The EUMETSAT
Network of
Satellite Application
Facilities

GRAS SAF
GRAS Meteorology

EUMETSAT Satellite Application Facility on GRAS Meteorology

PRODUCT USER MANUAL

Version 1.6

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

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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
Version 1.3	15/05/09	FRR	ORR-B1 version. Minor updates to products tables in Chapter 3, to align this document with the PRD. New chapter 5.2 included.
Version 1.4	01/02/10	FRR	Version associated with GRM-01 being upgraded to version 1.3 and declared operational (chapter 5.1 updated). New colour codes in Table 1-1, new logo and updates from ORR-B1 RIDs # 1 → 21, 56 → 60, 62 → 77, 105, 106, 119, 121. Chapter 5.2 temporarily removed pending GRM-02 → 05 being declared operational.
Version 1.5	08/02/11	FRR	ORR-B Close-Out version. Updates from RID # 120 (plots in chapter 3.2). Updated appendices.
Version 1.6	09/06/11	FRR	Updates according to Action 2 from ORR-B1 Close-Out; Chapter 5.2 reinserted

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1. INTRODUCTION

1.1 Purpose of the Document

This document is the GRAS SAF Product User Manual (PUM) and is dedicated to the users of the products.

The GRAS SAF is a EUMETSAT project that develops an operational radio occultation processing system for the GRAS instrument onbord the EPS/Metop satellites (and potentially other RO missions). The GRAS SAF is responsible for delivering refractivity, temperature, pressure, and humidity profiles and related climate products, and the ROPP (Radio Occultation Processing Package) software package for assimilation of RO data into NWP models, and for carrying out related research.
The GRAS SAF Leading Entity is DMI in Copenhagen, Denmark, with Cooperating Entities ECMWF in Reading, United Kingdom, IEEC in Barcelona, Spain, and Met Office in Exeter, United Kingdom. Read more about the project at the project web page http://www.grassaf.org/

The main content of the present manual is a description of the data products' content and format. It also briefly reviews the algorithms used and the processing methods adopted. The document only describes the NRT and Offline Products. The Climate Products will have a separate PUM and the ROPP software package has its own User Guide [see reference document RD.8, which is listed in chapter 1.6].

1.2 Status of Products, Dissemination, and Archiving

The current status of the products is listed in Table 1-1. The NRT refractivity product (GRM-01) is available as an operational product, the rest is still under development. For information about expected time of availability for the products still under development please refer to the project web page.

Beside these GRAS SAF deliverables, the EUMETSAT Central Application Facility 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 web page http://www.grassaf.org/.

1.3 Intellectual Property Rights

Please note that all intellectual property rights of the GRAS SAF products belong to EUMETSAT. The use of these products is granted to every interested user, free of charge. If you wish to use these products, EUMETSAT's copyright credit must be shown by displaying the words "copyright (year) EUMETSAT" on each of the products used.

Product identifier and status	Product name	Product acronym	Product type (product, soft-ware, 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-07	Error Covariance Matrix for NRT Products	NEM	Dataset	offline	Web	netCDF
GRM-08	OFL Bending Angle	OBA	Product	offline	Web	netCDF
GRM-09	OFL Refractivity Profile	ORP	Product	offline	Web	netCDF
GRM-10	OFL Temperature Profile	OTP	Product	offline	Web	netCDF
GRM-11	OFL Specific Humidity Profile	OHP	Product	offline	Web	netCDF
GRM-12	OFL Pressure Profile	OPP	Product	offline	Web	netCDF
GRM-13	OFL Surface Pressure	OSP	Product	offline	Web	netCDF
GRM-15	Error Covariance Matrix for OFL Products	OEM	Dataset	offline	Web	netCDF

= operational = pre-operational = demonstration

= development = stopped/superseded

Table 1-1 Current status of GRAS SAF deliverables (note that other product acronyms are used within UMARF). Climate products (GRM-17 → 21) and the ROPP software package (GRM-16) have their own user documents.

1.4 Structure of this Document

This document contains chapters on:
1: **Introduction**, introducing the project and its products, status, definitions, etc.
2: **The radio occultation method**, describing the processing principles and the GRAS instrument
3: **Product description**, describing all NRT and Offline products with specifications
4: **Format descriptions**, giving details on the NetCDF format
5: **Data quality**, describing the current results of validating the products
6: **Dissemination methods**, describing briefly the different means of receiving the products
Appendices

1.5 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.
Climate product: Gridded monthly zonal means of Offline products.

Level 0 data: Raw GRAS sounding, tracking and ancillary data, ground site observations, GNSS and METOP ancillary data, among others, 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)
CT2	Canonical Transform 2
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
FSI	Full Spectrum Inversion
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)
GRM	EUMETSAT acronym for the GRAS (Meteorology) SAF, used as product identifier
GSN	Ground Support Network
GTS	Global Telecommunication System
IEEC	Institut d'Estudis Espacials de Catalunya (Spain)
IGS	International Geodynamics Service
L1	GPS carrier frequency, 1575.42 MHz
L2	GPS carrier frequency, 1227.6 MHz
LC	L phase Corrected, linear combination of L1 and L2
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	Operation Readiness Review-A (EUMETSAT/GRAS SAF)
ORR-B	Operation Readiness Review-B (EUMETSAT/GRAS SAF)
POD	Precise Orbit Determination
PPF	Product Processing Facility (EPS/EUMETSAT)
PRD	Product Requirements Document (GRAS SAF)
RD	Reference Document (GRAS SAF)
RMDCN	Regional Meteorological Data Communication Network (GTS in WMO Region 6)
RO	Radio Occultation
RoC	Radius of Curvature
ROPP	Radio Occultation Processing Package (GRAS SAF)
SAF	Satellite Application Facility (EUMETSAT)
SNR	Signal-to-Noise Ratio
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.

1.6 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, Part I. Ref: SAF/GRAS/METO/UG/ROPP/003

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

[RD.10] M. 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

[RD.12] GRAS SAF Validation Report GRM 02, GRM 03, GRM 04, GRM 05. Ref: SAF/GRAS/DMI/RQ/REP/002

[RD.13] GRAS SAF Algorithm Theoretical Baseline Document: 1D-Var Algorithm. Ref: SAF/GRAS/DMI/ALG/1DV/002

[RD.14] Healy, S. B. and Eyre, J. R., Retrieving temperature, water vapor and surface pressure information from refractive–index profiles derived by radio occultation: A simulation study, Quart. J. Roy. Meteorol. Soc., 126, 1661–1683, 2000.

[RD.15] Andersson, E., Fisher, F., Munro, R., and NcNally, A., Diagnosis of background errors for radiances and other observable quantities in a variational data assimilation scheme, and the explanation of a case of poor convergence, Quart. J. Roy. Meteorol. Soc., 126, 1455–1472, 2000.

[RD.16] Persson and Grazzini, User guide to ECMWF forecast products. Meteorological Bulletin, M3.2 (available from ECMWF website), ECMWF.

[RD.17] Derber, J. and Bouttier, F., A reformulation of background error covariance in the ECMWF global data assimilation system, Tellus, 51A, 195–221, 1999.

[RD.18] Fisher, M., Background error covariance modelling., in ECMWF Seminar on Recent developments in data assimilation for atmosphere and ocean, 8-12 September 2003, pp. 45–64, 2003.

2. THE RADIO OCCULTATION METHOD

2.1 Overview

Products obtained from the radio occultation (RO) measurements consist of bending angles and 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.

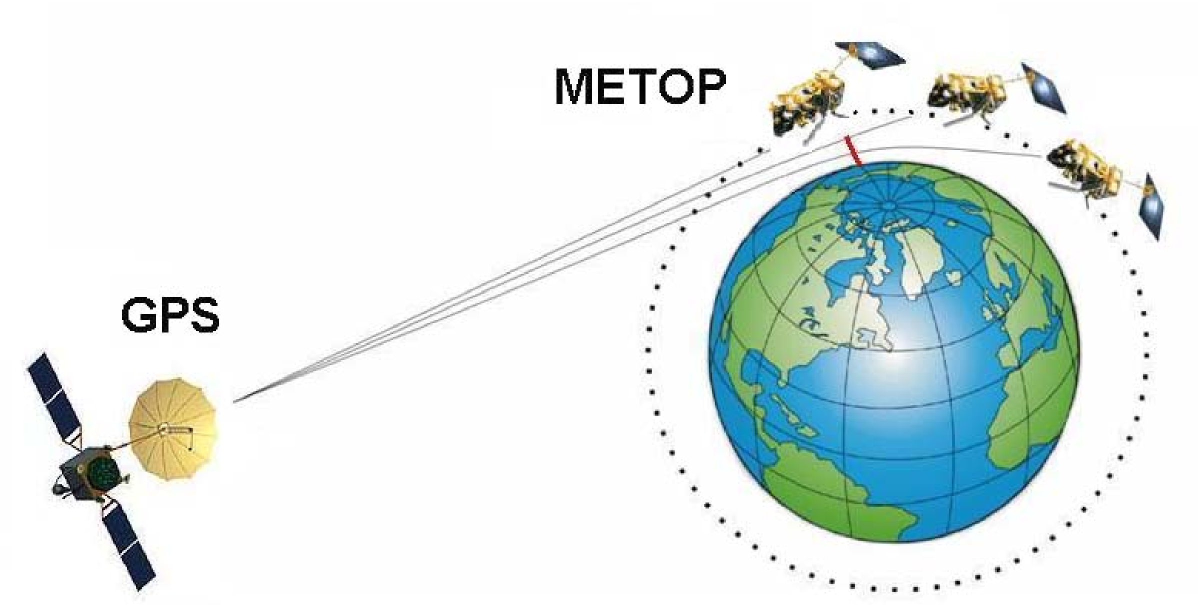

Figure 2-1. Schematic representation of the data (red line) observed by the GRAS instrument on Metop during an occultation.

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 radiosondes – 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 (about 5 - 30 km)
- 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). EUMETSATs EPS-CGS facility is responsible for GRAS Level 0 to Level 1b NRT processing (the products are subsequently disseminated to the GRAS SAF), whereas the GRAS SAF itself will be responsible for the Offline processing from GRAS Level 0 to higher levels. 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 configurable. The occultation measurement is nominally sampled at 50 Hz in closed-loop mode and 1000 Hz in open-loop/raw sampling mode.

