The EUMETSAT Network of Satellite Application Facilities

ROM SAF

Radio Occultation Meteorology

ROM SAF CDOP-2

Validation Report: Near Real-Time Level 2a Refractivity Profiles: Metop-A (GRM-01, NRPMEA) and Metop-B (GRM-40, NRPMEB)

Version 1.6

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European Centre for Medium-Range Weather Forecasts (ECMWF)
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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
Version 1.4	26 March 2014	SSY	Release combining the validation for Metop-A and Metop-B; prepared to obtain operational status of the Metop-B refractivity product after the upload of new tracking parameter settings to the Metop-A and -B satellites in 2013; description of statistics now based on data from November, 2013; included a section on external user validation
Version 1.5	10 October 2016	SSY	Release for ORR-8 review; introduction of Wave Optics processing; description of statistics now based on GS2 test data from September, 2016
Version 1.6	21 October 2016	SSY	Updated version after ORR-8 review; implemented RIDs #3, 5, 6

ROM SAF

The Radio Occultation Meteorology Satellite Application Facility (ROM SAF) is a decentralised processing center under EUMETSAT which is responsible for operational processing of GRAS radio occultation (RO) data from the Metop satellites and radio occultation data from other missions. The ROM SAF delivers bending angle, refractivity, temperature, pressure, humidity, and other geophysical variables in near-real time for NWP users, as well as reprocessed data (Climate Data Records) and offline data for users requiring a higher degree of homogeneity of the RO data sets. The reprocessed and offline data are further processed into globally gridded monthly-mean data for use in climate monitoring and climate science applications.

The ROM SAF also maintains the Radio Occultation Processing Package (ROPP) which contains software modules that aids users wishing to process, quality-control and assimilate radio occultation data from any radio occultation mission into NWP and other models.

The ROM SAF Leading Entity is the Danish Meteorological Institute (DMI), with Cooperating Entities: i) European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading, United Kingdom, ii) Institut D'Estudis Espacials de Catalunya (IEEC) in Barcelona, Spain, and iii) Met Office in Exeter, United Kingdom. To get access to our products or to read more about the ROM SAF please go to:http://www.romsaf.org.

List of Contents

1 Introduction

1.1 Purpose of document

This document describes the validation results for the ROM SAF NRT level 2a products, GRM-01 and GRM-40: NRT refractivity profiles from the GRAS instrument on Metop-A (NRPMEA) and Metop-B (NRPMEB). The report is submitted for an Operational Readiness Review in order to decide on the validation status of the GRM-01 and GRM-40 products with the introduction of Wave Optics (WO) processing of bending angles at the EUMETSAT CF.

The product version numbers of both GRM-01 and GRM-40 validated in this report is 1.6. The high-resolution level 1b data are based on EUMETSATs PPF, version 4.4.0. The refractivity is retrieved at DMI using GPAC system version 0.4.2, with 'Invert' software version 3.5.044 and ROPP software version 8.1. Quality Control (QC) of the GRAS data analysed in this report is done with version QC-1.3.

Chapter 2 gives the background for the validation, and Chapter 3 contains the validation results. Open issues are listed in Chapter 4, and conclusions are made in Chapter 5.

1.2 Applicable and Reference documents

1.2.1 Applicable documents

The following list contains documents with a direct bearing on the contents of this document.

[AD.1] CDOP-2 Proposal: Proposal for the Second Continuous Development and Operations Phase (CDOP-2), Ref: SAF/GRAS/DMI/MGT/CDOP2/001 Version 1.1 of 21 March 2011, approved by the EUMETSAT Council in Ref. EUM/C/72/11/DOC/10 at its 72^{nd} meeting on 28-29 June 2011;

[AD.2] CDOP-2 Cooperation Agreement: Agreement between EUMETSAT and DMI on the Second Continuous Development and Operations Phase (CDOP-2) of the Radio Occultation Meteorology Satellite Applications Facility (ROM SAF), approved by the EUMETSAT Council in Ref. EUM/C/72/11/DOC/15 at its 72^{nd} meeting on 28-29 June 2011 and signed on 29 June 2011 in Copenhagen;

[AD.3] ROM SAF CDOP-2 Product Requirements Document, Ref. SAF/ROM/DMI/MGT/PRD/001;

