GRAS Satellite Application Facility

PRODUCT USER MANUAL

Version 1.2.1

31 March 2009

Danish Meteorological Institute (DMI)
European Centre for Medium-Range Weather Forecasts (ECMWF)
Institut d'Estudis Espacials de Catalunya (IEEC)
Met Office (MetO)

DOCUMENT SIGNATURE TABLE

	Author(s)	***Function***	***Date***	***Signature***
Prepared by:	Frans Rubek	GRAS SAF Project Team	31/03/09	
Approved by:	Kent Bækgaard Lauritsen	GRAS SAF Project Manager	31/03/09	

DOCUMENTATION CHANGE RECORD

Issue / Revision	***Date***	***By***	***Description***
Version 0.1	03/05/07	FRR	1st draft
Version 1.0	16/05/08	FRR	ORR-A version
Version 1.1	02/09/08	FRR	ORR-A Close-out version based on RIDs # 1 → 16, 31, 33, 35 → 38, 60, 72, and 73. Parts of Chapter 4 moved to Chapter 3 for better text structure. Textual updates to chapter 1.2, 2.4, 3.1, 3.2.10, 3.3.1, 3.4, 4.3.2, 4.3.3, and 5, and to Figure 6-1.
Version 1.2	27/03/09	FRR	Update related to declaring the NRT Refractivity Product pre-operational
Version 1.2.1	31/03/09	FRR	Minor corrections to version 1.2

List of Contents

List of Figures

1. INTRODUCTION

1.1 Purpose

This document is the GRAS SAF Product User Manual and is dedicated to the products' users. The main content of the manual is a description of the data products' content and format. It also briefly reviews the algorithms used and the processing methods adopted. The current version of the document only describes the NRT and Offline Products. The Climate Products will be included in a future version.

The main purpose of the GRAS SAF is to continuously process radio occultation (RO) data from the GRAS instrument onbord the EPS/Metop satellite (and potentially other RO missions) into Level 2 products. A second objective of the GRAS SAF is to supply the Radio Occultation Processing Package (ROPP) software for assimilation of RO data into NWP models, for more details about ROPP see [RD.8].

1.2 Status of Products

The current (March 2009) status of the products is listed here. The NRT refractivity and validation products and the ROPP package (GRM-01, GRM-06, and GRM-16) are available as pre-operational or demonstration products, the rest are still under development:

Product identifier and status	**Product name**	**Product acronym**	**Product type (product, software, dataset, information)**	**Dissemination type (NRT/offline)**	**Dissemination means**	**Format**
GRM-01	NRT Refractivity Profile	NRP	Product	NRT	GTS EUMETCast	BUFR BUFR/netCDF
GRM-02	NRT Temperature Profile	NTP	Product	NRT	GTS EUMETCast	BUFR BUFR/netCDF
GRM-03	NRT Specific Humidity Profile	NHP	Product	NRT	GTS EUMETCast	BUFR BUFR/netCDF
GRM-04	NRT Pressure Profile	NPP	Product	NRT	GTS EUMETCast	BUFR BUFR/netCDF
GRM-05	NRT Surface Pressure	NSP	Product	NRT	GTS EUMETCast	BUFR BUFR/netCDF
GRM-06	NRT Validation Products	NVP	Information	NRT	Web	N/A
GRM-07	Error Covariance Matrix for NRT Products	NEM	Dataset	offline	Web	netCDF
GRM-08	OFL Bending Angle	OBA	Product	offline	FTP/DVD	netCDF
GRM-09	OFL Refractivity Profile	ORP	Product	offline	FTP/DVD	netCDF
GRM-10	OFL Temperature Profile	OTP	Product	offline	FTP/DVD	netCDF
GRM-11	OFL Specific Humidity Profile	OHP	Product	offline	FTP/DVD	netCDF
GRM-12	OFL Pressure Profile	OPP	Product	offline	FTP/DVD	netCDF
GRM-13	OFL Surface Pressure	OSP	Product	offline	FTP/DVD	netCDF
GRM-14	OFL Validation Products	OVP	Information	offline	Web	N/A

GRM-15	Error Covariance Matrix for OFL Products	OEM	Dataset	offline	Web	netCDF
GRM-16	Radio Occultation Processing Package	ROPP	Software	N/A	Web	tarballs
GRM-17	CLM Bending Angle	CBA	Product	offline	FTP/DVD	netCDF ASCII
GRM-18	CLM Refractivity	CRG	Product	offline	FTP/DVD	netCDF ASCII
GRM-19	CLM Temperature	CTG	Product	offline	FTP/DVD	netCDF ASCII
GRM-20	CLM Specific Humidity	CHG	Product	offline	FTP/DVD	netCDF ASCII
GRM-21	CLM Geopotential Height	CZG	Product	offline	FTP/DVD	netCDF ASCII

= operational = pre-operational = degraded

= stopped = demonstration = development

Table 1-1 Current status of GRAS SAF deliverables (note that other product acronyms are used within UMARF). For information about expected time of availability for the products still under development please refer to the project web page http://www.grassaf.org/ .

Beside these GRAS SAF deliverables, EUMETSAT is disseminating full-resolution GRAS bending angles on EUMETCast and thinned GRAS bending angles in BUFR format on EUMETCast and GTS, cf. [RD.3] and [RD.4]. Thinned versions of the full-resolution EUMETSAT bending angles are also included in the GRAS SAF Level 2 products for convenience.

Archived GRAS data products and the ROPP software package can be downloaded at the GRAS SAF Archive and Retrieval Facility (GARF) web page http://garf.grassaf.org/.

1.3 Structure of this Document

This document contains chapters on:
1: Introduction
2: The radio occultation method
3: Product description
4: Format descriptions
5: Data quality
6: Dissemination methods
7 : References
Appendices

1.4 Definitions, Acronyms and Abbreviations

The data products from the GRAS receiver are grouped in *levels* and are either *NRT* or *Offline* products.

NRT product: Product delivered less than three hours after measurement.
Offline product: Enhanced product delivered less than 30 days after measurement.

Level 0 data: Raw GRAS sounding, tracking and ancillary data, ground site observations, GNSS and METOP ancillary data, a.o., after restoration of the chronological data sequence for each instrument, i.e. after demultiplexing of the data by instrument, removal of any data overlap due to the data dump procedure, and relevant quality checks. Raw instrument data information (telemetry packets) is maintained during this process. Delivered by EPS/CGS.
Level 1a data: Phase delays, SNR, a.o., METOP, GNSS and ground site instrument data in full resolution with radiometric and geometric (i.e. earth location) calibration applied. NRT products delivered by EPS/CGS, Offline products delivered by GRAS SAF.
Level 1b data: Bending angles and impact parameters, calibrated, earth located and quality controlled, with doppler shifts and the needed ancillary, engineering and auxiliary data (including a subset of Level 1a data). NRT products delivered by EPS/CGS, Offline products delivered by GRAS SAF.
Level 2 products: Refractivity, pressure, temperature, and humidity profiles, time, earth location, quality information, and background temperature/humidity profiles, spatially and temporally sub-sampled from the Level 1b data. Also includes selected Level 1b parameters like bending angle and impact parameter plus POD and support information. Delivered by GRAS SAF.

BUFR	Binary Universal Form of Representation
CGS	Core Ground Segment (EPS)
CHAMP	CHAllenging Minisatellite Payload (Germany)
DMI	Danish Meteorological Institute
ECF	Earth-Centered, earth-Fixed
ECI	Earth-Centered Inertial
ECMWF	European Center for Medium-range Weather Forecast
EGM96	Earth Geopotential Model 1996. Standard model for geoidal undulations and gravity field, referenced to the WGS-84 ellipsoid
EPS	EUMETSAT Polar satellite System
ESA	European Space Agency
EUMETSAT	EUropean organisation for the exploitation of METeorological SATellites
GARF	GRAS SAF Archive and Retrieval Facility
GNSS	Global Navigation Satellite System (generic name for GPS, GLONASS, and similar future systems)
GPS	Global Positioning System (US)

GRAS	GNSS Receiver for Atmospheric Sounding (METOP instrument)
GSN	Ground Support Network
GTS	Global Telecommunication System
IEEC	Institut d'Estudis Espacials de Catalunya (Spain)
IGS	International Geodynamics Service
I-RR	Infrastructure Readiness Review (GRAS SAF)
LEO	Low Earth Orbit
METOP	METeorological Operational Polar satellite (EPS/EUMETSAT)
MSL	Mean Sea Level (The geoid)
NetCDF	Network Common Data Form
NRT	Near-Real Time
NWP	Numerical Weather Prediction
ORR-A	Operational Readiness Review-A (EUMETSAT/GRAS SAF)
POD	Precise Orbit Determination
RMDCN	Regional Meteorological Data Communication Network (GTS in WMO Region 6)
RO	Radio Occultation
ROPP	Radio Occultation Processing Package (GRAS SAF)
SAF	Satellite Application Facility (EUMETSAT)
UKMO	The UK Meteorological Office (aka: Met Office)
UMARF	Unified Meteorological Archive and Retrieval Facility (EUMETSAT)
URD	User Requirements Document (GRAS SAF)
UT1	Universal Time 1, non-linear, approximates the mean diurnal motion of the Earth
UTC	Universal Time Coordinated (previously known as Greenwich Mean Time), piecewise linear atomic timescale, interrupted by leap seconds ($\lvert$UTC-UT1$\rvert$ < 0.9 seconds)
WGS84	World Geodetic System 1984; standard Earth model ellipsoid.

2. THE RADIO OCCULTATION METHOD

2.1 Overview

Products obtained from the radio occultation (RO) measurements consist of vertical profiles of refractivity, temperature, pressure, and humidity as functions of height.

The various profiles (e.g. temperature) are obtained from the excess phases of radio signals travelling through the atmosphere along horizontal paths (see Figure 2-1). The signals are emitted from the GPS (Global Positioning System) satellites orbiting some 20,000 km above the Earth surface and received by the GRAS instrument on the Metop satellite. The GPS radio signals scan the atmosphere horizontally until they are occulted by the Earth (setting occultation) or from the moment they appear behind the Earth (rising occultation).