Bending angles are provided for heights above the Earth's surface ranging from 80 km down to, or close to, the surface (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 nominal daily 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 (Level 1b) is performed at the EUMETSAT Central Facilities 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 two GPS radio frequencies (L1 and L2) 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 (LC). 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 geometric optics processing at EUMETSAT is based on the phase data only, even in the lower troposphere where multipath propagation occurs frequently. The goal for Offline processing (not yet operational) is to process the data using both the phase and the amplitude to solve for the multipath propagation using wave-optics methods like CT2 (see [RD.7]) 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]. See also e.g. [RD.6] for a detailed description of the various algorithms and processing steps.
In order to arrive at an estimate for the temperature, pressure and humidity (Level 2), 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, see [RD.8] about 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. This problem is referred to as the “water vapour ambiguity”.
It would also be possible to calculate temperature and pressure directly from the refractivity (i.e. without the use of background data) using the ideal gas law under the assumption of no water vapour in the atmosphere, but these “dry” products are unlikely to meet accuracy requirements, and the GRAS SAF does not provide them.

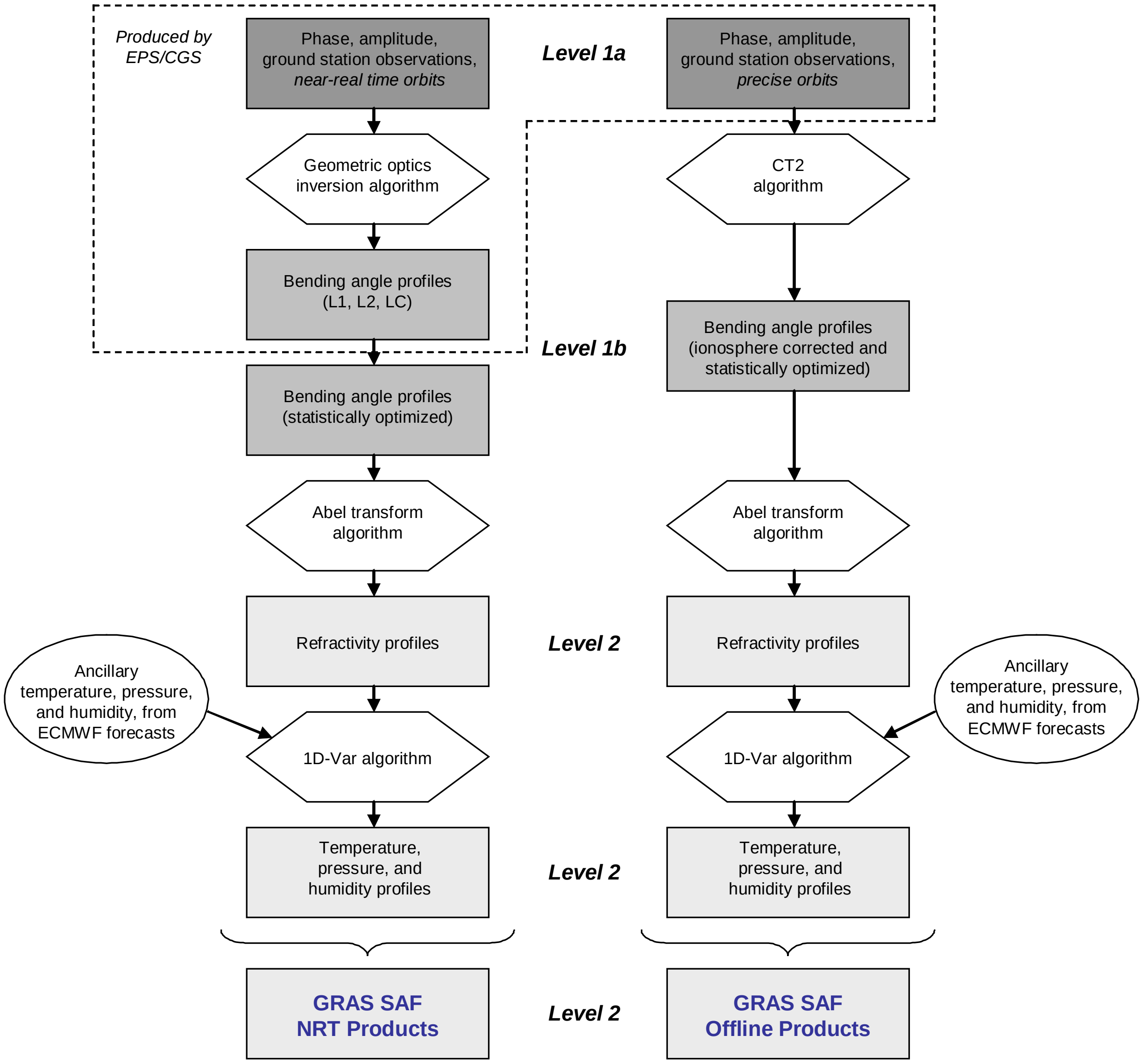

*Figure 2-2 **Left**: Schematic showing of the NRT processing steps to SAF Level 2 products. Ancillary temperature and humidity profiles are used as background in the statistically optimal retrieval in the 1D-VAR scheme. SAF Level 2 products include a thinned bending angle profile derived from the EUMETSAT 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 products**: Those produced with operational timeliness restrictions (3 hours).
- **Offline products**: Those produced with a timeliness restricttion 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 height
	Level 2b	Temperature, humidity, and pressure as a function of height
	Level 2c	Surface pressure
	Level 2d	Additional data describing the vertical level structure

Table 3-1 GRAS and GRAS SAF product level descriptions. Product files on each level contain further additional data, appropriate to the specific type of product, see Appendices for details. 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 Leading Entity. 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 Leading Entity.
Users may request offline products via the GRAS SAF Product Archive and/or UMARF. The GRAS SAF retrieves forms with the requests from the UMARF Client.

3.1.1 NRT Products

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 main parameters are:

- Refractivity profiles
- Temperature profiles
- Pressure profiles
- Specific humidity 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 algorithms and post-processed GPS and Metop precise orbital determination (POD) information 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
- Specific humidity 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 (height above geoid/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, and uncorrected bending angles in its archived products.

3.1.4 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 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

Read more about Error Covariance Products in Chapter 3.5.

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.

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 (height above MSL/geoid and 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	Offline: 0.4% or 1 μrad	whichever is greater. Level 1b requirement

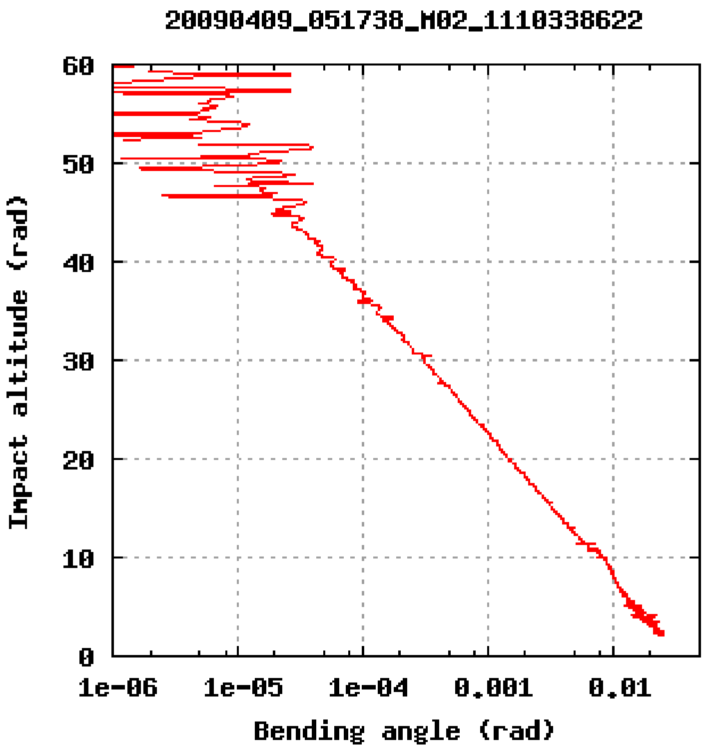

Figure 3-1 Typical GRAS bending angles as function of impact altitude.

3.2.3 Refractivity Profile

This parameter is a profile and contains the neutral refractivity as a function of height level (above geoid/MSL and geopotential, see Chapter 3.2.8) 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 resolution	150-250 m		
Target accuracy	NRT	Offline	
0-5 km	0.6%-2%	0.5%-2%	
5-30 km	0.6%	0.5%	
30-50 km	0.03 N-units	0.02 N-units	

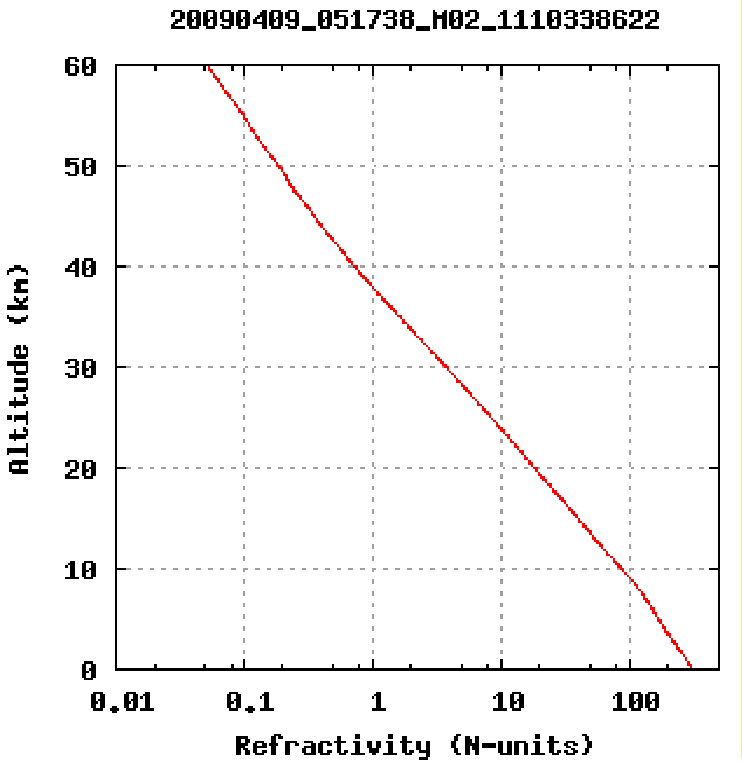

Figure 3-2 Typical GRAS refractivity profile

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. The heights are given on fixed model levels, see [RD.8] for details.

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 1DVAR method simultaneously produces temperature, specific humidity and surface pressure. The forecast used is always the most recent one available. See Chapter 2.4 and [RD.13] for more details.