[AD.4] ROM SAF CDOP-2 Service Specifications, Ref. SAF/ROM/DMI/RQ/SESP/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] Algorithm Theoretical Baseline Document: Level 2a Refractivity Profiles; Ref. SAF/ROM/DMI/ALG/REF/001;
[RD.2] The Radio Occultation Processing Package (ROPP) – An Overview, Ref. SAF/ROM/METO/UG/ROPP/001;
[RD.3] The Radio Occultation Processing Package (ROPP) User Guide, Part I: Input/Output module, Ref. SAF/ROM/METO/UG/ROPP/002;
[RD.4] WMO FM94 (BUFR) Specification For Radio Occultation Data, Ref. SAF/ROM/METO/FMT/BUFR/001;
[RD.5] S. Syndergaard, K. B. Lauritsen, H. Wilhelmsen, and K. R. Larsen, Analysis of Metop/GRAS data products with new on-board tracking parameters and L2 extrapolation. Presented at the Joint OPAC-5 & IROWG-3 Workshop, Seggau Castle, Leibnitz, Austria, 5–11 September 2013, http://www.uni-graz.at/opacirowg2013/data/public/files/opac2013_Stig_Syndergaard_presentation_730.pdf;
[RD.6] Operations Report 2015 H2, Ref. SAF/ROM/DMI/MGT/OR15/002;

1.3 Acronyms and abbreviations

BAROCLIM	Bending Angle Radio Occultation Climatology
BUFR	Binary Universal Format for data Representation
CF	Central Facility
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
GO	Geometrical Optics
GPAC	GNSS Processing and Archiving Center
GRAS	GNSS Receiver for Atmospheric Sounding
Metop	Meteorological operational polar
MSL	Mean Sea Level
NCO	Numerically Controlled Oscillator
NRT	Near Real-Time
NWP	Numerical Weather Prediction
PPF	Product Processing Facility
PRD	Products Requirements Document
QC	Quality Control
RO	Radio Occultation
ROM SAF	Radio Occultation Meteorology SAF
ROPP	Radio Occultation Processing Package
SAF	Satellite Application Facility
SLTA	Straight Line Tangent Altitude
SNR	Signal-to-noise Ratio
UTLS	Upper Troposphere Lower Stratosphere
WO	Wave Optics

1.4 Definitions

RO data products from the GRAS instrument onboard Metop and RO data from other missions are grouped in data levels (level 0, 1, 2, or 3) and product types (NRT, Reprocessed, or Offline). The data levels and product types are defined below. The lists of variables should not be considered as the complete contents of a given data level, and not all data may be contained in a given data level.

Data levels:

Level 0: Raw sounding, tracking and ancillary data, and other GNSS data before clock correction and reconstruction;

Level 1A: Reconstructed full resolution excess phases, total phases, pseudo ranges, SNR's, orbit information, I, Q values, NCO (carrier) phases, navigation bits, and quality information;

Level 1B: Bending angles and impact parameters, tangent point location, and quality information;

Level 2: Refractivity, geopotential height, "dry" temperature profiles (level 2A), pressure, temperature, specific humidity profiles (level 2B), surface pressure, tropopause height, planetary boundary layer height (level 2C), ECMWF model level coefficients (level 2D); quality information;

Level 3: Gridded or resampled data, that are processed from level 1 or 2 data, and that are provided as, e.g., daily, monthly, or seasonal means on a spatiotemporal grid, including metadata, uncertainties and quality information.

Product types:

NRT product: Data product delivered less than 80 min (95%; EPS-SG Global), 40 min (95%; EPS-SG Regional) and 3 hours (EPS) after measurement;

Reprocessed product: Climate Data Record (CDR) covering an extended time period of several years, generated using a fixed set of processing software in order to provide a homogeneous data record appropriate for climate usage;

Offline product: Data product which typically extends a CDR from a reprocessing, thus providing an "interim" CDR; delivered from less than 5 days to up to 6 months after measurement depending on the requirements.

2 Background

2.1 EUMETSAT bending angle data

The validation in this report is based on high-resolution level 1b bending angle data from the GS2 environment at the EUMETSAT Central Facility (CF), PPF 4.4.0. These data have been made available to DMI via FTP for both Metop-A and Metop-B since August 3, 2016. The PPF 4.4.0 is identical to PPF 4.4.2 (the operational code since October 20, 2016) except for changes related to the thinned data. Since the ROM SAF processes un-thinned data the validation is also valid for PPF 4.4.2.