The first step is to compute the bending angle of the signal as an integrated measure along the entire signal path. The refractivity at a given so-called tangent point is then derived through an inversion of the bending angle. The fact that parts of the signal paths travel through the same levels of the atmosphere causes the profile errors to be vertically correlated. This statistical correlation will be separately specified in an error covariance matrix.

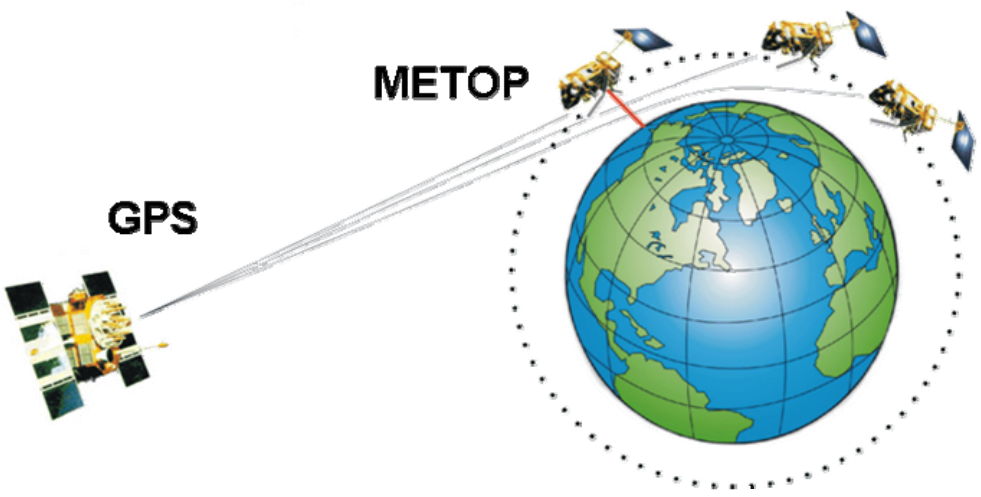

Figure 2-1. Schematic representation of the data (red line) observed by the GRAS instrument on Metop during an occultation.

It should be noted that in general the profile will not be given along a straight, vertical line but rather along a slightly curved, skew line such that the deviation of the topmost point relative to the point closest to the Earth (the so-called tangent point drift) can be more than 100 km. The

(temperature) profiles will cover the Earth evenly but the locations of the individual profiles vary from profile to profile and locations are not repeatable. Also, note that the profiles are generated at random times (i.e. not at synoptic times), in common with most polar orbiting satellite data products.

For more details refer to [RD.2], [RD.3], and [RD.4].

2.2 Benefits of Radio Occultation profiling

Despite the relatively poor horizontal sampling (mean spacing) of RO data from a single instrument – but still better than the global average for radio-sondes – and the techniques' inherent horizontal line-of-sight resolution of some 250 km, the system has several very significant benefits:

- High stability – both in time for one instrument and inter-instrument, leading to very stable long-term data for climate applications
- High accuracy – better than 1K over much of the middle atmosphere
- High vertical resolution – of order 200 m or better in the lower troposphere – comparable to radiosondes and significantly superior to current vertical passive sounders
- All weather capability – GNSS signals are virtually unaffected by cloud and precipitation
- Global coverage
- The single GRAS instrument on Metop generates approximately 500 - 650 profiles per day, depending on the actual number of GNSS satellites

The general characteristics of the RO method make it a quite complementary observing system within the WMO's WWW programme. The potential of the RO technique has been amply demonstrated with the CHAMP and COSMIC missions

.

2.3 Characteristics of the GRAS Instrument

The main objective of the GRAS instrument is the measurement of the excess phase of signals from GNSS satellites as they are refracted by the atmosphere. Excess phase, measured as the phase change in the signal carrier phase, depends on the refractive index of the atmosphere, which is a function of electron density, temperature, pressure, and humidity.

The GRAS instrument provides carrier phase measurements for the occultation mission and also for the navigation mission (top-side antenna). The processing algorithms within the CGS enable the conversion of the instrument Level 0 data to the defined Level 1b data product within its performance requirements. The GRAS SAF is responsible for processing the NRT Level 1b data into Level 2 products.

The sampling rate of the carrier phase, pseudo-range, signal amplitude, occultation and navigation measurement is separately selectable among the following steps: 0.1, 0.5, 1, 10, 25, 50 Hz. The occultation measurement is nominally sampled at 50 Hz.

Bending angles are provided for heights above the Earth's surface ranging from 80 km down to 2 km or lower (for both setting and rising occultations). The bending angle accuracy requirement is to be better than 1μrad or 0.4% (whatever is larger). The impact parameter localisation in Earth co-ordinates is required to be better than 0.01° in longitude and latitude, and better than 6 metres in altitude. With the nominal GPS constellation the GRAS instrument generates some 500 occultations per day, globally distributed, although the current 31 GPS satellites yield as much as 650 occultations.

2.4 Overview of processing to Level 2 products

Figure 2-2 shows schematically the data flow for near-real time (NRT) and Offline processing up to GRAS SAF Level 2 products. Processing up to bending angle is performed at EUMETSAT for GRAS/Metop NRT data. The difference between the two product types is described in more detail in Section 3.1. [RD.6] specifies the algorithms which are used to process the occultation data. The current version of this document (and the figure) does not contain information on the Climate Products (GRM-17 to GRM-21). These products are currently under development.

The two GPS radio frequencies received by GRAS at the Metop satellite are characterised by their amplitude and phase values. The bending angle profiles are obtained using the positions and velocities of the GPS and Metop satellites. The bending angle profiles are subject to a correction in order to eliminate the effect of the ionosphere on the signals. In the case of single ray propagation the phase contains all the necessary information in order to derive the bending angle whereas in the case of multiple ray propagation (multipath), caused by strong vertical gradients in the atmosphere, both the amplitude and the phase are needed to obtain a bending angle profile free of multipath artifacts. The current NRT processing at EUMETSAT is based on the phase data only, even in the lower troposphere where multipath propagation occurs frequently. The ultimate goal is to process the data using both the phase and the amplitude to solve for the multipath propagation using radio-holographic algorithms like CT2 and/or FSI.

The index of refraction (from which the refractivity is derived), is obtained from a statistically optimized bending angle profile through the use of the so-called Abel transform inversion method, cf. [RD.7] and [RD.10].
In order to arrive at an estimate for the temperature, pressure and humidity, some ancillary data are needed. For the GRAS SAF products we use as ancillary data profiles of temperature, humidity and surface pressure from ECMWF forecasts, appropriate to the time and location of the occultation (interpolated bi-linearily in the horizontal on model levels). This set of ancillary data ('background' or 'first-guess') in combination with the refractivity is then used in a 1DVAR algorithm in order to simultaneously estimate the temperature, humidity and pressure profiles,

together with surface pressure. The solution is constrained by the assumption that the atmosphere is in hydrostatic equilibrium. Note that unique humidity profiles cannot be obtained from radio occultation measurements without using some source of ancillary information on temperature.

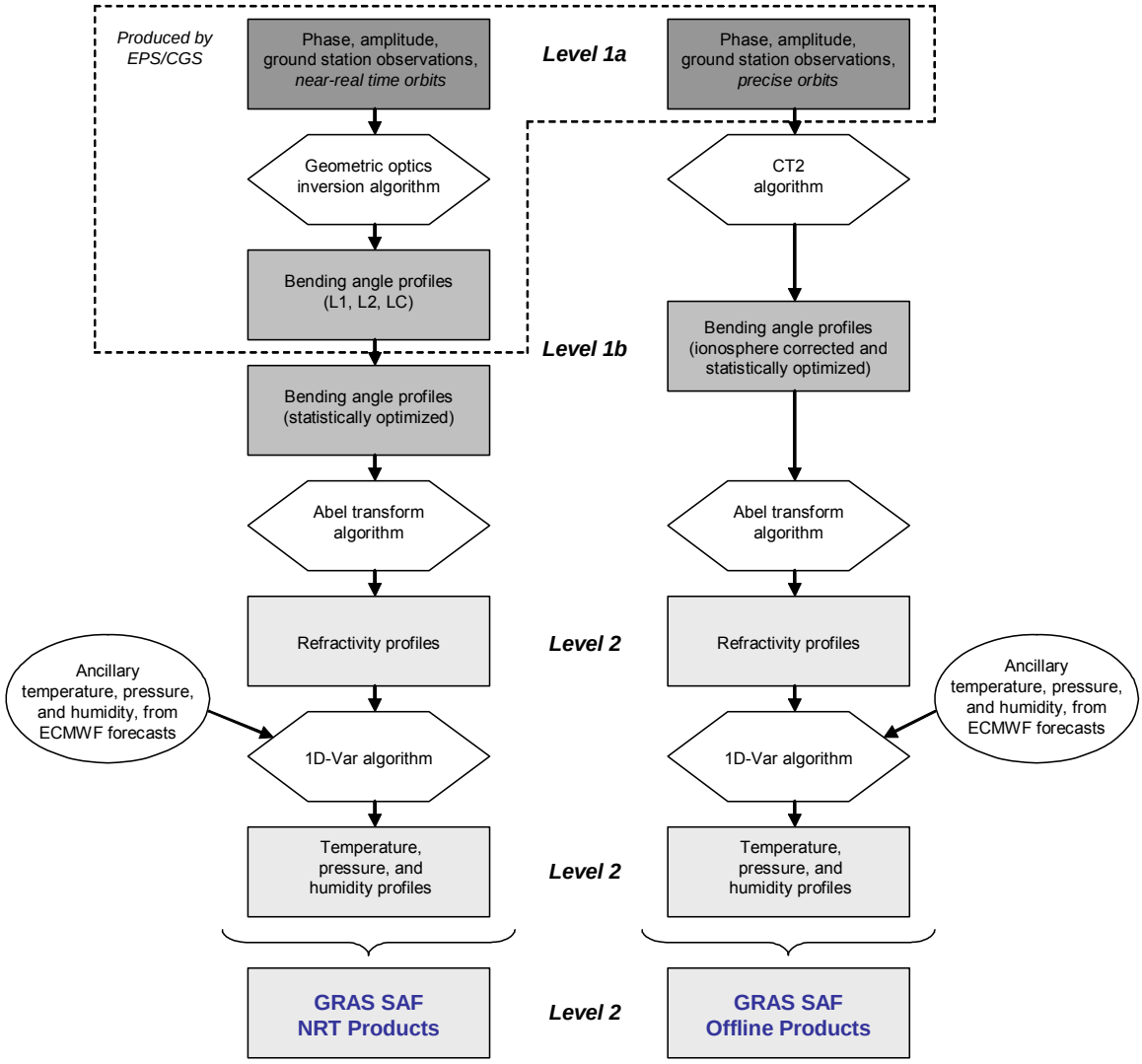

Figure 2-2 ***Left****: Schematic showing of the NRT processing steps to SAF Level 2 products. Ancillary temperature and humidity profiles are used as background in the statistically optimal retrieval in the 1D-VAR scheme. SAF Level 2 products include a thinned bending angle profile derived from the EUMETSAT Level 1b profile.* ***Right****: Schematic showing of the Offline processing steps to SAF Level 2 products.*