Quantity	Values		Remarks
Units	Kelvin (K)		
Domain	0–50 km		Surface to ~1 hPa
Range	180–350 K		
Precision	0.1 K		
Vertical resolution	250-500 m		depends on background pressure levels
Target accuracy	NRT	Offline	
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	3–5 K	

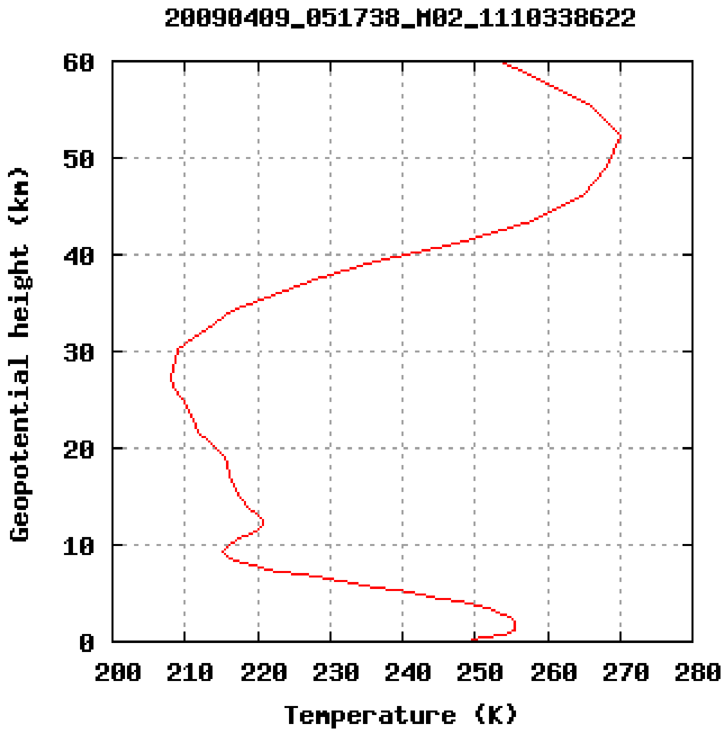

Figure 3-3 GRAS temperature profile at 76.02N 15.28W on April 9 2009 05:17:38UT

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 (on model levels) 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, see Chapter 2.4.

Quantity	**Values**	**Remarks**
Units	g/kg	Specific humidity
Domain	0–15 km	Surface to ~100 hPa
Range	0–50 g/kg	
Precision	0.001 g/kg	
Vertical resolution	250-500 m	depends on background pressure levels
Target accuracy	10% or 0.2 g/kg (NRT) 5% or 0.1 g/kg (Offline)	whichever is greater

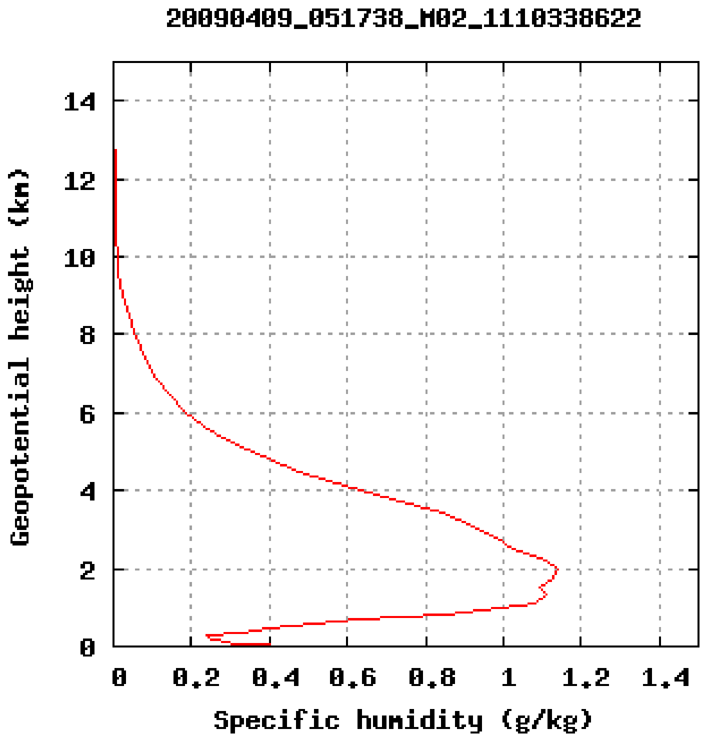

Figure 3-4 GRAS specific humidity profile at 76.02N 15.28W on April 9 2009 05:17:38UT

3.2.6 Pressure Profile

This parameter is a profile and contains the atmospheric pressure as a function of height (on model levels) 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	hectoPascal (hPa)	
Domain	0–50 km	Surface to ~1 hPa
Range	0.01–1100 hPa	
Precision	0.001 hPa	
Vertical resolution	250-500 m	depends on background pressure levels
Target accuracy	0.2% or 2 hPa (NRT) 0.1% or 1hPa (Offline)	whichever is greater

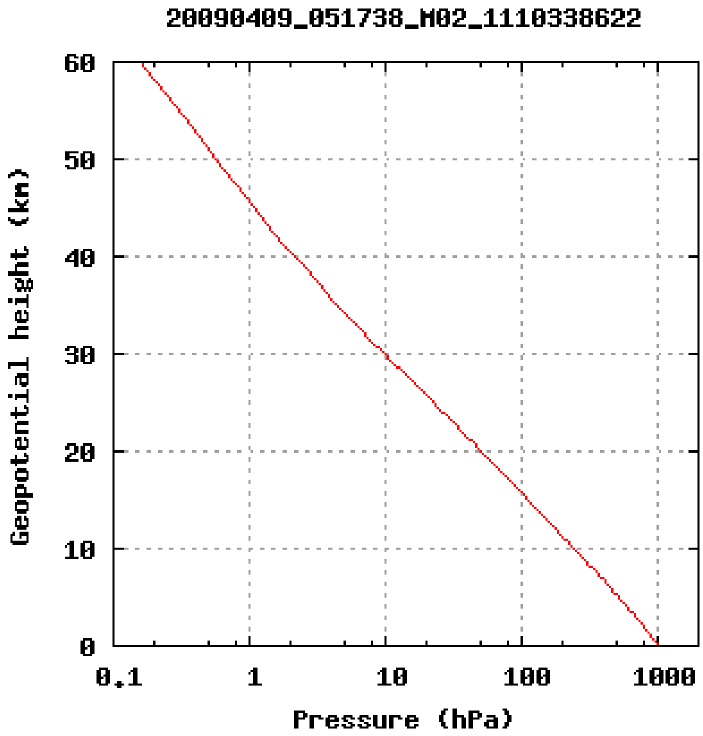

Figure 3-5 Typical GRAS pressure profile

3.2.7 Surface Pressure

The surface pressure is derived from the refractivity profile using a 1DVAR algorithm, see Chapter 2.4.

Quantity	Values	Remarks
Units	hectoPascal (hPa)	
Domain	Surface	Horizontal location nominally at the location where the straight line connecting GPS and MetOp grazes the surface (WGS 84 ellipsoid).
Range	300–1100 hPa	
Precision	0.1 hPa	
Vertical resolution	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) geopotential metres (gpm)	(a) Heights above MSL (referenced to geoid EGM96) (b) Geopotential heights
Domain	-0.15 – 50 km	Surface to ~1 hPa
Range	-150 – 50,000 m	
Precision	1 m	
Vertical resolution	N/A	
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 resolution	N/A	
Accuracy	0.01°	~1 km

3.2.10 Quality Information

The GRAS SAF Sounding Products contain the following quality information:

- Boolean flags showing the results of quality tests ('Product Confidence Data', see Appendix A or [RD.8 chapter 2.3.5] for more details). Flags include (but are not limited to):
  - ✓ summary status (0=nominal quality, 1=non-nominal)
  - ✓ 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, FSI 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 Orbits (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, see [RD.4] for details.

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 resolution	5 Hz	
Accuracy	0.2 m (NRT) 0.1 m (Offline)	Level 1b requirement. See [RD.4] for details.

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	0.01×10^{-3} $m.s^{-1}$	
Vertical resolution	5 Hz	
Accuracy	0.2×10^{-3} $m.s^{-1}$ (NRT) 0.1×10^{-3} $m.s^{-1}$ (Offline)	Level 1b requirement. See [RD.4] for details.

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 resolution	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 resolution	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 resolution	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 resolution	N/a	
Accuracy	1 m	

3.3.3 Background Profiles from ECMWF

The GRAS SAF 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 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 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 Data

Validation data consist of summary statistical information on the reliability and quality of the Sounding Products.
Validation data 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 (NWP field model levels, see [RD.8] for details)
- Latitude bands (NH, Tropics, SH)
- Surface (Land/Sea)
- Regional zones (e.g. 5° x 5° 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://www.grassaf.org/monitoring

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 *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 (GRM-07 in Table 1-1)
- Covariance matrix for Offline Sounding Products (GRM-15 in Table 1-1)

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. The matrices are not actively disseminated, but are available for download from the GRAS SAF web site. These files are expected to change only infrequently (if at all) after the Metop commissioning period, as the statistics become more stable, and are included with the ROPP software package. The latest versions will always be 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]. The common file naming principle is given in Chapter 4.3.3 and file types in Table 4-1 Description of GRAS SAF file types. For detailed information on the ROPP levels, see [RD.8].

4.3 netCDF Format

The data format for the GRAS SAF products is netCDF.

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 variables values
- Additional datasets for metadata (e.g. quality flags).

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.

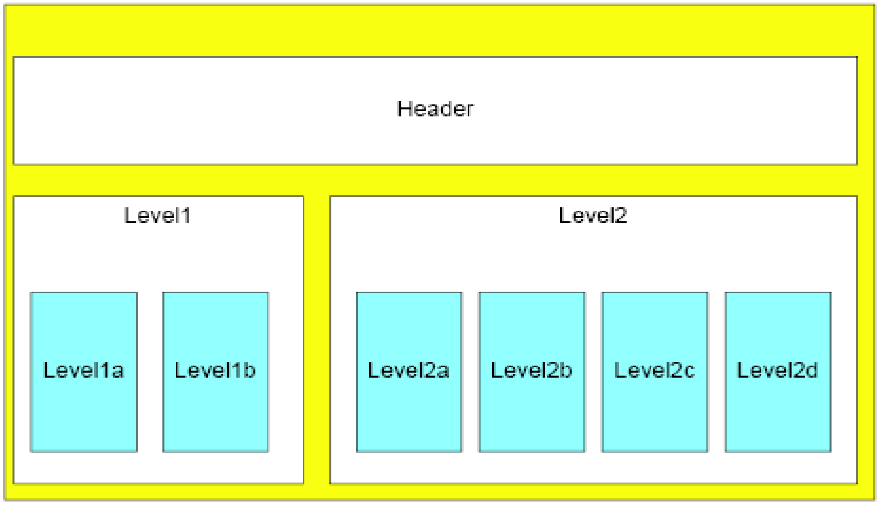

Figure 4-1 Overview of the ROPP netCDF file structure

Detailed information of each variable 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 product 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`

The letter in MODE has the following meaning:
N = NRT
P = postprocessing (= Offline)
R = reprocessing
T = test
V = validation

Type	ROPP levels	Format	Description
dis	1a 1b 2a 2b 2c 2d	NetCDF	This file type is the input to the BUFR file that is disseminated on GTS and EUMETCast. The content is bending angle and impact parameter originating from GSN and the refractivity profile and 1DVAR output derived from this. This file holds LEO and GNSS positions and velocities from the GSN NRT product.
bfr	-	BUFR	This file type is based on the “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 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
wet	2b 2c 2d	NetCDF	This file contains output from the 1DVAR i.e. temperature, pressure and humidity

Table 4-1 Description of GRAS SAF file types. For detailed information on the ROPP levels, see [RD.8].