2.2 ROM SAF processing

The data presented in this report were processed at the ROM SAF at DMI using GPAC version 0.4.2. Details on the operational processing at DMI can be found in [RD.1]. The GPAC system returns the refractivity in both high-resolution (with a vertical spacing of about 100 m) and in low-resolution (247 pre-defined levels between the surface and 60 km) [RD.2]. The high-resolution refractivity profile is written to a NetCDF file together with the EUMETSAT high-resolution bending angle profile and other key parameters. The low-resolution refractivity profile is disseminated in NRT in BUFR format together with the EUMETSAT low-resolution bending angle profile. The bending angle profile in the BUFR dissemination from DMI is identical to that disseminated by EUMETSAT, although very small differences may exist because of round-off errors. The refractivity profile in the BUFR dissemination from DMI is a thinned version of the high-resolution refractivity profile without any smoothing. The high-resolution refractivity profile is based on the EUMETSAT L1 and L2 (extrapolated) high-resolution bending angle profiles.

The validation of refractivity in this report is based on 5 days of data from September 1 to September 5, 2016. A total of 6759 bending angle profiles were input to the GPAC system, of which 94.9% were flagged as nominal from EUMETSATs side. Of the nominal bending angle profiles, 4.9% failed the GPAC processing, meaning that no refractivity profile was obtained in those cases.

2.3 Quality Control (QC)

The refractivity products are quality-controlled and flagged as non-nominal if one of the following is true:

1. Bending angle profile is flagged as non-nominal by EUMETSAT
2. Retrieved altitude is not monotonically increasing
3. One or more points in the refractivity profile is negative
4. Refractivity profile does not reach below 20 km
5. One or more points in the refractivity profile differ by more than a given threshold below 10 km when compared to a corresponding profile obtained from the most recent ECMWF forecast:

    - The threshold is linearly decreasing from 20% at 0 km to 5% at 10 km

6. One or more points in the refractivity profile differ by more than a given threshold between 10 and 40 km when compared to a corresponding profile obtained from the most recent ECMWF forecast:
    - The threshold is set to 5% between 10 and 30 km
    - The threshold is set to 10% between 30 and 40 km
7. L1 and L2 bending angles for rising occultations diverge beyond a given threshold:
    - The threshold is set to $|\Delta\alpha_{strat} - \Delta\alpha_{trop}| > 0.5$ mrad

    where $\Delta\alpha_{strat}$ is the median of L1−L2 bending angle between 30 and 60 km, and $\Delta\alpha_{trop}$ is the median of L1−L2 bending angle between 0 and 20 km
8. One or more points in the LC bending angle profile (un-optimized) differ by more than a given threshold between 30 and 70 km when compared to the background bending angle profile used for the statistical optimization:
    - The threshold is set to the maximum of 25% and 5 μrad between 30 and 60 km
    - The threshold is set to 20 μrad between 60 and 70 km

Two of these checks are new (number 5 and number 8), and have been implemented in the course of the validation of the WO data. They will be discussed specifically in paragraphs below.

The QC checks are performed in the above order, and when a profile fails a QC check, the remaining checks are not performed for that profile (the first check is an exception: bending angles marked non-nominal by EUMETSAT are still checked further at the ROM SAF, but those that fail one of the remaining checks are not reflected in Table 2.1). If a profile pass all the QC checks it is considered nominal and flagged as such. Additionally, nominal profiles are marked with a percent confidence value (termed 'refrac_qual' in NetCDF files; 'percent confidence' in BUFR) of 100 above the ECMWF model surface, but always with a percent confidence value of 0 below the model surface [RD.3; RD.4]. Non-nominal profiles are marked with a percent confidence value of 0 throughout the profile.

This QC is referred to as version QC-1.3, and flags about 75% of the processed profiles as nominal. For the data investigated in this report, i.e., data in the period from September 1 to September 5, 2016, Table 2.1 shows the percentage of profiles (out of a total of 3375 for Metop-A; 3384 for Metop-B) that failed each of the QC checks (only the first fail in the above order is registered), or did not result in a refractivity profile even though the bending angle was flagged as nominal.