3. PRODUCT DESCRIPTION

3.1 Overview of GRAS SAF Data Products Deliverables

In this chapter, we list all the GRAS SAF data products. The products of the GRAS SAF operational system are targeting different types of user groups. NRT (near-real time) products are targeting National Meteorological Centres, and comparable regional or independent centres. These users will receive the products with a timeliness of 3 hr. Offline products (and later the dedicated Climate products) are targeting climate research and atmospheric science centers. The design does not distinguish between users, but does instead have different types of products and means of delivery.

- **NRT sounding and validation products**: Those produced with operational timeliness restrictions (3 hours).
- **Offline sounding and validation products**: Those produced with a timeliness restriction of 30 days.
- **NRT delivery**: Only available for NRT products, through guaranteed performance channels and with operational timeliness restrictions.
- **Offline delivery**: Available for all products, through a variety of possible channels. Exclusive means of delivery for offline products.

Each product type is divided into levels, as listed in this table:

Data product		
Level 1	Level 1a	SNR excess phases and POD data as function of time
	Level 1b	Bending angle as function of impact parameter
Level 2	Level 2a	Refractivity as function of altitude
	Level 2b	Temperature, humidity, pressure and geopotential height on model levels
	Level 2c	Surface pressure
	Level 2d	Additional data describing the vertical level structure (e.g. level coefficients for vertical hybrid or eta–coordinates)

Table 3-1 GRAS and GRAS SAF product level descriptions. Further descriptions are available in [RD.8].

The operational GRAS SAF system consists of a data retrieval and processing system and an archival system, both situated at the Leading Entity DMI.
The input data for NRT is level 1b data received from EPS/CGS through the EUMETCast terminal placed at the hosting institute. Auxiliary data sources are forecasts and analyses received from ECMWF and satellite orbits received from the GRAS GSN.

The product holding is reported to UMARF in form of metadata. This is done via the UMARF Client, also physically situated at the hosting institute.
Users may request offline products via GARF and/or UMARF. The GRAS SAF retrieves forms with the requests from the UMARF Client.

3.1.1 NRT Products

The main parameters in the NRT Sounding Data Products are:

- Refractivity profiles
- Temperature profiles
- Pressure profiles
- Water vapour profiles
- Surface pressure

In addition, a thinned-out version of the EUMETSAT Level 1b (ionosphere corrected) bending angle is included in the Level 1b NRT data products. Various supporting data and selected parameters (with some post-processing applied) are included with the Level 2 NRT Sounding Products – see below.

3.1.2 Offline Products

The main parameters in the Offline Products are identical to those contained in the NRT Products (plus the bending angles). The Offline Products have been processed to a different specification than the NRT Products, the major differences being the use of reprocessed RO data using the optimum post-processed GPS and Metop orbital information (POD) and the inclusion of other auxiliary data, which may not have been available on the timescale of the NRT Products. Offline products are available to users within 30 days of observation time.

- Bending angles
- Refractivity profiles
- Temperature profiles
- Pressure profiles
- Water vapour profiles
- Surface pressure

3.1.3 Supporting Data

GRAS SAF NRT and Offline Sounding Products also include (but are not limited to) the following supporting parameters:

- LEO and occulting GPS satellite identifiers
- Horizontal location (latitude, longitude)
- Vertical location (ellipsoidal height, height above MSL, geopotential height, pressure level)
- Date and time
- Quality information (estimated errors, Q/C flags)
- POD information
- Radius of curvature information
- Impact parameter (smoothed & sampled)
- Bending angle (ionosphere-corrected, smoothed & sampled)
- SAF software version

Note that the GRAS SAF also includes 'raw' parameters such as signal-to-noise ratio, excess phase, Doppler or uncorrected bending angles in its archived products. Users wishing to start processing at this level should access the GARF archive or obtain Level 1b products from UMARF.

3.1.4 Validation Products

Validation Products consist of summary statistical information on the reliability and quality of the Sounding Products. There are separate Validation Products for NRT and Offline Sounding Products. Validation Products include (but are not limited to):

- Analysis of observation delay (time differences between the observation and the start of dissemination of the Level 2 sounding product from the SAF to the users)
- Analysis of availability (number of Level 2 sounding products made available to users relative to the number of Level 1b occultations received by the SAF from the CGS)
- Analysis of refractivity quality (differences in Level 2 values of refractivity from refractivity synthesised from an NWP model and/or other observational data at the same location, expressed as bias and rms or standard deviation)
- Analysis of temperature, humidity and surface pressure quality (differences in Level 2 temperature and humidity profiles and surface pressure from equivalent NWP model values and/or other observational data, expressed as bias and rms or standard deviation)

These products are available in the form of:

- Summary single or tabulated numbers
- Graphical representations – e.g. histogram of delays, time series and geographical maps of temperature differences at selected levels.

Validation products are not actively disseminated, but are updated and posted on a regular basis (daily for NRT, monthly for Offline) on the GRAS SAF web site http://www.grassaf.org/.

3.1.5 Error-Covariance Products

The error covariance matrix is a data product that specifies the correlations in the observation errors between all possible pairs of vertical observation data levels. It is given as a 2-dimensional array, of size *N*x*N* , where N is the number of vertical levels in the sounding product.

There are two basic Error-Covariance Matrix Products:

- Covariance matrix for NRT Sounding Products
- Covariance matrix for Offline Sounding Products

Each matrix is provided in one or more versions reflecting potential variations with geographical areas (e.g. latitude) and with season. The 'Day 1' product is a single time-invariant, globally-applicable matrix; further matrices will be provided if and when further analysis of GRAS operational data shows their necessity. These matrices are not expected to change often (if at all) after the commissioning phase. They are included with the ROPP software package, and latest versions are also available via the GRAS SAF web site http://www.grassaf.org/

3.2 NRT and Offline Data Products

3.2.1 General

This chapter contains a detailed description of all parameters in the GRAS SAF NRT and Offline (Level 2) sounding products. Unless otherwise stated, the description for Offline data is the same as for NRT data. For format descriptions, please refer to Chapter 4. Note that all accuracies given in this chapter are target accuracies from the PRD [RD.2], i.e. not reflecting the current status of the products. The current status is described in Chapter 5.

- The GRAS SAF's primary data product is the Level 2 products processed in near-real time (NRT) – within 3 hours of observation. Since this time constraint may mean that processing is simplified, and some ancillary data may not be available in time, NRT products may not represent the optimum possible quality, although it will still meet user requirements for NRT data.

- The GRAS SAF also reprocesses the radio occultation data in Offline mode using the optimum algorithms and post-processed GNSS and LEO precise orbit determination (POD) information and including other auxiliary data, which may not have been available on the time scale of the NRT product. Offline products are available to users within 30 days of observation time.

For each parameter, the description includes the output quantities (e.g. units and ranges of values), as required in 4.2.2-1 and 4.2.2-2 in [RD.1]. Data in the form of profiles are provided as a function of height (ellipsoidal height, height above MSL/geoid, geopotential height) and pressure, or as a function of time, consistent with the user requirements. All product profiles are given in ascending (rising) order, regardless of whether the occultation was setting or rising.

The product domain is global, and from the surface to a maximum of 80 km. The height range of individual Level 2 profiles produced by the SAF critically depends on the output of the GRAS instrument and processing up to Level 1b within the CGS. The geographical and temporal coverage of the GRAS SAF products are limited only by the characteristics of the radio occultation instrument and not by the processing algorithms.

The following specifications are common to all Level 2 NRT and Offline parameters:

Delay from observation to start of delivery to users:	>95% within 3 hours (NRT) >98% within 30 days (Offline)	PRD-1-06, [RD.2]
Horizontal domain:	Global	See Annex A of the PRD [RD.2]
Horizontal sampling:	All available occultations	See Annex A of the PRD [RD.2]

The algorithms used to process the CGS Level 1b products to GRAS SAF Level 2 Sounding Products for both NRT and Offline types, can be found in [RD.6] and [RD.9].

3.2.2 Bending Angle

This parameter is a sub-set of the bending angle 'profile' as a function of impact parameter, produced by the CGS as Level 1b NRT GRAS products. Level 1b data is sampled at 1-100 m, depending on altitude. Note that although this is an Offline product, a thinned version of the EUMETSAT bending angle is included in the NRT Level 2 products.

Quantity	**Values**	**Remarks**
Units	radians (rad)	
Range	-0.0001 to 0.05 rad	
Precision	0.1 μrad	
Vertical sampling	1-100 m	Depending on altitude
Target accuracy	0.4% or 1 μrad	whichever is greater. Level 1b requirement

3.2.3 Refractivity Profile

This parameter is a profile and contains the neutral refractivity as a function of height (ellipsoidal, above MSL, and geopotential) above a given location on the Earth.

