double	Hz
`frequency_l5`	Frequency of L5 signal being tracked	-	double	Hz
`impact`	Impact parameter	`(z)`	double	m
`impact_height`	Impact height (wrt WGS 84 ellipsoid)	`(z)`	double	m
`bangle_l1`	Bending angle (L1)	`(z)`	double	rad
`bangle_l1_sdev`	Bending angle (L1) estimated standard deviation	`(z)`	double	rad
`s4_amplitude_l1`	Amplitude scintillation index (L1)	`(z)`	double	–
`s4_phase_l1`	Phase scintillation index (L1)	`(z)`	double	rad
`lat_tp_l1`	Latitudes for tangent points (L1 bending angle)	`(z)`	double	<degN>
`lon_tp_l1`	Longitudes for tangent points (L1 bending angle)	`(z)`	double	<degE>
`impact_l1_top`	Highest impact parameter (L1)	-	double	m
`impact_l1_bot`	Lowest impact parameter (L1)	-	double	m
`bangle_l5`	Bending angle (L5)	`(z)`	double	rad
`bangle_l5_sdev`	Bending angle (L5) estimated standard deviation	`(z)`	double	rad
`s4_amplitude_l5`	Amplitude scintillation index (L5)	`(z)`	double	–
`s4_phase_l5`	Phase scintillation index (L5)	`(z)`	double	rad
`lat_tp_l5`	Latitudes for tangent points (L5 bending angle)	`(z)`	double	<degN>
`lon_tp_l5`	Longitudes for tangent points (L5 bending angle)	`(z)`	double	<degE>
`impact_l5_top`	Highest impact parameter (L5)	-	double	m
`impact_l5_bot`	Lowest impact parameter (L5)	-	double	m
`azimuth_tp`	GNSS -> LEO line of sight azimuth angles at tangent points (clockwise against True North)	`(z)`	double	<deg>

Bit	Meaning if Set	Remarks
0	Missing input products	N/A; always unset†
1	Data gaps	N/A; always unset†
2	Corrupted input products	N/A; always unset†
3	Instrument anomaly	
4	Missing or degraded auxiliary data	N/A; always unset†
5	Data quality degraded	Based on `overall_quality_ok`
6-15	TBD	

† . . . as no RO level 1 products will have been generated if one of these degradations applies.

Tab. 3.28: Meaning of bits in the `overall_quality_flag` attribute. Note that individual bits are set to indicate degraded conditions; some of the generic EPS-SG bits are also not applicaple to RO Level 1 data.

`dtime_mean`	Mean measurement epoch (used for georeferencing only)	`(z)`	double	<time>

Tab. 3.27: Attributes and variables in the `/data/ionosphere/high_resolution` group.

3.8 Quality Group

The `/quality` data group collects logical quality control flags set during the level 1 processing of RO data. Probably the most important one of those flags is `overall_quality_ok`; if `True`, data quality is nominal. If `False`, the product is considered to be degraded.

The `overall_quality_ok` flag is obtained from the logical `and` combination of several other flags which are set during the processing. In particular, data quality is considered nominal if the following conditions are met:

- Signal-to-Noise Ratios of the closed loop tracking for both L1 and L5 are above threshold values (both `cl_snr_l1_ok` and `cl_snr_l5_ok` are `True`);
- The ionospheric correction could be performed and produced no issues (`iono_corr_ok` is `True`);
- High altitude bending angles only exhibit biases and standard deviations below certain threshold values (both `bangle_bias_ok` and `bangle_sdev_ok` are `True`);
- The vertical coverage of the neutral atmospheric bending angle profile (`impact_top_ok` and `impact_bot_ok` are `True`) as well as that of L1 and L5 bending angle data is within expectations (`impact_l1_top_ok`, `impact_l1_bot_ok`, `impact_l5_top_ok` and `impact_l5_bot_ok` are `True`).

In order to be consistent with the EPS-SG GPFS, the RO level 1 data format also provides the following quality flag:

`overall_quality_flag`: Similar to `overall_quality_ok`, but condensing various generic quality information into a single bitmask. Overall, the interpretation of the bitmask is that the data product is of nominal quality if all bits are unset. The meaning of individual bits for RO data is shown in Tab. 3.28

In contrast to other EPS-SG level 1 products, RO level 1b products do not contain variables describing the possible data gaps, or missing or corrupted input data. The reason is that occultation observations, being measurements of opportunity, are not based on a permanent stream of raw level 0 data. Instead, they consist of short batches of level 0 data for individual occultations (which might overlap each other), each occultation being contained in its own level 1b granule. For periods without occultation (or auxiliary) data being available, no level 1b products will therefore be generated, and the notion of level 0 (or auxiliary) data gaps therefore does not make sense for RO level 1 data products.