Table 2.1: *Percentage of profiles failing each of the QC checks. The first column with QC check 0 indicates the percentage of profiles that failed the processing at GPAC, even though the bending angle was flagged as nominal. A percentage of 0.0 means that the number is less than 0.05%.*

QC check	0	1	2	3	4	5	6	7	8	All
Metop-A	4.5%	5.7%	0.0%	0.1%	0.0%	4.4%	1.4%	0.0%	14.1%	30.3%
Metop-B	4.8%	4.5%	0.0%	0.2%	0.0%	3.9%	1.0%	0.1%	14.6%	29.0%

A total of 4756 occultations (2354 for Metop-A; 2402 for Metop-B) were thus successfully processed and flagged as nominal, which results in an average of about 951 occultations per day (~471 for Metop-A; ~480 for Metop-B).

Figure 2.1 shows the global refractivity statistics against ECMWF forecasts for the WO data validated in this report compared to the Geometrical Optics (GO) data from the NRT stream for the same time period. The statistics for the WO data includes only the occultations that passed the QC checks described above, whereas the GO NRT data includes only the occultations that passed the QC checks described in [RD.6] (QC-1.2; excluding checks number 5 and 8, and where check number 6 was applied down to 8 km).

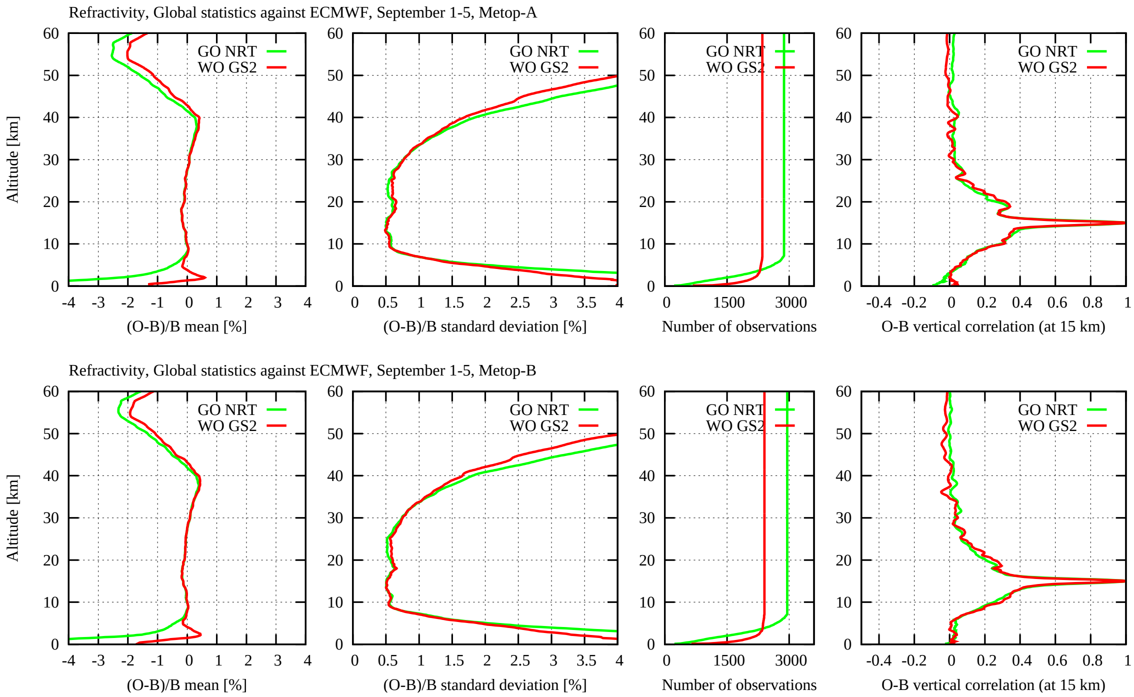

Figure 2.1: *Global statistics (5 days in September 2016; separated into setting and rising occultations) comparing refractivity to corresponding profiles from ECMWF forecasts. Top: Metop-A. Bottom: Metop-B. From left to right: Mean; standard deviation; number of observations; and correlation at 15 km with the rest of the profile. All as a function of altitude above MSL.*

Several things can be noted. First, the quality of the WO GS2 data below 8 km has improved as compared to the GO NRT data, and profiles generally reach down to lower altitudes. The mean difference is considerably smaller, and the standard deviation is also somewhat reduced. The new QC check number 5 has only a minor influence on the statistics below 8 km, but has reduced the mean difference and standard deviation slightly as compared to statistics without it. Second, between ~18 and 30 km, the standard deviation is slightly larger for the WO GS2 data, which is due to less smoothing than in the GO NRT data (C. Marquardt, personal communication). However, above ~35 km the standard deviation for the WO GS2 data is smaller, and this is due to the new QC check number 8. Without this check, the standard deviation would be larger also at these altitudes. Finally, the number of profiles in the statistics is considerably smaller for the WO GS2 data than for the GO NRT data. This is a consequence of the new QC checks 5 and 8.