Quantity	Values	Remarks
Units	Refractivity units (N)	Neutral atmosphere
Domain	0-50 km	Surface to 1 hPa
Range	0-450 N-units	
Precision	0.1 N-units	
Vertical sampling	0.5 km	
Target accuracy	NRT: 0-5 km: 0.6%-1% 5-30 km: 0.3% 30-50 km: 0.03 N-units Offline: 0-5 km: 0.3%-0.5% 5-30 km: 0.15% 30-50 km: 0.02 N-units	

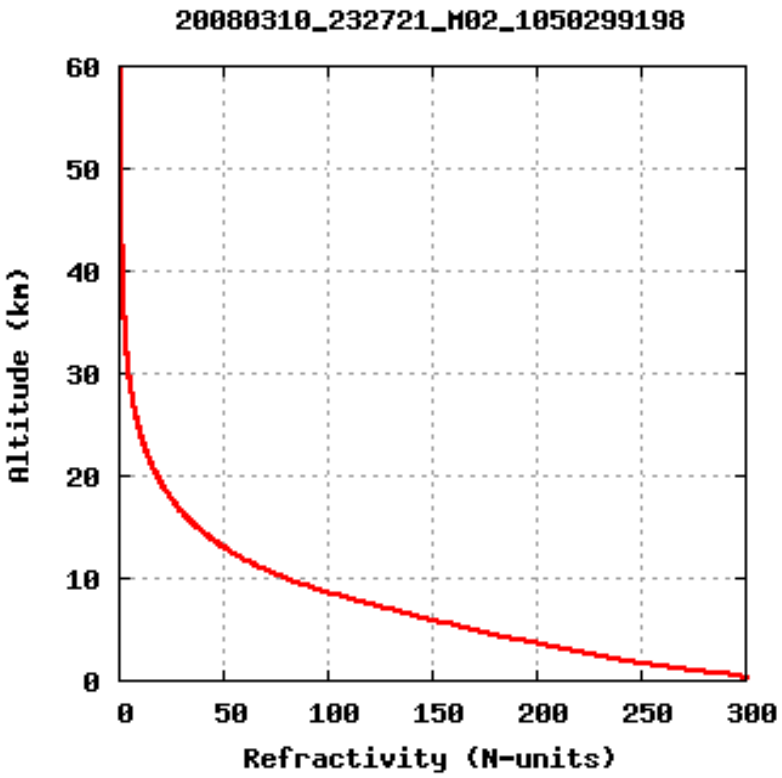

Figure 3-1 Typical GRAS refractivity profile

3.2.4 Temperature Profile

This parameter is a profile and contains the atmospheric temperature as a function of height above a given location on the Earth.

For NRT data, the RO 'retrieved' temperature profile is derived from the refractivity profile using a 1DVAR algorithm. This uses an ECMWF NWP model short-period forecast temperature and humidity profile plus surface pressure as a first-guess background. This procedure overcomes the 'water vapour ambiguity' and takes full account of the observation and NWP errors in an optimal way. The forecast used is always the most recent one available, usually a six-hour forecast.

Quantity	Values		Remarks
Units	Kelvin (K)		
Domain	0–50 km		Surface to 1 hPa
Range	180–350 K		
Precision	0.1 K		
Vertical sampling	0.5 km		depends on background pressure levels
Target accuracy	NRT	Offline	'Dry' temperatures are unlikely to meet accuracy requirements at the lowest levels except in regions of very low humidity.
0–5 km	2–3 K	1-2 K	
5–30 km	1 K	0.5 K	
30–40 km	1–5 K	0.5–3 K	
40–50 km	5–10 K	3–5K	

3.2.5 Humidity Profile

This parameter is a profile and contains the atmospheric water vapour content, as specific humidity, as a function of height above a given location on the Earth. Both retrieved and any background (first-guess) humidity profiles are given in the sounding products.

The RO humidity profile is derived from the refractivity profile using a 1DVAR algorithm. This uses an ECMWF NWP model short-period forecast temperature and specific humidity profile plus surface pressure as a first-guess background. This procedure overcomes the 'water vapour ambiguity' and takes full account of the observation and NWP errors in an optimal way. The forecast used is always the most recent one available, usually a six-hour forecast.

Quantity	Values	Remarks
Units	$kg.kg^{-1}$	Specific humidity
Domain	0–15 km	Surface to 100 hPa
Range	0–50 $g.kg^{-1}$	
Precision	0.001 $g.kg^{-1}$	

Vertical sampling	0.5 km	depends on background pressure levels
Target accuracy	10% or 0.2 $g.kg^{-1}$ (NRT) 5% or 0.1 $g.kg^{-1}$ (Offline)	whichever is greater

3.2.6 Pressure Profile

This parameter is a profile and contains the atmospheric pressure as a function of height above a given location on the Earth, for the same set of heights as the derived temperature and humidity values. Profiles are given in order of decreasing pressure (ascending height), regardless of whether the occultation was setting (descending profile) or rising (ascending profile) with time.

Quantity	**Values**	**Remarks**
Units	hectoPascals (hPa)	
Domain	0–50km	Surface to 1 hPa
Range	0.01–1100 hPa	
Precision	0.001 hPa	
Vertical sampling	0.5 km	depends on background pressure levels
Target accuracy	0.2% or 2 hPa (NRT) 0.1% or 1hPa (Offline)	whichever is greater

3.2.7 Surface Pressure

The surface pressure is derived from the refractivity profile using a 1DVAR algorithm. This uses an NWP model short-period forecast temperature and humidity profile plus surface pressure as a first-guess background.

Quantity	**Values**	**Remarks**
Units	HectoPascals (hPa)	
Domain	Surface (mean sea level)	Horizontal location nominally at the location of the lowest point in the refractivity profile.
Range	900–1100 hPa	
Precision	0.1 hPa	
Vertical sampling	N/A	
Accuracy	2 hPa (NRT) 1 hPa (Offline)	

3.2.8 Heights

This parameter is the vertical coordinate for the refractivity and of the pressure levels for the retrieved temperature and humidity profiles. Height values are derived from the Level 1b impact parameter and local radius of curvature at the location of the occultation and the refractivity profile. The heights are provided in several reference frames.

Profiles are given in order of increasing height, regardless of whether the occultation was setting (descending profile) or rising (ascending profile) in time.

Quantity	Values	Remarks
Units	metres (m) metres (m) geopotential metres (gpm)	(a) Ellipsoidal heights (referenced to WGS-84) (b) Heights above MSL (referenced to geoid EGM96) (c) Geopotential heights (geometric transform of (b))
Domain	0–50 km	Surface to 1 hPa
Range	0–50,000 m	
Precision	1 m	
Vertical sampling	0.5 km	
Accuracy	n/a	Heights are taken to be the independent coordinate.

3.2.9 Location

This parameter is the horizontal coordinate for the refractivity, temperature and humidity profiles, surface pressure and local radius of curvature. A pair of latitude and longitude value is given for each point in the profile, as the tangent point drift can be more than 100 km during an occultation. The horizontal location of the surface pressure parameter and radius of curvature is taken from the EUMETSAT Level 1b file.

Quantity	Values	Remarks
Units	degrees (°) of latitude and longitude	Geodetic latitude
Range	Latitude: ±90° Longitude: ±180°	Positive in N. Hemisphere positive east of Greenwich
Precision	0.001°	~0.1 km
Vertical sampling	0.5 km	
Accuracy	0.01°	~1 km

3.2.10 Date and Time, Time-Tag

These parameters are the time coordinates for the refractivity, temperature and humidity profiles.

The absolute date/time is given once per occultation, and indicates the start of the occultation (first data point). The time-tag is given for each point in the profile as an offset from the start time. Since profiles are always given in an ascending height order, the time-tag for setting (descending profiles) is in decreasing time order. Time-tags always have positive values.

Quantity	Values	Remarks
Units	Year, Month, Day, Hour, Minute, Second, Millisecond	*Absolute:* date & time at start of profile in UTC
	Milliseconds (ms)	*Time-tag*: offset from start of profile
Range	2000–2049y, 1–12m, 1–31d, 0–23h, 0–59mn, 0–59.999s	00:00 1-Jan-2000 to 23:59 31-Dec-2049
	0–100,000 ms	Up to 100 s duration (nominal max. 60 s)
Precision	1 ms	
Vertical sampling	5 Hz	nominal time equivalent for time-tag
Accuracy	1 ms	

3.2.11 Quality Information

The GRAS SAF Sounding Products contain the following quality information:

- Boolean flags showing the results of quality tests ('Product Confidence Data'). Flags include (but are not limited to):
  - ✓ summary status (0=nominal quality, 1=non-nominal – check error flags)
  - ✓ product type (0=NRT, 1=Offline)
  - ✓ occultation type (0=setting, 1=rising)
  - ✓ results of various error and other threshold tests (0=pass, 1=fail). These results are independent, e.g. a profile with a flag indicating nominal processing of refractivity can have a flag indicating non-nominal bending angle processing
- A quality indicator value derived from a combination of other values; e.g. the 1DVAR residual fit value or a 'percentage confidence' value (0=bad, 100=good)

- Estimated RMS error values for all derived parameters (refractivity, pressure, temperature, humidity profiles and surface pressure).
- Trace-back to information on the processing algorithms used (indicating nominal, back-propagation and/or canonical transform, 1DVAR, etc)

3.3 Supporting Data

Supporting data include Level 1b parameters produced by the EPS CGS (for NRT) or by the GRAS SAF (for Offline), though they may have been post-processed within the Level 2 processor to a form more suitable for most end-users (see [RD.2]). Users requiring the unprocessed support data should access the Level 1b data directly.

3.3.1 Satellite State Vectors (POD)

This parameter is a sub-set of the LEO and GNSS satellite state vectors (POD locations and velocities), as a time-series, produced by the CGS as Level 1b GRAS products. In order to minimise data volumes, POD data may instead be given once per occultation together with a set of polynomial coefficients which allow the POD reconstruction to sufficient accuracy for any arbitrary time during the occultation - see Section 6.3.1.1 in [RD.4]. The feasibility of this approach is following tests of the generation of the state vector interpolation Lengendre polynomials by EUMETSAT.

