GRAS Satellite Application Facility

Validation Report:

GRM-01: Near Real Time Refractivity Profile (NRP)

(TR_PV-090-full_1)

Version 1.3

18 September 2009

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European Centre for Medium-Range Weather Forecasts (ECMWF)
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Document Signature Table

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Document Change Record

Issue/Revision	Date	By	Description
Version 0.1	12 May 2008	SSY	Initial draft
Version 1.0	16 May 2008	SSY	Initial release for ORR-A
Version 1.1	2 September 2008	SSY	Release for ORR-A close-out; according to RIDs #26, 44, 47–48, 50, 52, 56, 62, 65–66, 68, 74; detailed description of statistics now based on data from August, 2008
Version 1.2	26 March 2009	SSY	Release following pre-operational status of the refractivity product starting 25 March 2009; updates reflecting the latest PPF version of the bending angle product; deleted some sections and discussions no longer relevant because of the improved bending angle product; description of statistics now based on data from January, 2009
Version 1.2.1	1 April 2009	SSY	Release with minor updates following comments from EUMETSAT
Version 1.3	18 September 2009	SSY	Release including documentation for reduction of refractivity bias in the upper stratosphere using a two-parameter fit in combination with global search of climatological bending angles; description of statistics now based on data from April, 2009

Contents

1 Introduction

1.1 Purpose of document

This document presents the most recent validation results obtained for the GRAS SAF GRM-01 product (NRT refractivity profile). The current GRM-01 refractivity product version is 1.3 (in agreement with the version number of this report). The profiles are retrieved at DMI based on GRAS data (level 1b bending angle profiles) received from EUMETSAT. The data validated here are based on EUMETSATs PPF, version 2.12. The refractivity is retrieved at DMI using GPAC system version 0.3.5, with ‘Invert’ software version 3.4.042 and ROPP software version 3.0. Statistics are generated by comparison with ECMWF forecasts.

Chapter 2 describes the bending angle data received from EUMETSAT, and outlines briefly the processing at DMI, including pre-screening and QC. Validation of refractivity profiles are reported in Chapter 3. Chapter 4 lists open issues, and conclusions are made in Chapter 5.

1.2 Applicable & Reference documents

1.2.1 Applicable documents

The following documents have a direct bearing on the contents of this document.

[AD.1] Proposal for Continuous Development and Operations Phase (GRAS SAF CDOP) as endorsed by Council 30 November 2006 (SAF/GRAS/DMI/MGT/CDOP/001).

[AD.2] GRAS SAF Product Requirements Document (SAF/GRAS/METO/RQ/PRD/001).

1.2.2 Reference documents

The following documents provide supplementary or background information and could be helpful in conjunction with this document.

[RD.1] EPS GRAS Product Validation Board Report (EUM/MET/REP/08/0071, v1B).

[RD.2] EPS GRAS Product Validation Board Report (v2.9) (EUM/MET/REP/08/0071, v1D).

[RD.3] EPS GRAS Product Validation Board Report (v2.10) (EUM/MET/REP/08/0071, v2).

[RD.4] Gorbunov, M. (2004): Operational Processing of CHAMP data: Mathematical Methods, Data Filtering and Quality Control, and Software Implementations.

[RD.5] CT2 Processing Code: Operational Processing of CHAMP and COSMIC data: Mathematical Methods, Data Filtering and Quality Control (SAF/GRAS/DMI/ALG/CT2/001).

[RD.6] Gorbunov, M. E. (2002): Ionospheric correction and statistical optimization of radio occultation data. *Radio Sci.*, **37**, 1084, doi:10.1029/2000RS002370.

[RD.7] Radio Occultation Processing Package (ROPP), An Overview (SAF/GRAS/METO/UG/ROPP/001).

1.3 Acronyms, Abbreviations & Initialisms

BUFR Binary Universal Format for data Representation

CDOP	Continuous Development and Operational Phase (SAFs)
CHAMP	Challenging Mini–Satellite Payload
COSMIC	Constellation Observing System for Meteorology, Ionosphere & Climate
DMI	Danish Meteorological Institute
ECMWF	European Centre for Medium-Range Weather Forecasts
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GNSS	Global Navigation Satellite Systems
GPAC	GRAS SAF Processing and Archiving Center
GRAS	GNSS Receiver for Atmospheric Sounding (onboard MetOp)
MetOp	Meteorological Operational polar satellites (EUMETSAT)
NRT	Near Real Time
NWP	Numerical Weather Prediction
PLL	Phase-locked Loop
PPF	Product Processing Facility
PVB	Product Validation Board
PRD	Products Requirements Document
QC	Quality Control
RO	Radio Occultation
ROPP	Radio Occultation Processing Package
SAF	Satellite Application Facility (EUMETSAT)
SNR	Signal-to-noise Ratio
SO	Statistical Optimization