Name	Description	Shape	Type	Units
Attributes				
`title`	Short description of the data set or group contents	–	string	–
Variables				
`cl_ol_l1_continuous`	True if L1 closed loop and open loop data form continuous time series	-	ubyte	–
`cl_ol_l1_consistent`	True if L1 closed loop and open loop data are consistent in the overlap region	-	ubyte	–
`snr_l1_ok`	True if upper level (60.0 km $<$ SLTA $<$ 80.0 km) mean L1 carrier phase SNR $>$ 200.0 V/V	-	ubyte	–
`cl_ol_l5_continuous`	True if L5 closed loop and open loop data form continuous time series	-	ubyte	–
`cl_ol_l5_consistent`	True if L5 closed loop and open loop data are consistent in the overlap region	-	ubyte	–
`snr_l5_ok`	True if upper level (60.0 km $<$ SLTA $<$ 80.0 km) mean L5 carrier phase SNR $>$ 50.0 V/V	-	ubyte	–
`cl_data_available`	True if closed loop data is available	-	ubyte	–
`ol_data_available`	True if open loop data is available	-	ubyte	–
`external_navbits_ok`	True if external navigation bit data are available	-	ubyte	–
`gns_orbit_ok`	True if GNSS orbit estimates are available	-	ubyte	–
`gns_clock_ok`	True if GNSS clock error estimates are available	-	ubyte	–
`rec_orbit_ok`	True if receiver orbit estimates are available	-	ubyte	–
`rec_clock_ok`	True if receiver clock error estimates are available	-	ubyte	–
`rec_clock_estimated`	True if receiver clock error has been estimated (False if interpolated due to missing epochs from POD estimation)	-	ubyte	–
`ol_data_used`	True if open loop data was used in retrieval	-	ubyte	–
`overall_quality_flag`	'0' if retrieval is ok	-	ubyte	–
`overall_quality_ok`	True if retrieval is ok	-	ubyte	–
`high_resolution_ok`	True if high resolution retrieval is ok	-	ubyte	–
`thinned_ok`	True if thinned retrieval is ok	-	ubyte	–
`bangle_bias_ok`	True if upper level (60 - 80 km) mean bending angle is ok	-	ubyte	–
`bangle_sdev_ok`	True if upper level (60 - 80 km) bending angle residual standard deviation is ok	-	ubyte	–
`iono_corr_ok`	True if ionospheric correction is ok	-	ubyte	–
`impact_top_ok`	True if uppermost impact parameter height is ok	-	ubyte	–
`impact_bot_ok`	True if lowermost impact parameter height is ok	-	ubyte	–
`impact_l1_top_ok`	True if uppermost L1 impact parameter height is ok	-	ubyte	–

Tab. 3.29: Attributes and variables in the `/quality` group.

Name	Description	Shape	Type	Units
impact_l1_bot_ok	True if lowermost L1 impact parameter height is ok	-	ubyte	–
impact_l5_top_ok	True if uppermost L5 impact parameter height is ok	-	ubyte	–
impact_l5_bot_ok	True if lowermost L5 impact parameter height is ok	-	ubyte	–
signal_cutoff_done	True if deep occultation signal cut-off was done.	-	ubyte	–
iono_high_resolution_ok	True if ionosphere high resolution retrieval is ok	-	ubyte	–
iono_thinned_ok	True if ionosphere low resolution retrieval is ok	-	ubyte	–
overall_quality_iono_ok	True if ionosphere retrieval is ok	-	ubyte	–

Tab. 3.29: Attributes and variables in the `/quality` group.

With respect to ionospheric data, we note that only three quality flags are included in the `/quality` data group. These do not impact the overall quality parameters characterising an RO level 1 product as either “nominal” or “degraded” are based on the neutral atmospheric quality control parameters only.

4 REPROCESSED RO LEVEL 1B PRODUCTS

RO data obtained from the EPS-SG RO instruments will be reprocessed in regular intervals.

Reprocessed RO level 1 data will be provided in essentially the same data format as operational data. However, two meta data attributes will be added to each product: a Digital Object Identifier (DOI) characterising the reprocessed data set itself (as a global attribute called `doi` in each data set's root group), as well as an attribute named `baseline` in the `/status/processing` data group identifying the baseline (or version) of the reprocessing activity.

Table 4.1 below lists the additional meta data attributes available in reprocessed RO level 1b data products.

Name	Description	Shape	Type	Units
`/`				
`doi`	Digital Object Identifier for reprocessed data	–	string	–
`/status/processing`				
`baseline`	Climate data record collection version for reprocessed data	–	string	–

Tab. 4.1: Attributes only available in reprocessed data products.

5 PRODUCT FORMAT VERSION CONTROL

This section provides *Product Format Version Control Numbers* for each product defined within this document. This version is reflected in the `format_version` global attribute present in each EPS-SG mission product centrally generated as described in the [GPFS].