Positions

Quantity	Values	Remarks
Units	metres (m)	*X,Y,Z* ECF frame
Range	±30,000 km (GNSS) ±10,000 km (LEO)	
Precision	0.01 m	
Vertical sampling	5 Hz	
Accuracy	0.2 m (NRT) 0.1 m (Offline)	Level 1b requirement

Velocities

Quantity	Values	Remarks
Units	metres per second ($m.s^{-1}$)	*X,Y,Z* ECI frame
Range	± 5 $km.s^{-1}$ (GNSS) ± 10 $km.s^{-1}$ (LEO)	
Precision	0.01 x 10^{-3} $m.s^{-1}$	
Vertical sampling	5 Hz	

Accuracy	0.2×10^{-3} m.s^{-1} (NRT) 0.1×10^{-3} m.s^{-1} (Offline)	Level 1b requirement

The tables for POD are based on requirements for CGS Level 1b data and given as radial position w.r.t the Earth and absolute velocities. The specification of two coordinate systems reflects the use of these data.

- Velocity POD is required for GNSS-LEO Phase and Doppler determination, which is independent of Earth-based coordinates, so the ECI coordinate system is most appropriate.
- Position POD is used for e.g. GNSS-LEO ray-tracing using Earth-centred coordinates, where the ECF system is most appropriate.

3.3.2 Local Radius of Curvature, Azimuth, and Geoid Height

This parameter is taken from the Level 1b product. Time and location of the local radius of curvature is specified. In addition, the local centre of curvature offset from the Earth's centre is given, together with the azimuth angle of the plane of occultation and the local geoid undulation.

Radius of Curvature

Quantity	Values	Remarks
Units	metres (m)	RoC value at one specified lat/lon representative for the entire profile
Range	6250–6450 km	
Precision	<1 m	
Vertical sampling	N/a	
Accuracy	<5 m	

Radius of Curvature Offset

Quantity	Values	Remarks
Units	Metres (m)	RoC offset as (X,Y,Z) ECF coordinates
Range	±10 km in each dimension	
Precision	<1 m	
Vertical sampling	N/a	
Accuracy	<1 m	

Azimuth Angle

Quantity	Values	Remarks
Units	Degrees wrt True North (degT), positive clockwise	Azimuth angle of GNSS to LEO line of sight

Range	0-360	
Precision	0.1 deg	
Vertical sampling	netCDF files: 50 Hz BUFR files: One interpolated value for each of the 247 model levels, cf. [RD.5]	
Accuracy	0.5 deg	

Geoid Height

Quantity	**Values**	**Remarks**
Units	Metres (m)	Geoid height (difference between local geoid (EGM96) and ellipsoid (WGS-84))
Range	±150 m	
Precision	0.1 m	
Vertical sampling	N/a	
Accuracy	1 m	

3.3.3 Background Profiles from ECMWF

The GRAS SAF Sounding Products contain meta-data on the background (first-guess) profiles of temperatures and humidities, which are used to constrain the retrievals. For both NRT and Offline data this is from an NWP model (ECMWF) forecast.
Background meta-information include: source, validity date & time, forecast period. Background data are not included, except in the NRT BUFR products.
The extracted co-located profiles from the background data are made available for research purposes on GARF the day after the measurement.

3.3.4 Other Data

The GRAS SAF Sounding Products also contain the following meta-data:

- Identifier of receiving LEO satellite (e.g. Metop-A)
- Identifier of transmitting GNSS satellite (e.g. GPS-03)
- Identifiers for POD type and source (e.g. Predicted & EPS/CGS)
- Timestamps of start of occultation and of processing

Data products also contain estimated *a priori* errors for all derived parameters, such as refractivity, pressure, temperature and humidity.

Note that the GRAS SAF does not include 'raw' parameters such as signal-to-noise ratio, excess phase, Doppler or uncorrected bending angles in its Level 2 NRT products. Users wishing to start processing at this level should access the GARF archive or obtain Level 1b products from UMARF.

3.4 Validation Products

Validation Products consist of summary statistical information on the reliability and quality of the Sounding Products. There are separate Validation Products for NRT and Offline Sounding Products. Specific requirements can be found in the Product Requirements Document (PRD) [RD.2].

Validation Products include:

- Analysis of observation delay (time differences between the observation and the start of dissemination of the Level 2 sounding product to users from the SAF)
- Analysis of availability (number of Level 2 sounding products made available to users relative to the number of Level 1b occultations received by the SAF from the CGS)
- Analysis of refractivity quality (differences in Level 2 values of refractivity from refractivity synthesised from an NWP model and/or other observational data at the same location, expressed as bias and rms or standard deviation)
- Analysis of temperature, humidity and surface pressure quality (differences in Level 2 temperature and humidity profiles and surface pressure from equivalent NWP model values and/or other observational data, expressed as bias and rms or standard deviation)

Validation is done globally and on the full vertical domain of the product, limited only by the availability of the comparison data.

The major source of comparison data is operational NWP global and regional models. Because of the random time of RO data, comparisons use short-period NWP forecasts in order to minimise the time differences to not more than 3 hours for NRT and Offline. The NWP fields at the appropriate time are bi-linearly interpolated in the horizontal to the location of the RO data. Two different NWP models may be used so that temporal differences – such as drifts or jumps in the bias times series – can be attributed to model or RO problems.

If there are sufficient quantities of other observational data with the necessary quality and other characteristics collocating with the RO data at the same times and locations (within defined limits, like 100 km and 3 hours) – such as radiosondes, ground-based remote sensing and passive satellite sounding (including other RO missions) – then the Validation Products for Offline Sounding Products use these sources too.

Validation Products show the statistics for:

- Global area and whole vertical domain ('bottom line' statistics)
- Standard vertical levels
- Latitude bands (NH, Tropics, SH)
- Surface (Land/Sea)
- Regional zones (e.g. 5°x5° latitude/longitude boxes) for mapping
- Occultation type (Rising/Setting)
- Daily for NRT data
- Monthly for NRT and Offline data

alone or in selected combinations.

These products are available to users in the form of

- Summaries in the form of single or tabulated sets of numbers.
- Graphical representations – for example histogram of delays, time-series and geographical maps of RMS temperature differences at selected levels.

Validation products are not actively disseminated, but are automatically updated and posted on a regular basis on the GRAS SAF web site. The URL for the NRT monitoring is:
http://monitoring.grassaf.org/

The GRAS SAF also generates a Collocation Product for *internal use only*. This product contains the Level 2 Sounding Product and the collocating NWP profile and any other validating observations. This product is the input to the statistical analysis, which outputs the Validation Products on a regular basis and Error-Covariance Products when appropriate.

By definition, during the Metop Commissioning Phase, the non-operational GRAS RO data were not assimilated operationally. Therefore ECMWF analyses, free of any RO information, provided the best validation data source. During the routine Operational Phase, where operational GRAS RO data will be assimilated at ECMWF, it will be normal to validate against 'background' – i.e. a short-term ECMWF forecast (typically 6 hours). Although the RO information will still have some influence on the forecast, this is not as direct as with an analysis, which has used the same RO information at the same time and place, and thus naturally is not appropriate for independent validation. Use of a short-term forecast for validation is common for all data types, including satellite data, and this methodology also forms the basis for the NWP SAF satellite monitoring systems.

3.5 Error Covariance Matrices

The error covariance matrix is a data product that specifies the correlations in the observation errors between all possible pairs of vertical observation data levels. It is given as a 2-dimensional array, of size NxN , where N is the number of vertical levels in the sounding product.

There are two basic Error-Covariance Matrix Products:

- Covariance matrix for NRT Sounding Products
- Covariance matrix for Offline Sounding Products

Each matrix is provided in one or more versions reflecting potential variations with geographical areas (e.g. latitude) and with season. These are not actively disseminated, but are available for download from the GRAS SAF web site. These files are expected to change only infrequently after the Metop commissioning period, as the statistics become more stable, and are included with the ROPP software package. Latest versions are also available via the GRAS SAF web site.

The Error-Covariance Matrices have the form:

$$\begin{pmatrix} E_{11} & E_{12} & E_{13} & E_{14} & \cdots \\ E_{21} & E_{22} & E_{23} & E_{24} & \cdots \\ E_{31} & E_{32} & E_{33} & E_{34} & \cdots \\ E_{41} & E_{42} & E_{43} & E_{44} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

where the E_{ij} values represent the error co-variances between levels i and j for the off-diagonals ($i \neq j$) and the diagonal values ($i = j$) are the error variances at each level.

4. FORMAT DESCRIPTIONS

4.1 Introduction

The GRAS SAF products come in two different formats, BUFR and netCDF, cf. [RD.11].

4.2 BUFR Format

The BUFR format is described in [RD.5]

4.3 netCDF Format

The internal data format for the GRAS SAF system is netCDF. Offline end products and internal products are thus in the same format, i.e. the delivered offline products have the same structure as the internal products or a subset of it.

4.3.1 Structure

The netCDF files in the GRAS SAF system have the following structure:

- A common set of attributes for all kinds of data, containing general information about the data
- A dataset for the parameter values
- Additional datasets for metadata (e.g. quality flags and information related to UMARF).

4.3.2 File format

The GRAS SAF products follow the ROPP data format structure (see [RD.8]). An overview of the structure of the netCDF product files is depicted in Figure 4-1. In the ROPP format all parts except the header is optional.

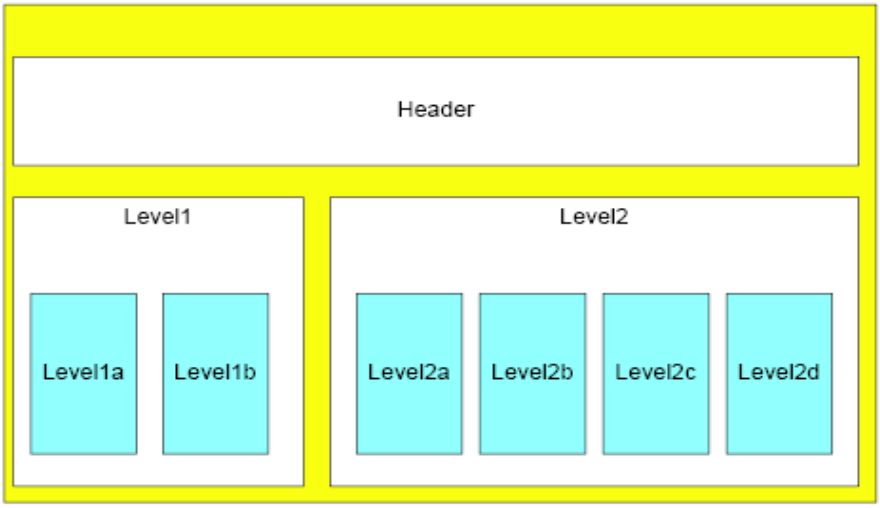

Figure 4-1 Overview of the ROPP netCDF file structure

Detailed information of each parameter available in the netCDF product files can be found in Appendix A, B, and C, taken from [RD.8].