5. DATA QUALITY

This chapter contains a description of the quality of all operational and pre-operational data products, as they become available. A full list of the products and status can be found in Table 1-1.

5.1 Statistics of the NRT Refractivity Product (GRM-01)

A short description of the validation results of the refractivity profiles (GRM-01) with respect to co-located ECMWF profiles is given in this chapter (for the full validation results see [RD.9]).
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 first 15 days of April, 2009. Each of the six panels are discussed below in terms of biases and standard deviations relative to the ECMWF forecasts.

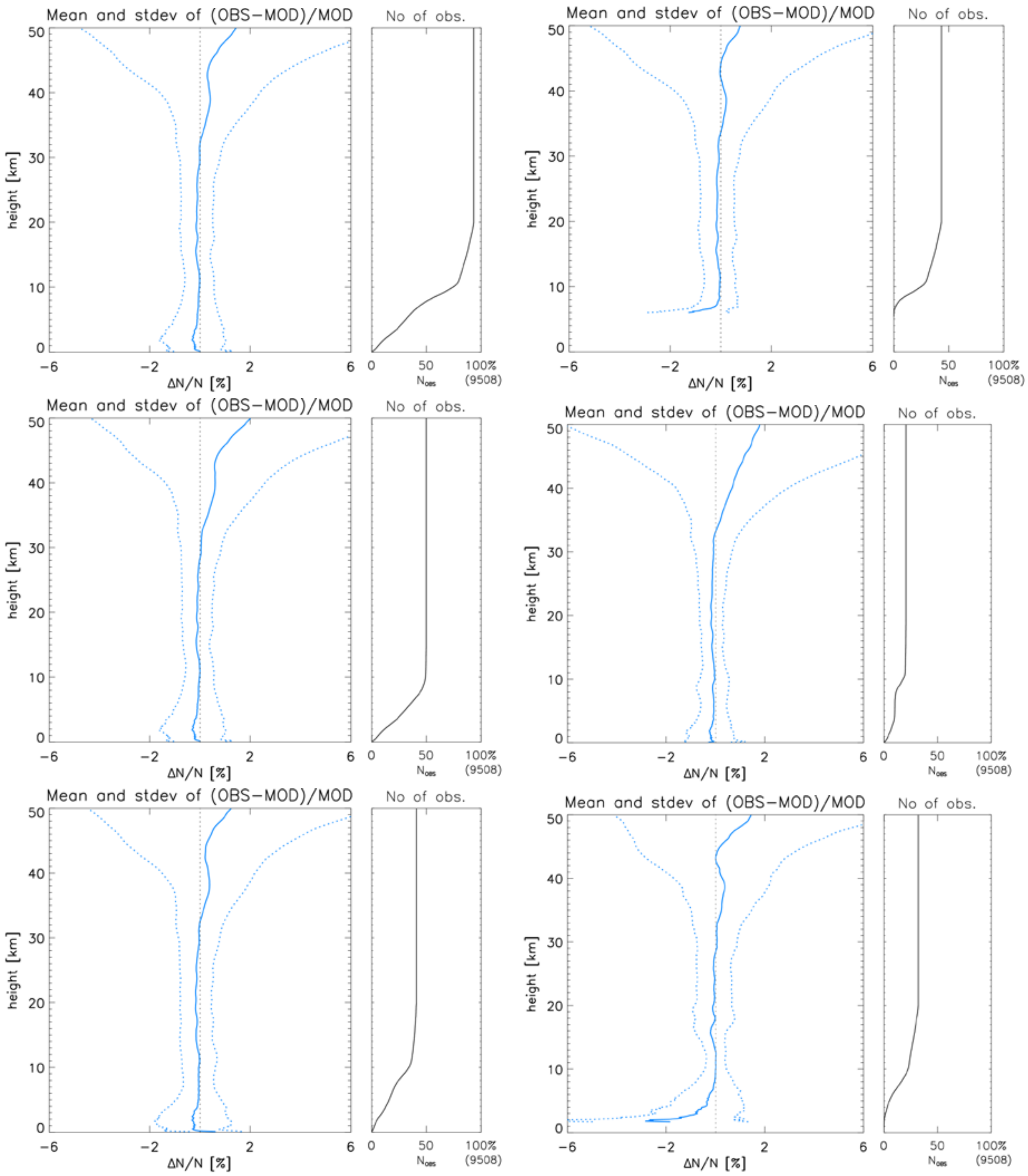

Figure 5-1 Refractivity results for the first 15 days of April, 2009, compared to ECMWF forecasts. The upper panels show all occultations (left) and rising (right). The mid panels show setting (left) and high latitudes (right). The lower panels show mid latitudes (left) and low latitudes (right). Solid 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 10 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 10–30 km the overall bias is small but slightly negative (less than 0.2%) around 15 and 20 km. Above 30 km there is an increasing positive bias reaching about 0.4% at 40 km and about about 1.5% at 50 km. The bias around 40 km is believed to be associated with a bias in the ECMWF fields.
• **std.dev.:** Below ~10 km the standard deviation is varying, but less than 2%. The standard deviation is 0.6–0.8% in the range 10–30 km, and increases above to reach about 2% at 40 km and 6% 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, although with a tendency towards the negative side relative to 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, although with a tendency towards the positive side
relative to all occultations.
• **std.dev.:** The standard deviation is similar to the standard deviation for all occultations.

High latitudes:
• **bias:** The bias is somewhat similar to the bias for all occultations, but without a pronounced local maximum near 40 km.
• **std.dev.:** The standard deviation is less than 0.5% in most of the 10 – 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.
• **std.dev.:** The standard deviation is similar to the standard deviation for all occultations.

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 2% at 2 km. Above 8 km the bias is somewhat similar to the bias for all occultations.
• **std.dev.:** The standard deviation is smallest around 12 km (about 0.4%) and otherwise somewhat similar
to the standard deviation for all occultations.

5.1.1 GRM-01 Compliance with Product Requirement

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 or within the target requirement.

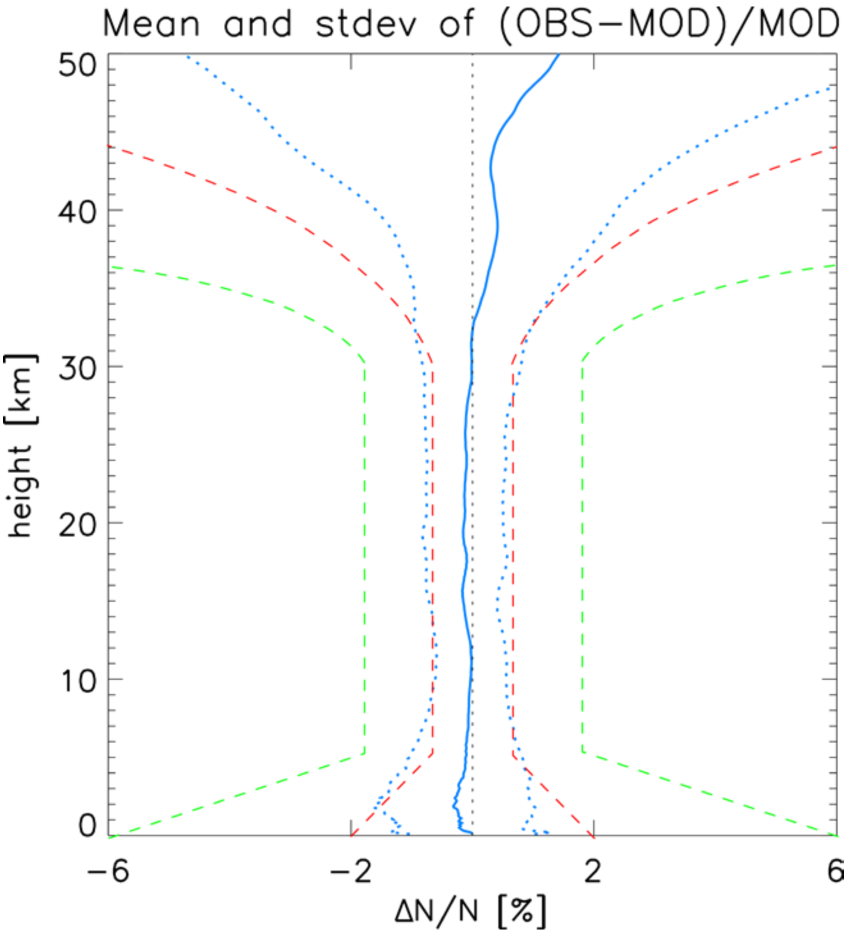

Figure 5-2 Same as the first panel in Figure 5-1, but with dashed lines superimposed indicating the target (red) and threshold (green) accuracies for NRT refractivity according to the PRD [RD.2].

5.2 Statistics of the NRT Products GRM-02 - 05

This chapter summarizes the most recent validation results for the GRAS SAF products GRM-02 (NRT Temperature Profile), GRM-03 (NRT Specific Humidity Profile), GRM-04 (NRT Pressure Profile) and GRM-05 (NRT Surface Pressure) product version numbers 1.0. These products are all outputs from the GRAS SAF 1D-Var processing using as input the GRAS SAF NRT Refractivity Profiles (GRM-01) together with ancillary information from ECMWF forecasts. The background profile is taken from the ECMWF 3-hourly forecast at the closest synoptic hour. 1D-Var processing is performed using ROPP software version 4.1 and 1DV version 2.4. For the full text, refer to [RD.12].