2 Background

2.1 EUMETSAT Bending angle data

EUMETSATs PPF 2.12 bending angle product was evaluated in several steps by PVB reports [RD.1; RD.2; RD.3] leading to the operational status of GRAS bending angle profiles on 15 April, 2008. The current operational version of the PPF is 2.15, but it does not differ from version 2.12 regarding the quality of the bending angle product.

Statistical analyses at EUMETSAT show that the GRAS data are of high quality and that the noise level (in off-line runs) at high altitudes is about 0.3 μrad, which is significantly lower than for other current RO missions. This noise level is, however, not yet achieved in the operational processing using the PPF.

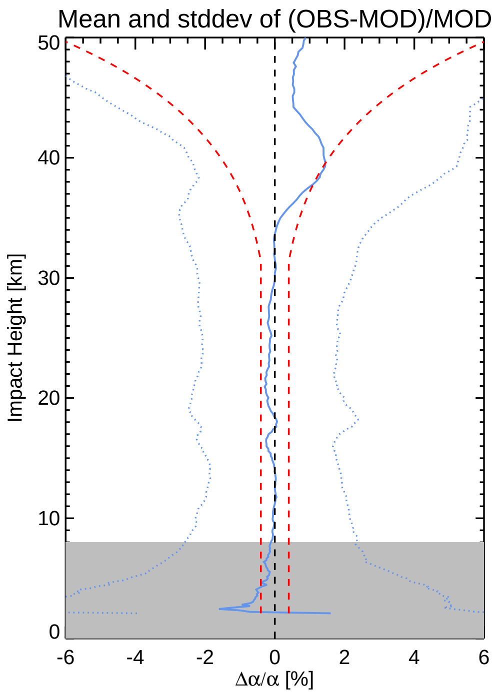

Figure 2.1: Bias (solid) and standard deviation (dotted) of GRAS bending angles compared to co-located ECMWF profiles (PPF 2.12, January 2009). Bending angle requirements are shown in red, they are expressed in absolute accuracy: 1 μrad or 0.4% (whichever is larger). The grey area indicates current processing limitation due to multipath [Figure courtesy of Axel von Engeln, EUMETSAT].

Figure 2.1 shows the statistics of EUMETSAT bending angle data when compared to ECMWF forward modeled results. The operational data provided by EUMETSAT to the GRAS SAF are currently based on phase-locked loop (PLL) tracking. By design, the GRAS receiver switches into raw sampling mode as soon as L2 tracking is lost (for setting occultations). For rising occultations, the onset of L2 tracking requires high SNR values. As EUMETSAT presently only provides data when both L1 and L2 carrier phases are being tracked, the SNR is expected to be sufficiently high for tracking errors not to occur. Below about 8 km, data may be affected by atmospheric multipath. Currently, the bending angle is retrieved using geometrical optics, and the bending angle in the grey area of Figure 2.1 should therefore be taken with care. The bias around 40 km is believed to be the result of a bias in the ECMWF model.

2.2 GRAS SAF processing at DMI

The level 1b profiles provided by EUMETSAT contains invalid data in some or all key fields at some altitudes when either L1 or L2 tracking were not acquired. Before the data are processed at DMI, they are pre-screened to include only connected blocks of valid data. Connected blocks of data at each end of a profile may be discarded until all values in the profile are valid. This way gaps are not introduced, but profiles may be cut shorter at each end.