QC check number 5:
QC check number 5 was implemented to flag profiles where the refractivity (and derived dry temperature) deviates significantly from the corresponding ECMWF forecasts below 10 km. This check flags about 4% of all profiles as non-nominal. Figure 2.2 shows a couple of cases that are quite characteristic for many of the profiles caught by check number 5. Although the dry temperature is not an official ROM SAF product, it is derived from the refractivity and is plotted here because it nicely shows a presumably false inversion around 5 km in both cases. The inversion correlates with a sudden increase in the EUMETSAT high-resolution bending angle around 7 km impact height. Without the dry temperature plot it is difficult to judge if the bending angle could be correct, but given the result in dry temperature, and its comparison to the ECMWF forecast, in particular, it becomes clear that the increase in bending angle can not be correct. Normally, temperature inversions in the atmosphere sit at a lower altitude or are less pronounced at such a relatively high altitude. There are many similar cases, and is not given that QC check number 5 catches them all, but it should catch the most prominent ones.

QC check number 8:
QC check number 8 was implemented to flag profiles where the refractivity (and derived dry temperature) exhibits large oscillations above 30 km. This check flags about 14% of all profiles as non-nominal. Figure 2.3 shows a couple of cases that are quite characteristic for many of the profiles caught by check number 8. Again, we plot the dry temperature because it nicely shows the effect of the large oscillations in the bending angle, and the size is a good indication that they can not be correct. The second of these cases also show the L1 and L2 bending angles, with a clear indication that the increased smoothing at EUMETSAT of the WO GS2 data at around 50 km seems to be different on L2 than on L1. We also note that the GO NRT data does not seem to have the same problem although the L1 and L2 bending angles of the GO NRT data are less smooth than the corresponding WO GS2 data at this altitude. There are many similar cases, and is not given that QC check number 8 catches them all, but it should catch the most prominent ones.