5.2.1 Background

5.2.1.1 The cost function

The purpose of the 1D-Var processing is to find a *maximum likelihood* estimate of a vertical atmospheric profile $\boldsymbol{x}$, given a set of *m* observations $\boldsymbol{y}^o$ of the refractivity and some *a priori* knowledge $\boldsymbol{x}^b$, also referred to as a *background*. Both the observations and the background have associated uncertainties described by an *observational error covariance matrix* $\boldsymbol{O}_{(m,m)}$ and *background error covariance matrix* $\boldsymbol{B}_{(n,n)}$. In the case of Gaussian error distributions, the statistically optimal solution that simultaneously fits both the observation and the background to within their respective errors, is obtained by minimising the cost function

$$J(\boldsymbol{x}) = \frac{1}{2}(\boldsymbol{x} - \boldsymbol{x}^b)^T \boldsymbol{B}^{-1}(\boldsymbol{x} - \boldsymbol{x}^b) + \frac{1}{2}(\boldsymbol{y}^o - \boldsymbol{H}(\boldsymbol{x}))^T \boldsymbol{O}^{-1}(\boldsymbol{y}^o - \boldsymbol{H}(\boldsymbol{x})) \qquad (1)$$

with respect to the state $\boldsymbol{x}$. Here, $\boldsymbol{H}$ is the forward operator mapping the atmospheric state into measurement space – in practice this means converting a vertical profile of pressure, temperature, and humidity given on the 1D-Var levels into a corresponding profile of refractivity given on the observed refractivity levels.

The state $\boldsymbol{x}$ and the background $\boldsymbol{x}^b$ are given on the 1D-Var levels, defined as a set of 91 model levels. Hence, the first term in the cost function $J(\boldsymbol{x})$ is evaluated on the 1D-Var levels, whereas the second term is evaluated on the observed levels which are expressed in terms of geopotential heights. It may be noted that the minimisation of the cost function J is effectively a least-square fitting procedure with $2J$ approximately having a χ^2 distribution with m degrees of freedom.

The MINROPP minimiser software (see [RD.12]) is used to determine the best solution by minimising J. MINROPP outputs both $2J/m$ and the number of iterations used. These quantities are used to judge the quality of the solution (see Chapter 5.2.2.1)

5.2.1.2 Observation error covariance

Radio occultation errors in the troposphere are dominated by horizontal gradients and the presence of water vapour (see [RD.12]). In the stratosphere, the circulation is nearly zonally symmetric and there is almost no water vapour, so RO measurements are generally good in this part of the atmosphere. Errors increase below because stratospheric conditions change into tropospheric ones, and water vapour abundance increases. Thus, the tropopause as boundary between stratosphere and troposphere also is the natural boundary between two different error regimes of radio occultation data. The error model employed in 1DV reflects this:

Figure 5-3 shows the observational error model that is implemented in 1DV. The refractivity error estimate is 2% at the surface, decreasing linearly to 0.2 % at the tropopause. Above the tropopause, the fractional errors are 0.2% or 0.02 N-units, whichever is greatest.

The altitude of the tropopause is determined from the background profile using the standard definition of the tropopause as the lowest level at which the lapse rate decreases to 2°K/km or less, provided that the average lapse rate between this level and all higher levels within 2 km does not exceed 2°K/km. This dynamically-determined tropopause height is then compared to a climatological value (see [RD.12]). If the pressure at the dynamically-determined tropopause height differs by more than a factor of 2 from the climatological value, the climatological value will be used instead of the dynamically-determined value.

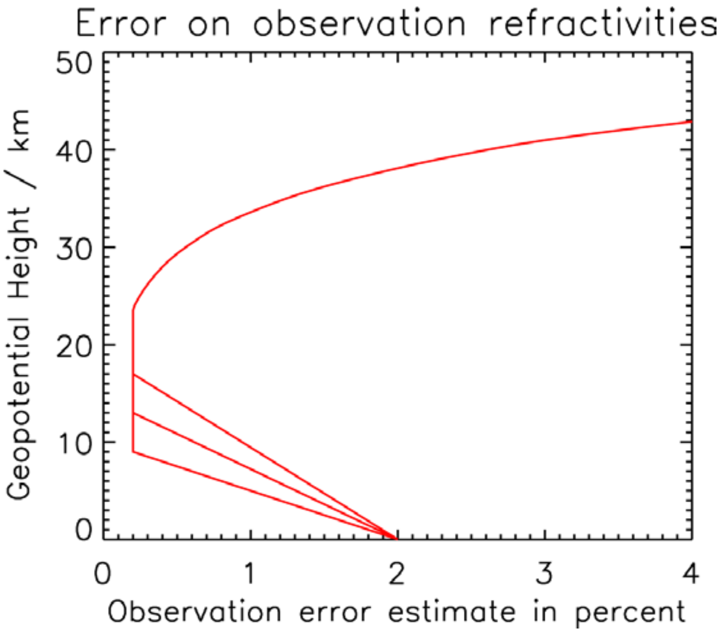

Figure 5-3 Fractional refractivity error estimates for 3 different tropopause heights (9km, 13km, 17km).

The observational error covariance matrix ***O*** used in 1DV is derived from the error estimates given above by the expression:

$$COV_{nm} = \sigma_n \sigma_m e^{-|z_n - z_m|/H} \qquad (2)$$

where σ_n and σ_m are the error estimates at two points *n* and *m* along a vertical profile, z_n and z_m are the geopotential heights and *H* is a characteristic *scale height*. A uniform scale height of 3 km is used in 1DV [RD.14].

5.2.1.3 Background Data

The background state is taken from an ECMWF global forecast from the standard dissemination stream. This forecast is specified on 91 model levels (to be modified in future versions).

Each occultation has latitude, longitude, and time associated with it. For the background, we select the newest ECMWF forecast at the closest 3-hourly time step (i.e. at UTC 0, 3, 6, 9, 12, 15, 18 or 21) taking care to avoid forecasts which will already have assimilated the observed RO profile. Since new ECMWF forecast streams are started at 0 UTC and 12 UTC the forecasts used in the nominal situation are as follows:

0:00 UTC - 1:30 UTC:	12-hour forecast for 0 UTC	(based on the analysis at 12 UTC)
1:30 UTC - 3:00 UTC:	15-hour forecast for 3 UTC	(based on the analysis at 12 UTC)
3:00 UTC - 4:30 UTC:	3-hour forecast for 3 UTC	(based on the analysis at 0 UTC)
4:30 UTC - 7:30 UTC:	6-hour forecast for 6 UTC	(based on the analysis at 0 UTC)
7:30 UTC - 10:30 UTC:	9-hour forecast for 9 UTC	(based on the analysis at 0 UTC)
10:30 UTC - 13:30 UTC:	12-hour forecast for 12 UTC	(based on the analysis at 0 UTC)
13:30 UTC - 15:00 UTC:	15-hour forecast for 15 UTC	(based on the analysis at 0 UTC)
15:00 UTC - 16:30 UTC:	3-hour forecast for 15 UTC	(based on the analysis at 12 UTC)
16:30 UTC - 19:30 UTC:	6-hour forecast for 18 UTC	(based on the analysis at 12 UTC)
19:30 UTC - 22:30 UTC:	9-hour forecast for 21 UTC	(based on the analysis at 12 UTC)
22:30 UTC - 24:00 UTC:	12-hour forecast for 24 UTC	(based on the analysis at 12 UTC)

No time interpolation is performed, but the model fields are linearly interpolated to the same geographic location as the observed profile. For each observed profile we thus obtain a corresponding model profile which provides the a priori information that is required for the 1D-Var analysis.

5.2.1.4 Background Error Covariance

The 1D-Var processing also needs as input a background error covariance matrix ***B***. As was the case for the observation error covariances, this matrix is constructed from one-dimensional profiles of error estimates combined with an error correlation matrix:

$$COV_{nm} = s_n s_m CORR_{nm} \qquad (3)$$

The error estimates for temperature and humidity are based on the variable type **ef** (error of the first guess) disseminated by ECMWF (see [RD.12], [RD.15], [RD.16], [RD.17], and [RD.18]). The standard deviation profiles at (ECMWF-) analysis time are found by linear interpolation to the same geographic location as the observed profile. To account for the increased error introduced by the forecast these standard deviations are multiplied by:

$$exp\left(\frac{fcperiod - 3hours}{36hours} \cdot ln(2)\right) \qquad (4)$$

where *fcperiod* is the forecast period (see [RD.12]). The **ef** fields are given for a time three hours after the analysis time, hence the "- 3 hours" appearing in eq. (4). Errors on temperature and humidity profiles are shown in Figure 5-5 and Figure 5-6 in Chapter 5.2.2.2.1.

The error estimate on the surface pressure is always set to 1 hPa.

The error correlations used in 1DV are shown in Figure 5-4 below. It is assumed that there are no cross-correlations between temperature, humidity and surface pressure errors.

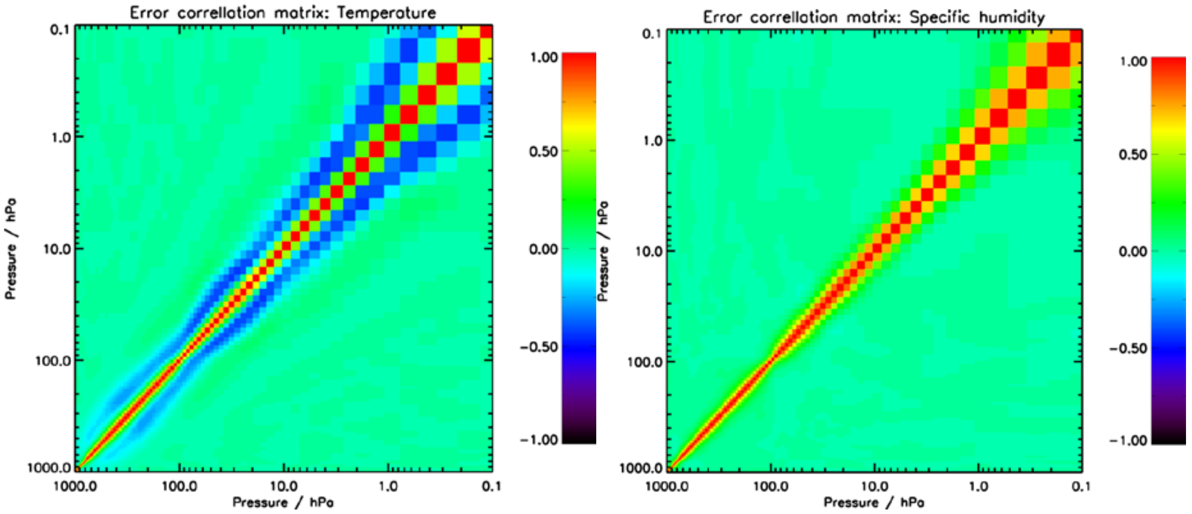

Figure 5-4 Vertical correlations for the background errors given on the 91 model levels plotted on a set of pressures for a typical sea-level profile with the top level at 0.1 hPa and the bottom level at 1012 hPa: T error correlations in the left panel and q error correlations in the right panel. It is assumed that there are no correlations between temperature errors and humidity errors.