4.3.3 File Names

The file name of the GRAS SAF input and output files is a string of up to 255 characters made of 6 fields separated by underscores with the following structure:

<TYPE><DATETIME>_<MISSION>_<OCCID>_<MODE><VERSION>_<FREE>.<EXTENSION>

Where:

- type is one of "atm", "bfr", "bgr", "occ", or "wet"
- DATETIME is the start date and time of the observation as YYYYMMDD_HHMMSS
- MISSION is the EPS name of the observing satellite
- OCCID is the occultation id (EPS format which includes id of occulting satellite)
- MODE is the processing mode: one of "N", "P", "R", "T", "V"
- VERSION is a four-digit code which maps to the software versions used for the processing
- FREE is a free field (4X)
- EXTENSION is
  - nc for NetCDF
  - bin for BUFR

An example of a filename is this netCDF file:
atm20080515_112209_M02_1080305747_N0002_XXXX.nc

Type	ROPP levels	Format	Description
bfr	-	BUFR	This file type is based on an internal "dis" file. The BUFR file holds a thinned set of the bending angles and refractivity from the "dis" file. Only the first position and velocity sample is contained in this file.
bgr	2d	NetCDF	This file type contains the model background used for the 1DVar retrieval
occ	1a	NetCDF	This file contains a "traditional" product: Signal to noise for the phases, the excess phases and the GNSS/LEO positions and velocities as function of time
atm	1b 2a	NetCDF	This file contains latitude, longitudes impact parameters, bending angles and refractivity, "dry" pressure and temperatures.
wet	2b 2c 2d	NetCDF	This file contains output from the 1DVar i.e. temperature, pressure and humidity

Figure 4-2 Description of GRAS SAF files types, all file types contain a "header" – a set of ancillary data useful for processing or describing each occultation. For detailed information on these parameters, see [RD.8].

5. DATA QUALITY

This chapter contains descriptions of the operational or pre-operational data products. Currently only the GRAS SAF NRT refractivity product is produced. A short description of the validation of the refractivity profiles (GRM-01) with respect to co-located ECMWF profiles is given in this chapter (For the full validation see [RD.9]).

5.1 Statistics of NRT data

Validation and statistics in this section are based on PPF version 2.12 operational data provided by EUMETSAT to DMI. The results shown are obtained using the GRAS SAF operational inversion software referred to as 'Invert'. The retrieved refractivity profiles (before thinning) are compared to the corresponding ECMWF profiles (forward modeled to refractivity as a function of altitude) by interpolating both to a common vertical grid.

Statistics are separated into setting and rising occultations, as well as high latitudes (above 60°N and below 60°S), mid latitudes (30–60°S and 30–60°N), and low latitudes (between 30°S and 30°N).
Figure 5-1 shows the results from the NRT monitoring for the month of January, 2009. Each of the six panels are discussed below in terms of biases and standard deviations relative to the ECMWF forecasts.

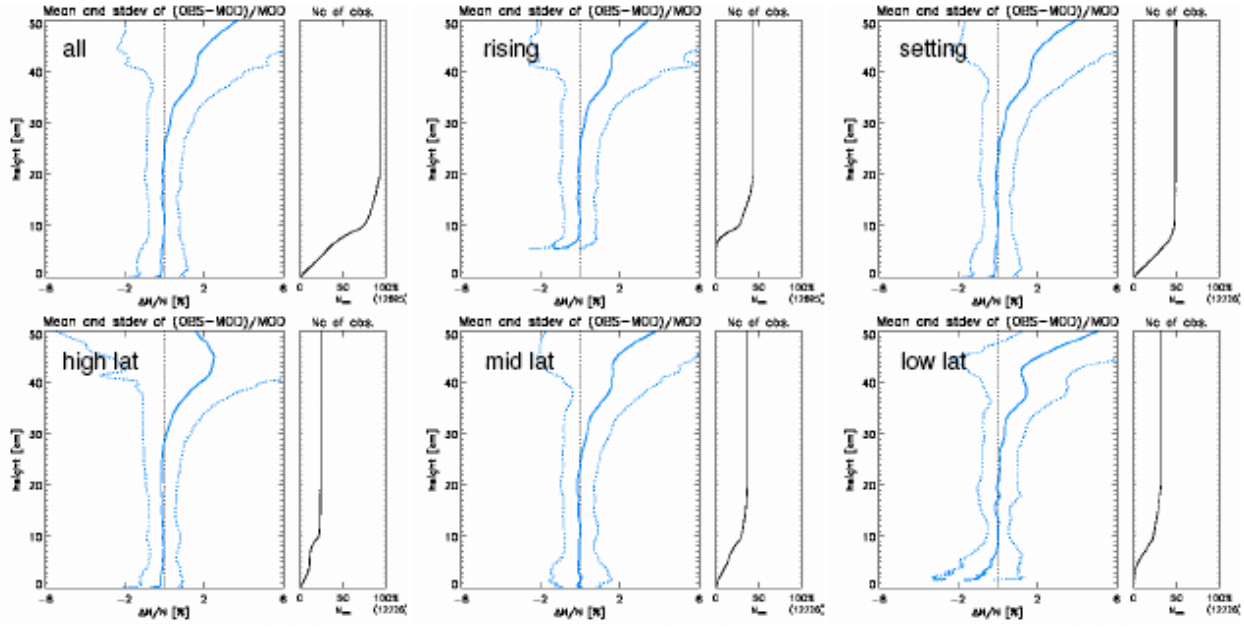

Figure 5-1 Refractivity results for the month of January, 2009, compared to ECMWF forecasts: The upper panels show all occultations (left), rising (mid), and setting (right). The lower panels show the results for high latitudes (left), mid latitudes (mid), and low latitudes (right). Solid blue lines indicate the bias, and dashed lines indicate the 1-σ standard deviation on both sides of the bias. The number of observations as a function of altitude included in the various statistics are given to the right of the respective statistic plot.

All occultations:

• **bias:** Below 8 km there is a small negative bias. Data in this region may be affected by atmospheric multipath. Currently, the bending angle is retrieved using geometrical optics. In the range 8 – 25 km the overall bias is small but slightly negative (less than 0.1%) around 15 and 20 km. Above 30 km there is an increasing positive bias exceeding 1.5% at 40 km and reaching about 4% at 50 km. Part of the bias above 30 km is believed to be associated with a bias in the ECMWF fields. The increasing bias above 45 km is not fully understood, but may be a result of the processing at high altitudes which includes the use of climatology. It is possible that the climatology also contributes to the bias below 45 km with exponentially decreasing magnitude at lower altitudes. It should be noted that the influence from the climatology is reduced in the processing by multiplying the climatology profile with a regression factor that is based on the difference between the climatology and the data at high altitudes.

• **std.dev.:** Below 8 km the standard deviation is varying, but less than 2%. The standard deviation is 0.8 – 1.0% in the range 8 – 25 km, and increases above to reach about 2.5% at 40 km and exceeds 5% at 50 km.

Rising occultations:
• **bias:** Below 8 km there is an increasing bias downward reaching about 1% at 6 km. Otherwise the bias is similar to the bias for all occultations.
• **std.dev.:** The standard deviation is similar to the standard deviation for all occultations in the range above ~10 km.

Setting occultations:
• **bias:** The bias is similar to the bias for all occultations.
• **std.dev.:** The standard deviation is similar to the standard deviation for all occultations.

High latitudes:
• **bias:** The bias is similar to the bias for all occultations, but slightly more negative in most of the range below 25 km. Above 30 km a positive bias emerges and becomes about 2% between 40 km and 50 km. It should be noted that a sudden stratospheric warming occurred at high latitudes in mid-January. The influence of the sudden stratospheric warming on the processing and the refractivity bias at high altitudes is not fully understood.
• **std.dev.:** The standard deviation is less than 1% in most of the 8 – 25 km range, and increases above to reach about 8% at 50 km.

Mid latitudes:
• **bias:** The bias is similar to the bias for all occultations, except below 8 km.
• **std.dev.:** The standard deviation is similar to the standard deviation for all occultations, except below 8 km.

Low latitudes:
• **bias:** Only a few profiles reach below 8 km at low latitudes, but enough to conclude that there is a negative bias growing downward to reach about 1% at 3 km and almost 2% at 1 km. A negative bias of maximum 0.2% is seen around 16 km, and a positive bias of maximum 0.2% between 20 and 25 km. Above 30 km the positive bias increases to become about 1.5% around 40 km and about 5% at 50 km.
• **std.dev.:** The standard deviation is smallest around 12 km (about 0.6%) and about 1% otherwise in the interval between 8 and 30 km. Above 30 km it increases to about 2% at 40 km and 4% at 50 km.

5.2 Compliance with requirements

The requirements for the GRAS SAF products are given in the Products Requirements Document (PRD) [RD.2]. Figure 5-2 shows that the standard deviation of the NRT refractivity product is close to the target requirement below 25 km and is within the threshold at all altitudes. It should be noted that the NRT comparison is done against ECMWF forecasts. Comparison against ECMWF analyses has shown to reduce the standard deviation with about 30%.