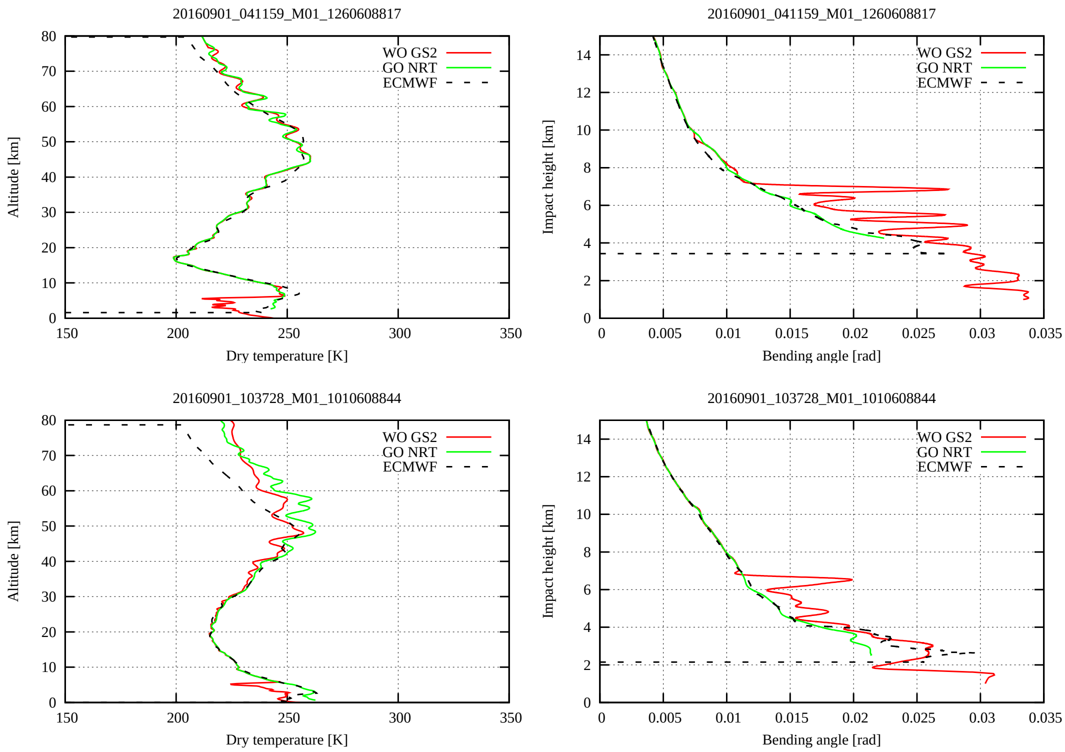

Figure 2.2: *Two examples of profiles marked non-nominal due to QC check number 5. Left: dry temperature. Right: bending angle below 15 km.*

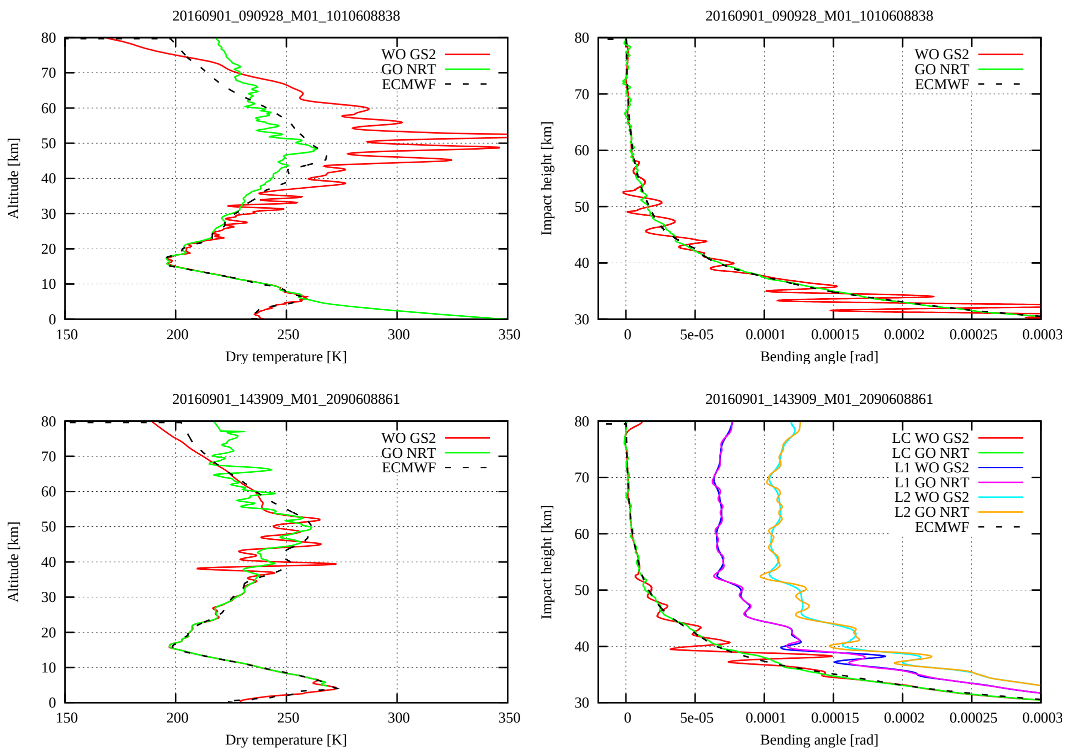

Figure 2.3: *Two examples of profiles marked non-nominal due to QC check number 8. Left: dry temperature. Right: bending angle above 30 km.*

3 Validation

3.1 Method

The retrieved refractivity profiles were compared to corresponding ECMWF profiles (forward modeled to refractivity as a function of altitude) by interpolating both to a common vertical grid. The ECMWF profiles were obtained from 6 or 12 hour forecasts (whichever was closest in time to the observation time) originating from analyses at 0 or 12 UTC, and interpolated to the reference locations of the occultations. Statistics were separated into setting and rising occultations, and also binned into 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).

3.2 Results

Figure 3.1 shows the global refractivity statistics, for Metop-A in the top panels, and for Metop-B in the bottom panels. The figure (as does the following figures) includes only the occultations that passed the QC checks described in Section 2.3. The panels from left to right show the mean difference to ECMWF profiles, the standard deviation, the number of observations, and the correlation of the difference at 15 km with that over the rest of the profile. The correlation is the ordinary Pearson correlation using relative differences. The number of samples included is generally different at each level, depending on how far down the profiles reach. Figures 3.2–3.4 show the same as Figure 3.1, but for low, mid, and high latitudes, respectively. Figure 3.5 shows the bending angle statistics for high latitudes for the same profiles as in Figure 3.4.