5.2.2 Validation

This section describes quality control and validation of the 1D-Var output. The figures in this section are based on all data from the month of April 2009. The background ECMWF forecasts are from ECMWF analysis cycle 35r2. Active 1D-Var variables that are found through the 1D-Var processing are profiles of temperature and specific humidity as well as the surface pressure. The pressure profile then follows from integration of the hydrostatic equation.

5.2.2.1 Quality Control

For all profiles the 1D-Var processing converged on a solution. After 1D-Var processing a small number of solution profiles are rejected based on diagnostics of the minimiser. Profiles are marked as bad if:

a) The *2J/m* quality score of the solution is above 5.
b) The MINROPP minimiser (see [RD.7]) used more than 25 iterations to find the solution.
c) The ingoing refractivity profile is marked as bad.

Out of a total of 18483 profiles from April 2009 based on ‘good’ refractivity profiles, 60 (0.32%) had too high *2J/m*. 60 (0.32%) had valid *2J/m* but too many iterations. The total fraction of solution profiles rejected is 0.64%.

5.2.2.2 Error Estimates

In addition to a solution profile the 1D-Var algorithm gives an estimate of the error on the solution in the form of an error covariance matrix. Taking the square root of the diagonal elements of the covariance matrix gives an estimated standard error profile. By comparing this error with the background error estimate one can get an idea of how much information was gained from the observation.

5.2.2.2.1 Temperature and specific humidity error estimates

Figure 5-5 shows the background and solution error estimate profiles for temperature. The temperature solution error estimates show a large improvement over the background in the range 9 km – 35 km indicating that the observation profiles carry significant new information about temperatures in this range. There is also some small improvement at higher altitudes. The minimum value that the solution error estimates approach in the region 15 km – 25 km reflects the 0.2 % minimum refractivity error (see Figure 5-3).

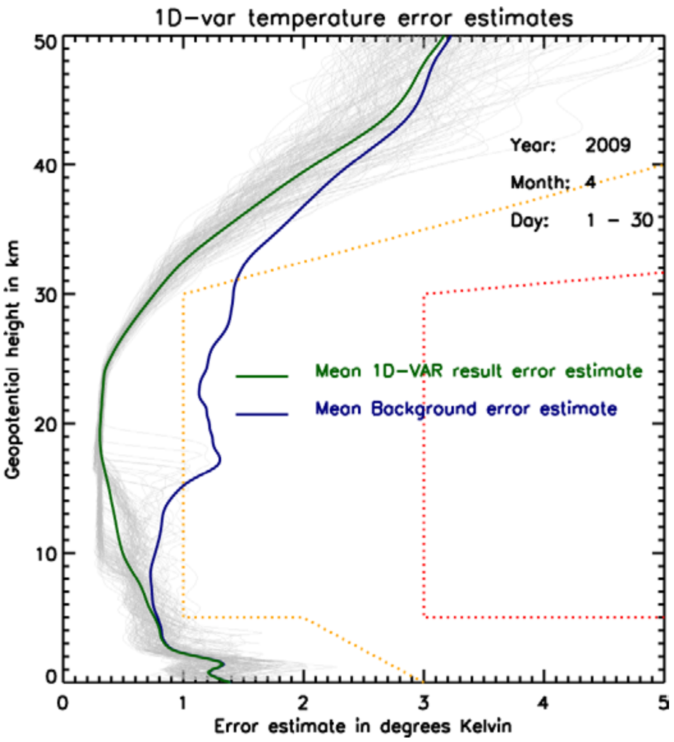

Figure 5-5 Background and solution error estimates for temperature. The thin lines show error estimates for a number of single solution profiles. Also shown are the formal 'Threshold' (red) and 'Target' (orange) data quality requirements.

The specific humidity solution error estimates are shown in Figure 5-6. The left side shows average error estimates in absolute values (g/kg), the right side shows the error estimates relative to the formal target requirement, which is defined as whichever is greater of 0.2 g/kg or 10% of the specific humidity. The specific humidity error estimates show only a limited improvement over the background on average. However, this covers a wide variation with many profiles showing no improvement at all (either because the atmospheric humidity is too low to have an appreciable influence on the refractivity or because the observed profile did not reach far enough down) and a few profiles showing a significantly improved solution error estimate indicating a real improvement in information of the atmospheric water vapour content.

As discussed in [RD.12] the introduction of open-loop processing and wave-optics algorithms in GRAS data processing will significantly improve the quality of GRAS refractivity data at low altitude in areas of high atmospheric humidity and we expect this to result in an improvement in the 1D-Var specific humidity product as well.

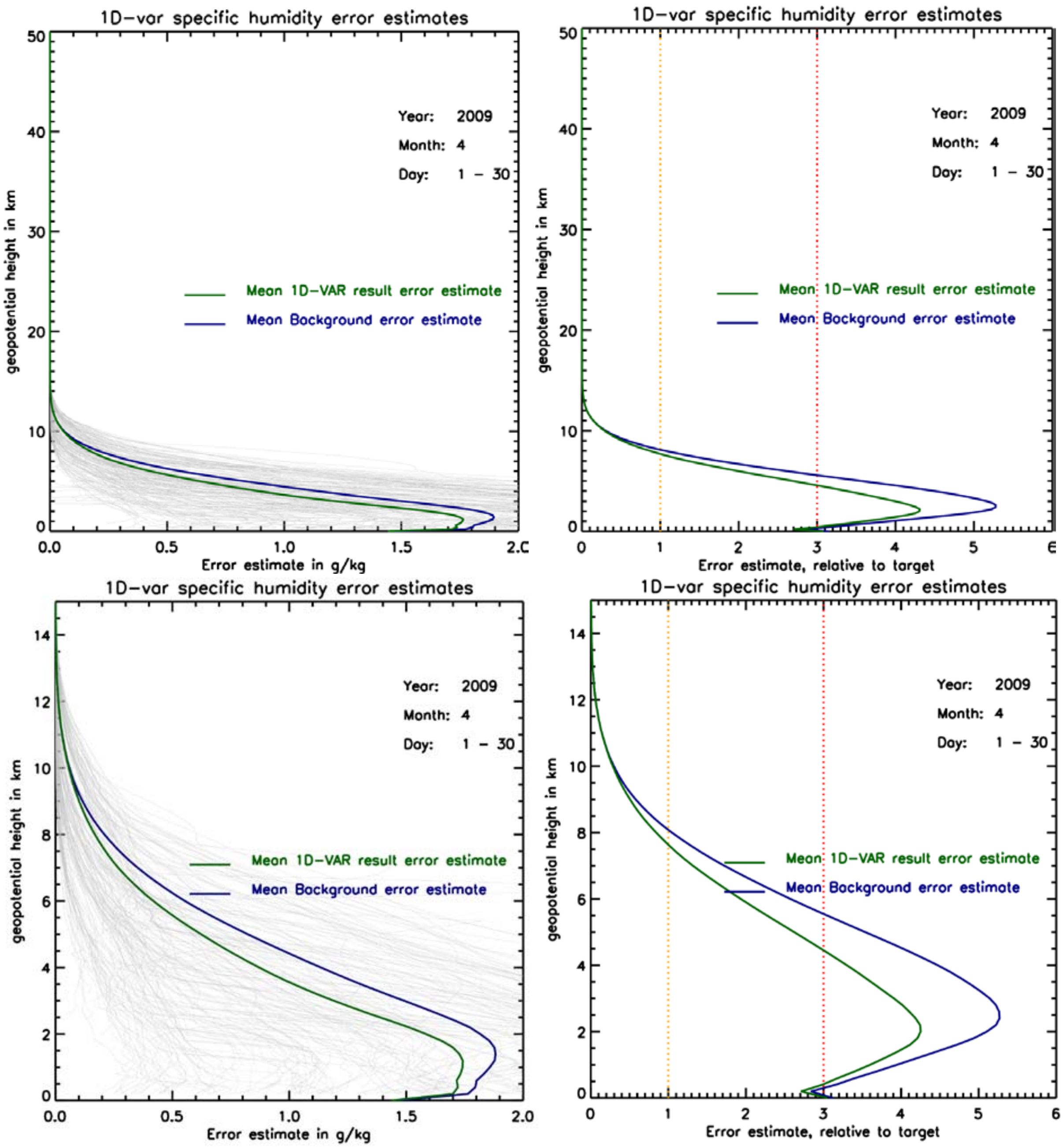

Figure 5-6 Background and solution error estimates for specific humidity. Left side shows absolute values. The thin lines on the left show error estimates for a number of single solution profiles. The right side shows values relative to the formal 'Target' requirement. The formal 'Threshold' (red) and 'Target' (orange) data quality requirements are also shown on the right hand side.

Another way of depicting the difference between background and solution error estimates is through the "improvement vector" defined as:

$$\text{Improvement vector} = (\sigma_B - \sigma_S)/(\sigma_B) \qquad (5)$$

where σ_B and σ_S represent the error estimates on the background and solution, respectively. The improvement vector ranges from 0 if no new knowledge has been gained towards 1 as the solution error estimate approaches 0.

Improvement vectors for temperature and specific humidity are shown in Figure 5-7. The figure also shows the improvement vectors for forward-modelled error estimates in refractivity, see [RD.12].

Figure 5-7 shows considerable improvement in the knowledge of the atmospheric temperature in the range 9 km – 35 km and some minor improvement for specific humidity around 5 km. One must, however, keep in mind that the improvement vectors only reflect reality in so far as the background and observation error estimates are accurate.

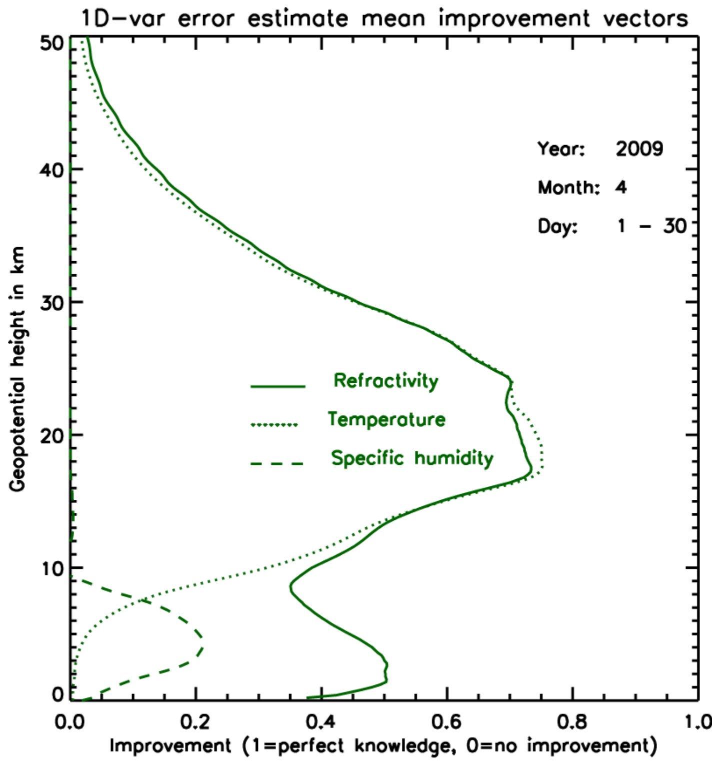

Figure 5-7 Mean improvement vectors for temperature (dotted line), specific humidity (dashed line) and refractivity (solid line).