Product ID	`format_version`	PFS Issue	GPFS Issue
RO_-1B-BND	14.0	this issue	4

As described in the [GPFS], the *Product Format Version Control Number* is updated whenever there is a change in the format or contents of a product that requires an update to software that has to read the product or has to check the product. This could be a change in the format itself (element is deleted, added, resized, re-typed,...), a change in the contents of an element (e.g. scale factor change) or a change in the way that element has to be interpreted. Any such element update requires the product format version number to be incremented.

A recommended way to use *major.minor* versions of the product format version control number both is to issue minor updates for a change resulting from a PFS update, and major updates for a change resulting from GPFS updates that affect all products. Then a GPFS update would reset all products back to a new major of (say) 12.0, and then 12.1, 12.2 etc. versions would indicate PFS-only updates.

A SIZE OF EPS-SG RO LEVEL 1 PRODUCTS

Table A.1 below shows the expected level 1 product sizes for the baseline (GPS, Galileo and Beidou) configuration of the RO instrument as well as for all four constellations (GPS, Galileo, Beidou and Glonass).

GPS & Galileo & Beidou		All GNSS	
Daily (GB)	**per Orbit (GB)**	**Daily (GB)**	**per Orbit (GB)**
44	3.2	56.7	4.0

Tab. A.1: RO level 1 per-orbit and daily product sizes.

B WMO BUFR

This Appendix describes the mapping between variables in the EPS 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 [RO-BUFR]. The recommendations of IROWG (see [IROWG-BUFR]) were taken into account, assuming they will be implemented in the foreseeable future.

The BUFR products will be distributed via EUMETCAST and via GTS (WMO network). For the GTS network, the BUFR product shall be packaged as described in Section 6 of the GPFS [GPFS]. This means that an additional product shall be generated, starting from the BUFR product, packaged as described in GPFS.

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

BUFR sections 1 is filled with meta data as described in the BUFR specification [RO-BUFR] 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_abstime` 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.

B.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 [RO-BUFR]. The mapping between BUFR and RO Level 1 product quality flags is described in Tab. B.1 below.

Bit	Description	Variable
1	Nominal / non-nominal quality	`/quality/overall_quality_ok`
2	NRT / Offline product	`/environment`
3	Descending / ascending occultation	`/data/occultation/occultation_type`
4	Excess phase processing (non-) nominal	`/quality/snr_[l1|l5]_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_used`
9	(No) Surface reflections detected	*Unused*
10	L2P / L2C GPS signals used	*Unused*
11-13	Reserved	*Unused*
14	Background profile (non-) nominal	*Unused*
15	Retrieved / background profile	*Unused*

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

Octet	Variable(s)	Remarks
Nominal Reporting Time		
7-12	/data/occultation/utc_georef_absdate /data/occultation/utc_georef_abstime	Assumes [IROWG-BUFR] is implemented
RO Summary Quality Information		
13	*various*	see Tab. B.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_fixed_bfr	...and velocities at georeferencing time
21	/data/transmitter/satellite/satellite_prn	First letter, e.g. Gxx → 401 (for GPS)
22	/data/transmitter/satellite/satellite_prn	Integer part, e.g. 1 → 1 (for PRN G01)
23-25	/data/occultation/position_gns_fixed	Positions...
26-28	/data/occultation/velocity_gns_fixed_bfr	...and velocities at georeferencing time
Local Earth Parameters		
29	*always zero*	Assumes [IROWG-BUFR] 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 L5 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_l1 /data/level_1b/thinned/bangle_l5	
46-48	*Currently unused*	

Tab. B.2: Mapping between BUFR Section 4 data fields and EPS-SG RO L1 data format variables.

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 3.4. For example, in case on Bit 1, the global attribute `environment` may exhibit values of "Operational", "Validation", "Development", "Offline","Integration & Verification", and "Support" (see section 3.5). 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. B.2 links data fields as used in BUFR Section 4 entries (see Table 5 of [RO-BUFR] 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.

B.3 Size of BUFR products

In the current EUMETSAT RO processing for EPS, thinned bending angle profiles are provided on a fixed set of 247 vertical impact height levels between the surface and 60 km altitude. However, the definition and vertical coverage of thinned RO level 1b data is under active scientific discussion, and may change over time as the resolution of NWP models increases. Apart from an increase in the number of vertical levels, additional information – in particular uncertainty estimates – will also be provided for EPS-SG

The current size of a BUFR product is around 13 kB for present EPS RO level 1b data per occultation. For EPS-SG, due to the larger vertical coverage of the instruments, a higher number of vertical levels and the additional uncertainty estimates, the expected BUFR product size per occultation is between 50 and 250 kB.

C XML DESCRIPTION OF EPS-SG RO LEVEL 1 FORMATS

An XML description of the NetCDF-4 EPS-SG RO L1 product is attached in the following file. We note that the file represents an example of reprocessed occultation. It therefore contains additional meta data attributes only present in reprocessed data sets (see Section 4).