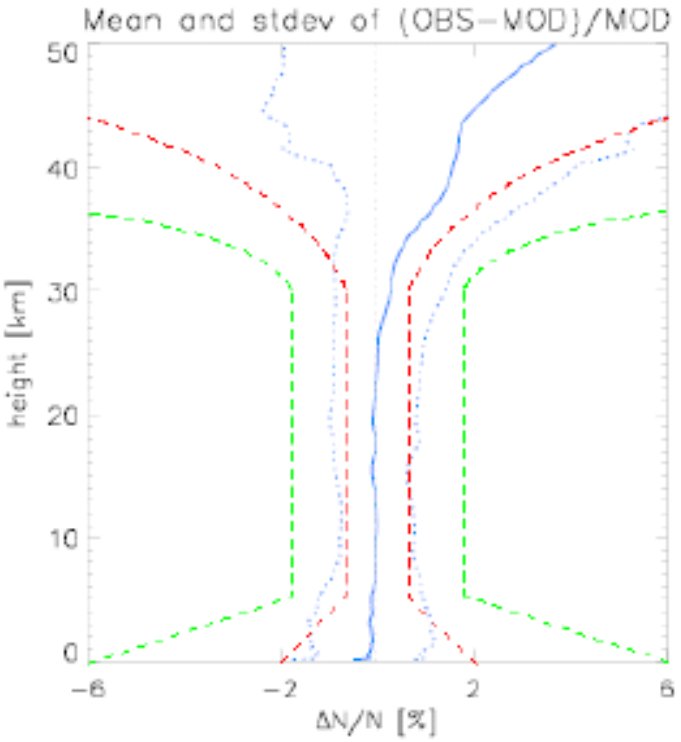

Figure 5-2 Same as the first panel in Figure 5.1, but with dashed lines superimposed indicating the target (red) and threshold (green) accuracies for NRT refractivity according to the PRD [RD.2].

6. DISSEMINATION METHODS

Products are disseminated/available through different media (cf. Figure 6-1):

- GTS/RMDCN network;
- Distribution to users (via FTP or DVDs);

The products that are distributed by each media are identified in Table 1-1.

For access to these data and also archived data, it is necessary to sign up as a registered user with the GRAS SAF. This is done at the web page of the GRAS SAF Archive and Retrieval Facility (GARF): http://garf.grassaf.org/, where the online registration form can be found.

6.1 NRT Distribution

The near real-time distribution of GRAS SAF products to the National Meteorological Services (NMSs) of EUMETSAT Member States and Co-operating States is through the GTS/Regional Meteorological Data Communication Network (RMDCN). This requires the GRAS SAF products to be compliant with the World Meteorological Organisation standard binary format, the BUFR format. See [RD.5] for the BUFR format descriptions.
The NRT data will be disseminated via EUMETCast as well. This data will be formatted in the netCDF format, see [RD.8]. The dissemination will be done by uploading data to the EUMETCast dissemination ftp server.
All NRT (BUFR and netCDF) files will also be available from the archive for non-real time purposes.

6.2 Offline Distribution

The distribution of Offline products is via FTP and/or DVDs.
FTP data delivery is serviced over the internet, not over specialized, guaranteed performance operational lines. The users are given several options as for the reception channel for the data. Unlike NRT products, which are actively broadcasted, offline products are passively made available at the archive for ftp retrieval by the user, or mailed by request on DVDs.

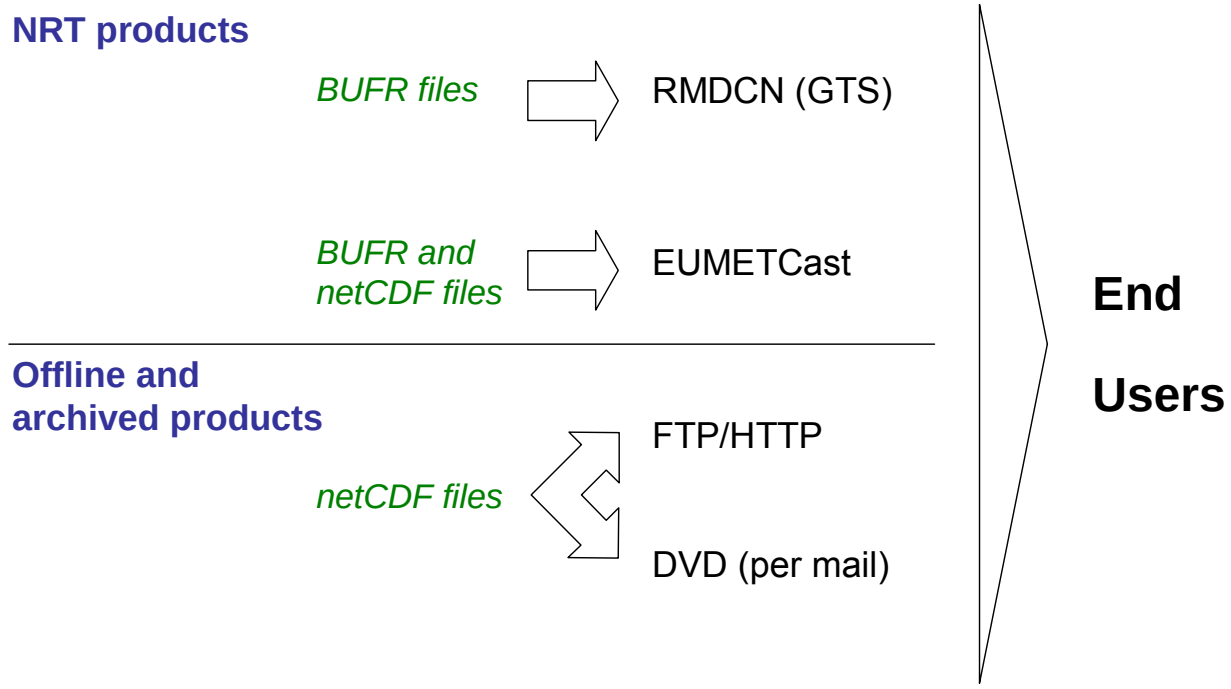

Figure 6-1 Overview of file formats and dissemination types

7. REFERENCES

The following list contains documents which are referenced in this document.

[RD.1] EPS End-User Requirements Document (EURD), Ref. EPS/MIS/REQ/93001 (also Annex I to EUM/C/36/97/DOC/54)

[RD.2] GRAS SAF Product Requirements Document. Ref: SAF/GRAS/METO/MGT/PRD/001

[RD.3] GRAS Level 1 Product Format Specification. Ref. EPS/MIS/SPE/97234

[RD.4] GRAS Level 1 Product Generation Specification. Ref. EPS/SYS/SPE/990010

[RD.5] GRAS Meteorology SAF WMO FM94 (BUFR) Specification for GRAS SAF Processed Radio Occultation Data
Ref: SAF/GRAS/METO/FMT/BUFR/001

[RD.6] GRAS SAF Science Plan. Ref. SAF/GRAS/DMI/ALG/SP/001

[RD.7] GRAS SAF CT2 Processing Code: Operational Processing of CHAMP and COSMIC data: Mathematical Methods, Data Filtering and Quality Control, version 1.1. Ref: SAF/GRAS/DMI/ALG/CT2/002

[RD.8] The Radio Occultation Processing Package (ROPP) User Guide.
Ref: SAF/GRAS/METO/UG/ROPP/002

[RD.9] GRAS SAF Validation Report: GRM-01: Near Real Time Refractivity Profile (NRP). Ref: SAF/GRAS/DMI/RQ/REP/001

[RD.10] Mikhail E. Gorbunov: Ionospheric correction and statistical optimization of radio occultation data. Radio Science, vol. 37, no. 5, 1084, doi:10.1029/2000RS002370, 2002

[RD.11] GRAS SAF Product Output Format Document.
Ref: SAF/GRAS/DMI/FMT/POF/001

Appendix A. NetCDF Header Format

From the ROPP User Guide [RD.8, version 2.0]:

Identifiers

Structure element	Parameter	Description	Range	Units
...%leo_id	LEO ID	LEO ID code (4 characters). The following ID codes are currently envisaged: META = MetOp–A METB = MetOp–B METC = MetOp–C COnn = COSMIC–*nn* CHMP = CHAMP GRAA = GRACE–A GRAB = GRACE–B TSRX = TerraSAR-X SACC = SAC–C GPSM = GPS/MET OERS = Oerstedt EQUA = EQUARS SUNS = SunSat = Other LEO codes may be defined in the future.	[A-Z,0-9]	
...%gns_id	GNSS ID	Letter identification (4 characters) and PRN of the occulting GNSS satellite ('Innn')	[A-Z,0-9]	
...%stn_id	Station ID	Ground station ID used for differencing (if any; IGS-style 4–character code)	[A-Z,0-9]	
...%occ_id	Occultation ID	Unique occultation ID; see section 2.3.6	[A-Z,0-9]	

Processing

Structure element	Parameter	Description	Range	Units
...%FmtVersion	Format version	Exact text	ROPP V1.0	
...%processing_centre	Processing Centre	Text indicating processing centre (40 characters)	[A-Z,0-9]	
...%software_version	Software Version	String indicating the version of the processing software	[A-Z,0-9]	
...%pod_method	POD algorithm	Text strings (40 characters) indicating algorithms used for deriving precise orbit, excess phase / amplitude, bending angle, refractivity and meteorological data	[A-Z,0-9]	
...%phase_method	Level 1 a algorithm		[A-Z,0-9]	
...%bangle_method	Level 1 b algorithm		[A-Z,0-9]	
...%refrac_method	Level 2 a algorithm		[A-Z,0-9]	
...%meteo_method	Level 2 b, c algorithm		[A-Z,0-9]	
...%thin_method	Profile thinning algorithm and version ID			

Background meta data

Structure element	Parameter	Description	Range	Units
...%bg%source	Background source	Source of meteorological or atmospheric data used as background ("ancillary") data	[A-Z,0-9]	
...%bg%year ...%bg%month ...%bg%day ...%bg%hour ...%bg%minute	Verification time	Verification time of background data (if applicable)	1995 01 01 00 00 — 2099 12 31 23 59	
...%bg%fcperiod	F/C period	Forecast period of background data (if applicable)	0 – 24	hours

Time stamps

Structure element	Parameter	Description	Range	Units
...%DTocc%year ...%DTocc%month ...%DTocc%day ...%DTocc%hour ...%DTocc%minute ...%DTocc%second ...%DTocc%msec	Date / time of occultation	Time stamp at start of occultation (UTC)	1995 01 01 00 00 00 000 — 2099 12 31 23 59 59 999	
...%DTpro%year ...%DTpro%month ...%DTpro%day ...%DTpro%hour ...%DTpro%minute ...%DTpro%second ...%DTpro%msec	Date / time of processing	Time stamp of processing (UTC)	1995 01 01 00 00 00 000 — 2099 12 31 23 59 59 999	

Georeferencing

Structure element	Parameter	Description	Range	Units
...%GEOref%time_offset	Time since start	Time since start of occultation to the time when georeferencing data and radius of curvature are determined.	0 – 239.999	s
...%GEOref%lat	Latitude	Position of tangent point as used for georeferencing	-90 ... 90	deg
...%GEOref%lon	Longitude		-180 ... 180	deg
...%GEOref%roc	Radius of curvature	Radius of curvature value	$6.2 - 6.6 \times 10^6$	m
...%GEOref%r_coc	Centre of curvature	Centre of curvature coordinates (ECF; X, Y, Z)	±10000	m
...%GEOref%azimuth	Line of sight	GNSS to LEO azimuth direction w.r.t. true North	0 – 359.9	deg_T
...%GEOref%undulation	Geoid undulation	Deviation of geoid (EGM–96) from the ellipsoid (WGS–84)[a]	±150	m

Quality

Structure element	Parameter	Description	Range	Units
...%PCD	Product confidence	Product confidence data (see Section 2.3.5)		bit flags
...%overall_qual	Data quality	Overall summary data quality	0 – 100	%

[a] If a height h_G is expressed with respect to the EGM-96 geoid, the height h_E with respect to the WGS-84 ellipsoid is given by $h_E = h_G + U$ where U is the undulation.