5.2.2.3 Comparison to ECMWF Analyses

In this section we validate the 1D-Var solutions by comparison with co-located ECMWF (cycle 35r2) 4D-Var analyses at the closest synoptic hour. Since we use an ECMWF forecast (not analysis) as background for the 1D-Var processing we are comparing the 1D-Var result against a different ECMWF field than was the basis for the 1D-Var calculation. As an example for an observation at 4 UTC we nominally perform the 1D-Var processing using the ECMWF 3-hour forecast at 3 UTC. Here we will then compare against the 4D-Var analysis at 6 UTC which has assimilated data around the time of the observation, including (normally) the RO observation itself.

5.2.2.3.1 Temperature and specific humidity

Figure 5-8 shows comparisons of the 1D-Var temperature solution profiles against ECMWF analyses. The following trends may be noted:

- Temperatures are unbiased up to 35 km except for a -0.1°K bias around 8 km –12 km and a similar bias around 30 km. Above 35 km there is an increasing positive bias reaching 0.3°K at 45 km.

- Temperature standard deviations stay within 1.0°K below 30 km and then increase to 2.0°K at 50 km.

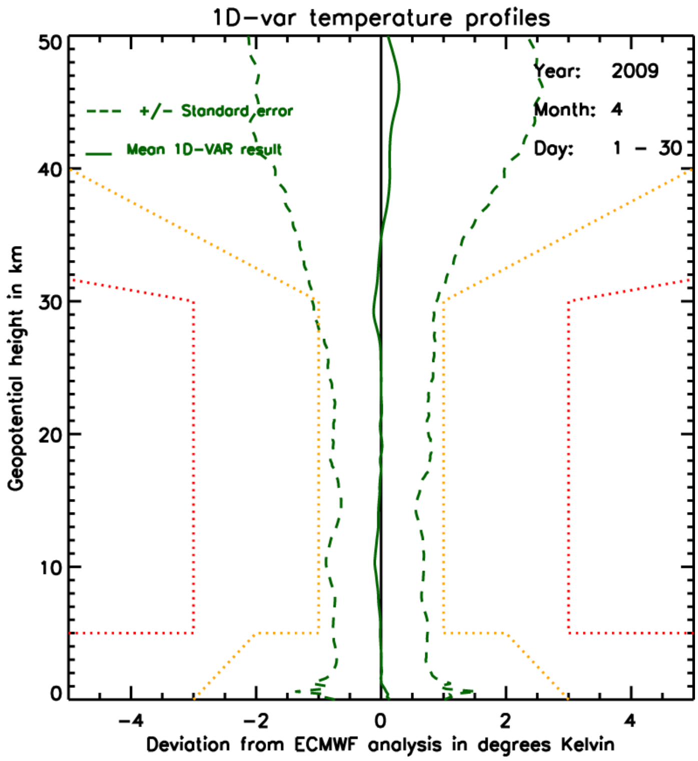

Figure 5-8 1D-Var solution data minus ECMWF 4DVAR analysis (cycle 35r2) for temperature. Also shown are the formal 'Threshold' (red) and 'Target' (orange) data quality requirements.

Figure 5-9 shows comparisons of 1D-Var specific humidity solution profiles against ECMWF analyses. These trends can be seen:

- Specific humidities show a negative bias peaking at about 3 km with a value of –0.2 g/kg.
- Specific humidity standard deviations peak at 0.8 g/kg 3 km above the ground dropping off above and below this level.

As discussed in [RD.12] we expect an improvement in processing at low altitudes to improve the quality of the specific humidity data product.

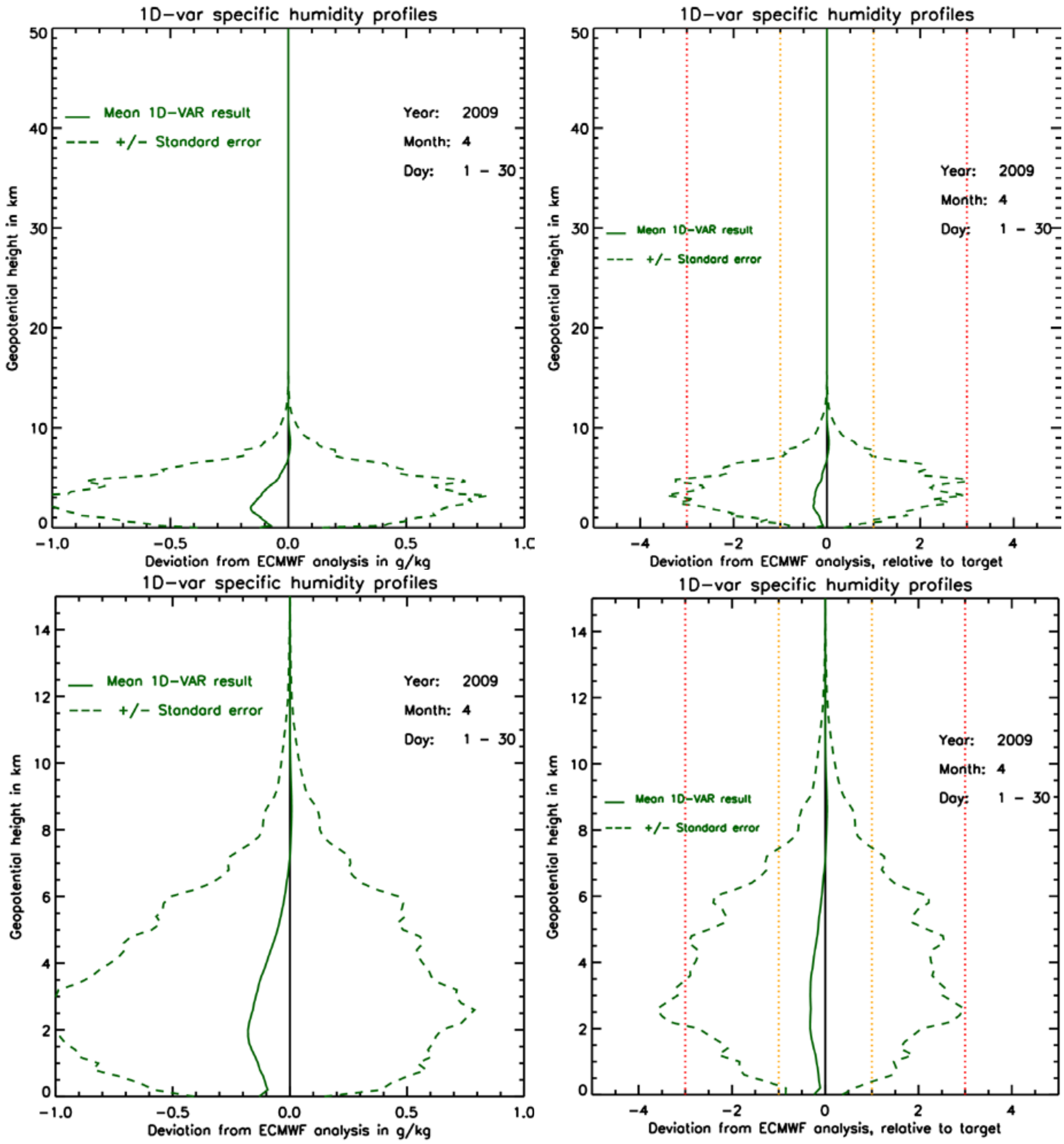

Figure 5-9 1D-Var solution data minus ECMWF 4D-Var analysis (cycle 35r2) for specific humidity. Left side shows absolute values, right side shows values relative to target requirements. Also shown on the left are the formal 'Threshold' (red) and 'Target' (orange) data quality requirements.

5.2.2.3.2 Pressure profile and surface pressure

The profile of pressure versus geopotential height is fully determined by the geoid together with the active 1D-Var variables surface pressure, temperature and specific humidity. The relative deviations of 1D-Var pressure from ECMWF analyses are shown in Figure 5-10.

- The pressure shows a negative bias of 0.1-0.2 % from 10 km and upwards.
- Pressure standard deviations increase from about 0.2 % at the ground to about 0.5 % at 40 km and increase more rapidly above this.

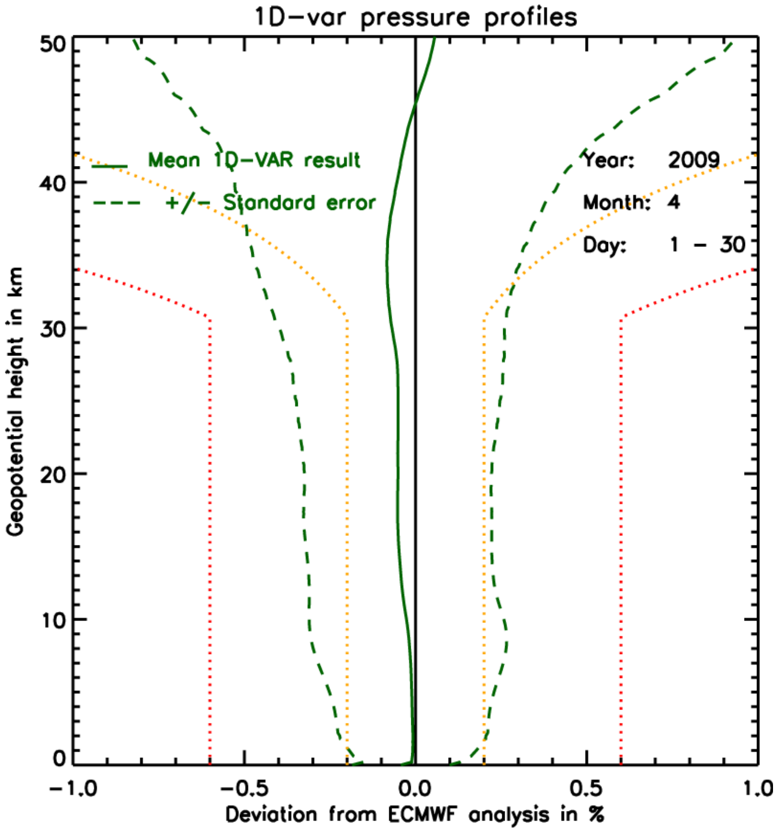

Figure 5-10 1D-Var solution data minus ECMWF 4D-Var analysis (cycle 35r2) for the pressure profile. Also shown are the formal 'Threshold' (red) and 'Target' (orange) data quality requirements for a typical profile.