The data are processed using GPAC software, version 0.3.5. The inversion to refractivity profiles are done by the software package 'Invert' [RD.5]. In particular, the L1 and L2 bending angles as functions of impact parameter are processed by 'Invert' to obtain a refractivity profile via the following steps:

1. Elimination of impact parameter ambiguities using iterative orthogonal projections and crawling monotonization
2. Linear interpolation to a fixed impact parameter grid with steps of about 50 m
3. Smoothing of bending angles using a sliding cubic polynomial fit with a window of about of 1 km.
4. Identification of a climatological bending angle profile:
   - Searching through a bending angle model (for every months, every 10 degrees latitude, and every 20 degrees longitude) based on the MSIS90 climatological model
   - For each model bending angle, $\varepsilon_{\text{model}}$, in this search, calcultation of two parameters (an offset, α, and a multiplication factor, β, in bending angle log-space) by linear regression to the data in the height interval 40–60 km (i.e. the best fit of $\alpha\varepsilon_{\text{model}}^{\beta}$ to the observed bending angle between 40 and 60 km)
   - Identification of the model bending angle for which $(\alpha, \beta - 1)$ has the smallest norm
5. Combined ionospheric correction and statistical optimization (SO) using a Bayesian optimal approach:
   - Calculation of strongly smoothed ionospheric signal (L1-L2)
   - Estimation of ionospheric signal and noise covariances using the highest part (above 50 km) of the occultation
   - Calculation of relative mean deviation of neutral bending angle from the model bending angle using the data at heights 12–35 km
   - Optimal linear combination using the covariances
6. Inversion to refractivity via the Abel transform using piece-wise analytical integration and asymptotic correction (i.e., assuming exponential decrease of the bending angle profile above $\sim$100 km)

A detailed description of methods and algorithms can be found in [RD.4; RD.5; RD.6].

The 'Invert' software returns the refractivity (as well as error covariances) at a grid with steps of about 100 m, which typically corresponds to about 800 vertical levels. The refractivity is written to a NetCDF file together with the EUMETSAT high resolution bending angle profile and other key parameters. The NetCDF file is then passed to ROPP subroutines [RD.7] and the profiles are thinned to 247 pre-defined levels when written to the BUFR format.

2.3 Quality control at DMI

The refractivity profiles are quality-controlled and flagged as ‘bad’ if one of the following is true:

1. Refractivity profile does not reach below 20 km
2. One or more points in the refractivity profile below 35 km differ by more than 10% from the corresponding profile obtained from the most recent ECMWF forecast.
3. Refractivity profile reach below model surface
4. Altitude is not monotonically increasing
5. Refractivity is negative

This QC is referred to as QC-1.0, and currently flags about 7% of the data as ‘bad’. Additionally, the refractivity is flagged as bad if the bending angle is flagged as ’bad’.

3 Validation

In this chapter, the retrieved refractivity profiles (before the thinning to the 247 pre-defined levels) are compared to the corresponding ECMWF profiles (forward modeled to refractivity as a function of altitude) by interpolating both to a common vertical grid.

3.1 Statistics of NRT data

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).

The first item on the QC list in section 2.3 is responsible for the number of observations in all plots reaching a maximum at (and staying the same above) 20 km altitude.

Figure 3.1 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.