Bit	Variable	Description	Meaning if	
			unset (0)	set (1)
1	PCD_summary	Quality	nominal	non–nominal
2	PCD_offline	Product type	NRT	off line
3	PCD_rising	Occultation type	setting	rising
4	PCD_phase	Excess phase processing	nominal	non–nominal
5	PCD_bangle	Bending angle processing	nominal	non–nominal
6	PCD_refrac	Refractivity processing	nominal	non–nominal
7	PCD_met	Meteorological processing	nominal	non–nominal
8	PCD_open_loop	Open Loop	not used	used
9	PCD_reflection	Surface reflections detected	no	yes
10	PCD_l2_signal	L2P or L2C GPS signal used	L2P	L2C
11	PCD_reserved_11	Reserved		
12	PCD_reserved_12	Reserved		
13	PCD_reserved_13	Reserved		
14	PCD_bg	Background profile	nominal	non–nominal
15	PCD_occultation	Profile type	observed	background
16	PCD_missing	PCD missing; bits 1–15...	valid	invalid

Product Confidence Data definition (the %PCD variable in the "Quality"-section above). PCD_nominal is a summary bit which is set if any of bits 4, 5, 6, 7 or 14 is set.

Appendix B. Level 1 Data NetCDF Formats

From the ROPP User Guide [RD.8, version 2.0]:

Level 1a

Structure element	Parameter	Description	Range	Units
...%Lev1a%dtime	Time since start	Time offset from time in header	0 – 239.999	s
...%Lev1a%snr_L1ca	Signal to noise ratio L1 (ca–code)	Relative signal amplitude for L1 (ca–code)	0 – 2000	V/V
...%Lev1a%snr_L1p	Signal to noise ratio L1 (p–code)	Relative signal amplitude for L1 (p–code)	0 – 2000	V/V
...%Lev1a%snr_L2p	Signal to noise ratio L2 (p–code)	Relative signal amplitude for L2 (p–code)	0 – 2000	V/V
...%Lev1a%phase_L1	Excess phase L1	L1 phase corrected for geometry	±10000	m
...%Lev1a%phase_L2	Excess phase L2	L2 phase corrected for geometry	±10000	m
...%Lev1a%r_gns	Transmitter position	Earth centred Earth fixed[a] phase centre (X, Y, Z)[b]	±43000000	m
...%Lev1a%v_gns	Transmitter velocity	Earth centred inertial[a] phase centre (X, Y, Z)[b]	±10000	m/s
...%Lev1a%r_leo	Receiver position	Earth centred earth fixed[a] phase centre (X, Y, Z)[b]	±10000000	m
...%Lev1a%v_leo	Receiver velocity	Earth centred inertial[a] phase centre (X, Y, Z)[b]	±10000	m/s
...%Lev1a%phase_qual	Quality	Percentage confidence value	0 – 100	%

[a] Using the Earth Centred Fixed (ECF) and Earth Centred Inertial (ECI) reference frames for satellite positions and velocities, respectively, are the *default* settings; these can be changed, e.g. to use ECF for both positions and velocities.
[b] Position and velocity variables are 3–dimensional arrays with dimension `(/n,3/)` in Fortran.

Level 1b

Structure element	Parameter	Description	Range	Units
...%Lev1b%lat_tp	Latitude	Longitude and latitude w.r.t. the WGS 84 ellipsoid of	±90	deg
...%Lev1b%lon_tp	Longitude	the tangential point of the generic bending angle profile	±180	deg
...%Lev1b%azimuth_tp	Azimuth	GNSS to LEO azimuth w.r.t. true North at tangent point	0 – 359.9	deg_T
...%Lev1b%impact_L1	Impact parameter (L1)	Impact parameter derived from L1 signal	$6.2 \times 10^6 - 6.6 \times 10^6$	m
...%Lev1b%impact_L2	Impact parameter (L2)	Impact parameter derived from L2	$6.2 \times 10^6 - 6.6 \times 10^6$	m
...%Lev1b%impact	Impact parameter	Impact parameter (generic)	$6.2 \times 10^6 - 6.6 \times 10^6$	m
...%Lev1b%impact_Opt	Impact parameter (Opt)	Impact parameter for optimised Bending Angles	$6.2 \times 10^6 - 6.6 \times 10^6$	m
...%Lev1b%bangle_L1	Bending angle (L1)	Bending angle derived from L1	−0.001 – 0.1	rad
...%Lev1b%bangle_L2	Bending angle (L2)	Bending angle derived from L2	−0.001 – 0.1	rad
...%Lev1b%bangle	Bending angle	Bending angle (generic)	−0.001 – 0.1	rad
...%Lev1b%bangle_Opt	Bending angle (Opt)	Bending angle optimised (usually smoothed) prior to performing the Abel Transform	−0.001 – 0.1	rad
...%Lev1b%bangle_L2_sigma	Bending angle errors (L1)	Estimated errors (one σ) of L1 bending angle values	0 – 0.01	rad
...%Lev1b%bangle_L2_sigma	Bending angle errors (L2)	Estimated errors (one σ) of L2 bending angle values	0 – 0.01	rad
...%Lev1b%bangle_sigma	Bending angle errors	Estimated errors (one σ) of bending angle values	0 – 0.01	rad
...%Lev1b%bangle_Opt_sigma	Bending angle errors (Opt)	Estimated errors (one σ) of optimised bending angle values	0 – 0.01	rad
...%Lev1b%bangle_L1_qual	Bending angle quality	Percentage confidence values for L1 bending angles	0 – 100	%
...%Lev1b%bangle_L2_qual	Bending angle quality	Percentage confidence values for L2 bending angles	0 – 100	%
...%Lev1b%bangle_qual	Bending angle quality	Percentage confidence values for bending angles	0 – 100	%
...%Lev1b%bangle_Opt_qual	Bending angle quality	Percentage confidence values for optimised bending angles	0 – 100	%

Appendix C. Level 2 Data NetCDF Formats

From the ROPP Userguide [RD.8, version 2.0]:

Level 2a

Structure element	Parameter	Description	Range	Units
...%Lev2a%alt_refrac	Height	Geometric height above geoid (EGM 96)	−1000 – 100000	m
...%Lev2a%geop_refrac	Geopotential height	Geopotential height above geoid (EGM 96)	−1000 – 100000	gpm
...%Lev2a%refrac	Refractivity	Derived refractivity	0 – 500	N-units
...%Lev2a%refrac_sigma	Refractivity error	Estimated errors (one σ) of refractivity values	0 - 10	N-units
...%Lev2a%refrac_qual	Refractivity quality	Percentage confidence value	0 – 100	%

Level 2b

Structure element	Parameter	Description	Range	Units
...%Lev2b%geop	Geopotential height	Geopotential height above geoid (EGM 96)	−1000 – 100000	gpm
...%Lev2b%geop_sigma	Geopotential height error	Estimated error (one σ) of geopotential heights	0 – 500	gpm
...%Lev2b%press	Pressure	Retrieved pressure	0.1 – 1100	hPa
...%Lev2b%press_sigma	Pressure error	Estimated error (one σ) of retrieved pressure	0 – 5	hPa
...%Lev2b%temp	Temperature	Retrieved temperature	150 – 350	K
...%Lev2b%temp_sigma	Temperature error	Estimated error (one σ) of retrieved temperature	0 – 5	K
...%Lev2b%shum	Specific humidity	Retrieved specific humidity	0 – 50	g / kg
...%Lev2b%shum_sigma	Specific humidity error	Estimated error (one σ) of retrieved specific humidity	0 – 5	g / kg
...%Lev2b%meteo_qual	Quality	Overall percentage confidence value	0 – 100	%

Level 2c

Structure element	Parameter	Description	Range	Units
...%Lev2c%geop_sfc	Geopotential height	Geopotential height of surface above geoid (EGM–96)	−1000 – 10000	gpm
...%Lev2c%press_sfc	Surface pressure	Retrieved surface (or reference) pressure	250 – 1100	hPa
...%Lev2c%press_sfc_sigma	Surface pressure error	Estimated error (one σ) of retrieved surface pressure	0 – 5	hPa
...%Lev2c%press_sfc_qual	Quality	Percentage confidence value	0 – 100	%

Level 2d

Structure element	Parameter	Description	Range	Units
...%Lev2d%level_type	level type	Level type; currently, only one of `HYBRID ECMWF`, `ECMWF HYBRID`, `HYBRID` or `ECMWF` are currently supported.		
...%Lev2d%level_coeff_a	α coefficients	Level coefficients α (hybrid vertical levels only)	0 – 2000	hPa
...%Lev2d%level_coeff_b	β coefficients	Level coefficients β (hybrid vertical levels only)	0 – 2	n/a