Figure 5-11 shows the surface pressure deviation from ECMWF analyses as a histogram (left) and as a function of latitude (right).

- The surface pressure shows a negative bias of around 0.25 hPa
- Surface pressure standard deviation is about 1.0 hPa consistent with a 1D-Var solution error estimate that is only slightly improved from the input background error estimate of 1 hPa.
- The surface pressure bias and standard deviation are mostly unaffected by latitude.

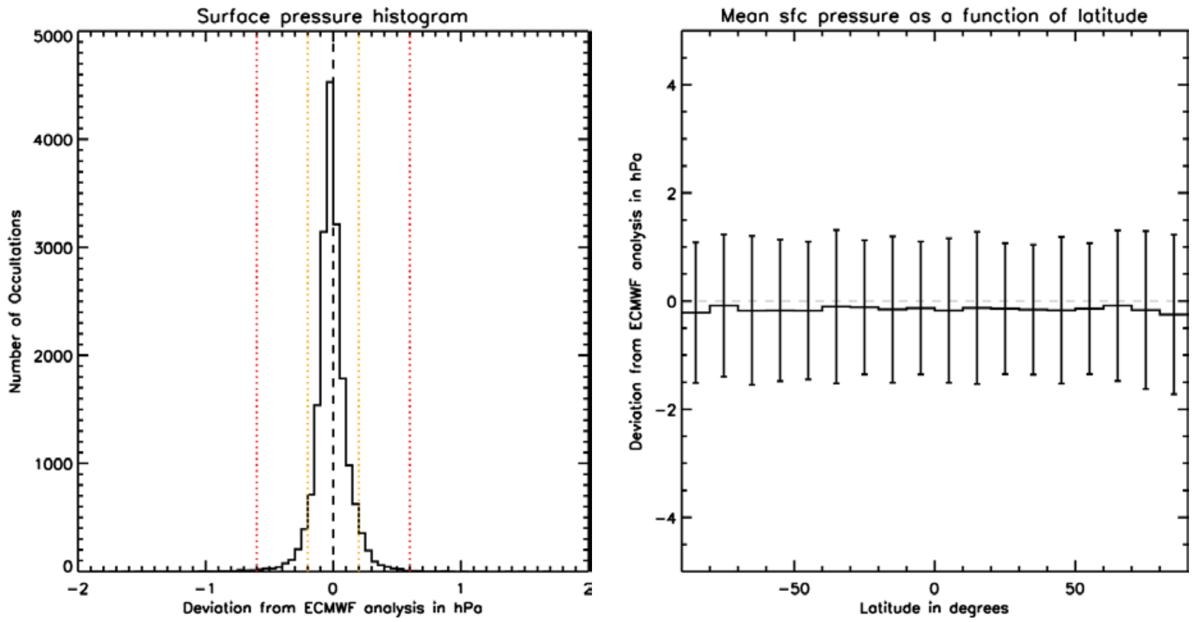

Figure 5-11 1D-Var solution data minus ECMWF 4D-Var analysis for surface pressure. On the left it is shown as a histogram. Also shown are the formal 'Threshold' (red) and 'Target' (orange) data quality requirements. On the right is shown the surface pressure deviations as a function of latitude. The error bars are the standard deviation of the surface pressure distribution (not the error on the mean).

For the improvement on forecasts, see [RD.12].

5.2.2.4 GRM-02 - 05 Compliance with Product Requirements

The formal requirements for the GRAS SAF data products are given in the Products Requirements Document [RD.2]. The threshold and target requirements are shown in Figure 5-5 and Figure 5-6, and Figure 5-8 to Figure 5-11.

Temperatures are within target values both when comparing against the 1D-Var solution error estimates (see [RD.12]) and when comparing to standard deviations of observed deviations from the ECMWF analysis (Figure 5-8).

Pressures are within threshold values and surface pressures are within target values (Figure 5-11), however the pressure profile shows standard deviations outside of target values at most altitudes above the surface (Figure 5-10)

Specific humidities are outside of target values. Standard deviations are within threshold (Figure 5-9), however, formal error estimates are outside of threshold (Figure 5-6).

6. DISSEMINATION METHODS

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

- GTS/RMDCN network;
- EUMETCast;
- Distribution to users (via HTTP 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: http://www.grassaf.org.

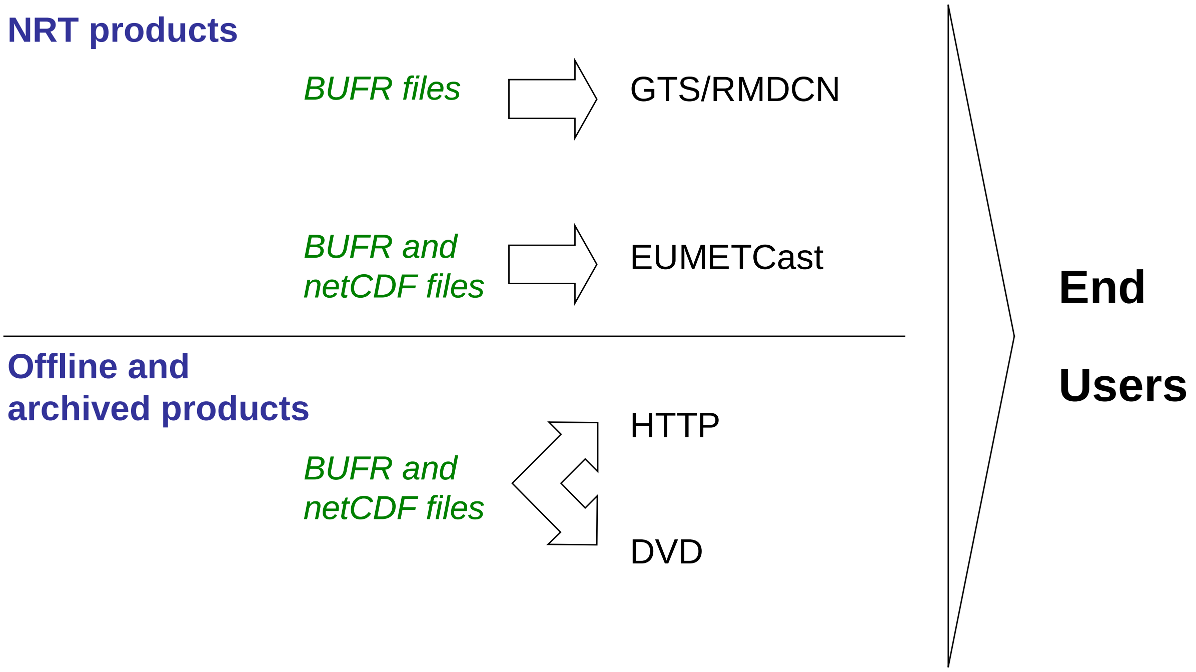

Figure 6-1 Overview of file formats and dissemination types

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 are disseminated via EUMETCast as well. These data are formatted in the netCDF format, see [RD.8]. The dissemination is done by uploading data to the EUMETCast dissemination FTP server. All NRT (BUFR and netCDF) files are also available from the archive for non-real time purposes.

6.2 Offline Distribution

The distribution of Offline products is via HTTP and/or DVDs.
HTTP data delivery is serviced over the internet, not over specialized, guaranteed performance operational lines. Unlike NRT products, which are actively broadcasted, Offline products are passively made available at the archive for HTTP retrieval by the user, or mailed by request on DVDs.

Appendix A. NetCDF Header Format

From the ROPP User Guide [RD.8, version 4.1]:

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 V1.1	
...%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 (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 geo-referencing 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 – 360.0	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)	Meaning if 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_summary 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 4.1]:

Level 1a

Structure element	Parameter	Description	Range	Units
`...%Lev1a%dtime`	Time since start	Time offset from time in header	-1.0 – 239.999	s
`...%Lev1a%snr_L1ca`	Signal to noise ratio L1 (ca–code)	Relative signal amplitude for L1 (ca–code)	0 – 50000	V/V
`...%Lev1a%snr_L1p`	Signal to noise ratio L1 (p–code)	Relative signal amplitude for L1 (p–code)	0 – 50000	V/V
`...%Lev1a%snr_L2p`	Signal to noise ratio L2 (p–code)	Relative signal amplitude for L2 (p–code)	0 – 50000	V/V
`...%Lev1a%phase_L1`	Excess phase L1	L1 phase corrected for geometry	$\pm$10000	m
`...%Lev1a%phase_L2`	Excess phase L2	L2 phase corrected for geometry	$\pm$10000	m
`...%Lev1a%r_gns`	Transmitter position	Earth centred Earth fixed[a] phase centre (X, Y, Z)[b]	$\pm$43000000	m
`...%Lev1a%v_gns`	Transmitter velocity	Earth centred inertial[a] phase centre (X, Y, Z)[b]	$\pm$10000	m/s
`...%Lev1a%r_leo`	Receiver position	Earth centred earth fixed[a] phase centre (X, Y, Z)[b]	$\pm$10000000	m
`...%Lev1a%v_leo`	Receiver velocity	Earth centred inertial[a] phase centre (X, Y, Z)[b]	$\pm$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 the tangential point of the generic bending angle profile	± 90	deg
`...%Lev1b%lon_tp`	Longitude		± 180	deg
`...%Lev1b%azimuth_tp`	Azimuth	GNSS to LEO azimuth w.r.t. true North at tangent point	$0 - 360.0$	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 User Guide [RD.8, version 4.1]:

Level 2a

Structure element	Parameter	Description	Range	Units
...%Lev2a%alt_refrac	Height	Geometric height above geoid (EGM–96)	−1000 – 150000	m
...%Lev2a%geop_refrac	Geopotential height	Geopotential height above geoid (EGM–96)	−1000 – 150000	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	0.0001 – 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%lat_2d*	Latitude position	Latitude position (*ROprof2d structure only*)	−90 – 90	deg
...*%Lev2c%lon_2d*	Longitude position	Longitude position (*ROprof2d structure only*)	−180 – 180	deg
...*%Lev2c%dtheta*	Angle	Angle between profiles (*ROprof2d structure only*)	$0 - \pi$	rad
...%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, ECMWF or METOFFICE 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