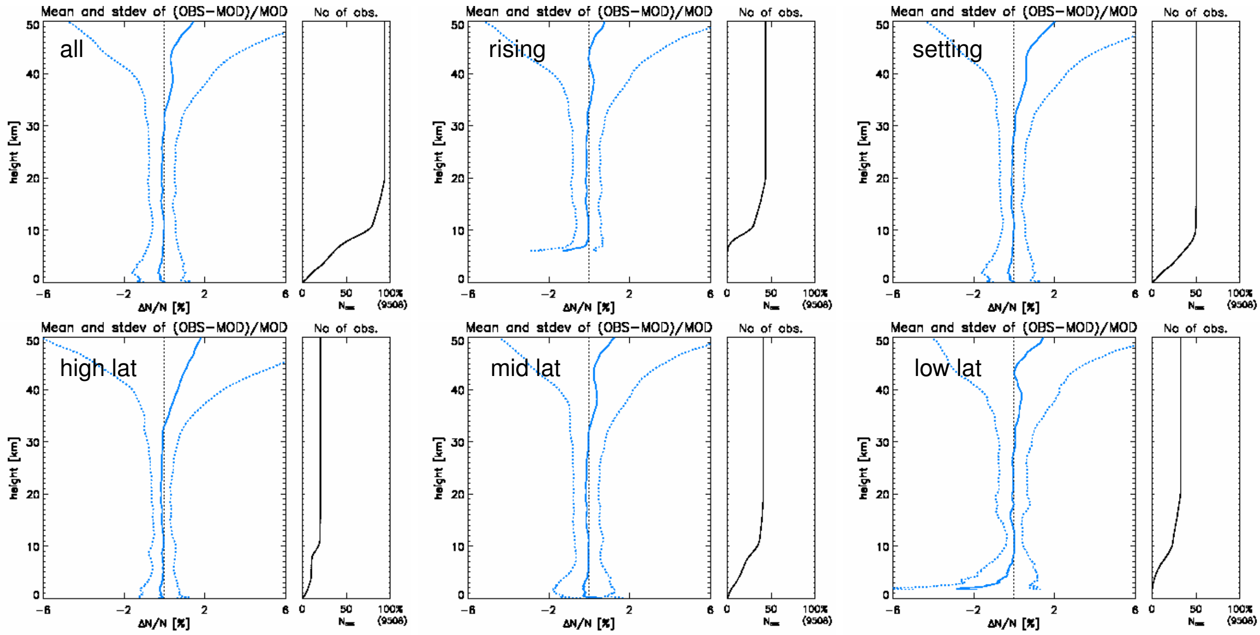

Figure 3.1: Refractivity results for the month of April, 2009 (15 days), compared to ECMWF forecasts: The upper panels show all occultations (left), rising (mid), and setting (right). The lower panels show the results for high latitudes (left), mid latitudes (mid), and low latitudes (right). Solid blue 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 about 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 we see 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.

3.2 Compliance with requirements

The requirements for the GRAS SAF products are given in the Products Requirements Document (PRD) [AD.2]. Figure 3.2 shows that the standard deviation of the NRT refractivity product is close to or within the target requirement.

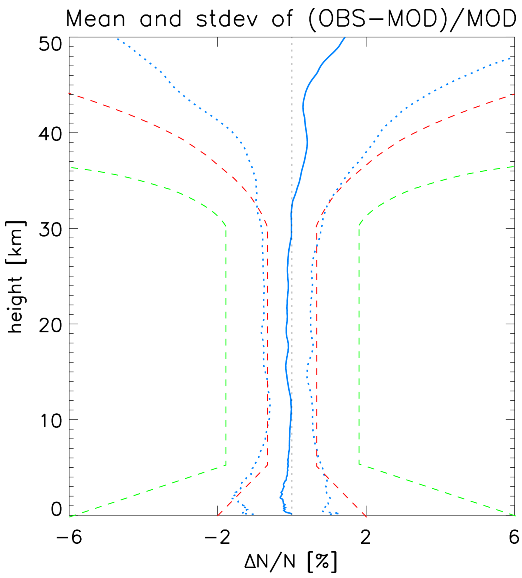

Figure 3.2: Same as the first panel in Figure 3.1, but with dashed lines superimposed indicating the target (red) and threshold (green) accuracies for NRT refractivity according to the PRD [AD.2].

4 Open issues

There are a few open issues and improvements that could be implemented in future updates. They are listed and discussed below.

4.1 Revision of QC

The current QC flags about 7% of all profiles as ‘bad’. More than half of these profiles are flagged because they do not reach below 20 km. It is possible that some of these profiles are good and could be used above 20 km.

If one or more points in the refractivity profile below 35 km differ by more than 10% from the corresponding profile obtained from the most recent ECMWF forecast, the profile is flagged as ’bad’. This check could be revised both with respect to the altitude range for this check and the threshold. After the current QC check, large discrepancies from the ECMWF model of up to 10% are rare below 35 km, but do occur a few times almost every day.

4.2 Processing in the lower troposphere

The operational data provided by EUMETSAT to the GRAS SAF are currently based on phase-locked loop tracking. It is anticipated that future versions of the bending angle product will be based on open loop tracking (raw sampling mode) in the lower troposphere.

Currently, the bending angle is retrieved using geometrical optics, but it is anticipated that future versions of the bending angle product will be processed using radio holographic methods.

5 Conclusion

On a daily basis, the GPAC processes about 650 EUMETSAT bending angle profiles into refractivity profiles. Of these about 7% fail a number of QC checks and are flagged as 'bad'.

The results in this report show that the NRT refractivity is of a sufficient quality for NWP at least above 8 km. The NRT bending angle is retrieved using geometrical optics, and the NRT refractivity profiles below 8 km is therefore expected to be of a reduced quality in regions where multipath propagation is common (primarily at low latitudes).

The bias plus the standard deviation of the NRT refractivity, as compared to ECMWF forecasts, is close to or within the target accuracy requirements of the PRD.

A few open issues are being investigated, but none of them are judged to be critical for using the retrieved NRT refractivity profiles in NWP.