3.3 Discussion

As seen there is a difference between setting and rising occultations for both Metop-A and Metop-B. In particular, the standard deviation of rising occultations are significantly larger than that of setting occultations between 10 and 20 km. This difference is related to the L2-extrapolation performed at EUMETSAT and the resulting larger vertical error correlations in bending angle, which propagates to refractivity. The right-most panel in each of the figures below shows the relatively broader vertical correlation at 15 km for rising occultations. The larger standard deviation for rising occultations is hardly seen in the bending angle statistics, not even at high latitudes where it is very clear in the refractivity. An analysis of the consequences of the L2-extrapolation for the retrieval of refractivity can be found in [RD.5].

There is also a clear difference between rising and setting occultations below about 8 km, both in the mean and in the standard deviation, and mostly so at high latitudes where there is a large positive mean difference and larger standard deviation for setting occultations. These differences are not fully understood, but are consistent with similar differences in the bending angle.

The differences in the mean and standard deviation (against ECMWF forecasts) for Metop-A and Metop-B observed here are smaller (or at most of similar size) than the usual day-to-day variations in the statistics for either Metop-A or Metop-B (not shown).

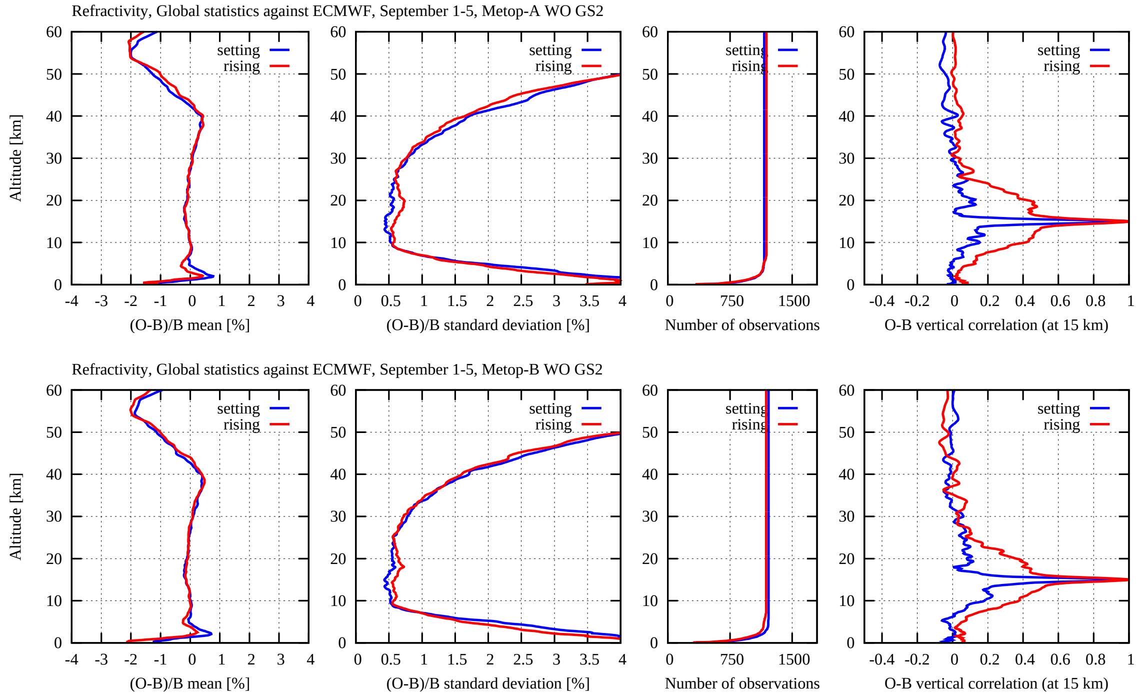

Figure 3.1: *Global statistics (5 days in September 2016; separated into setting and rising occultations) comparing refractivity to corresponding profiles from ECMWF forecasts. Top: Metop-A. Bottom: Metop-B. From left to right: Mean; standard deviation; number of observations; and correlation at 15 km with the rest of the profile. All as a function of altitude above MSL.*

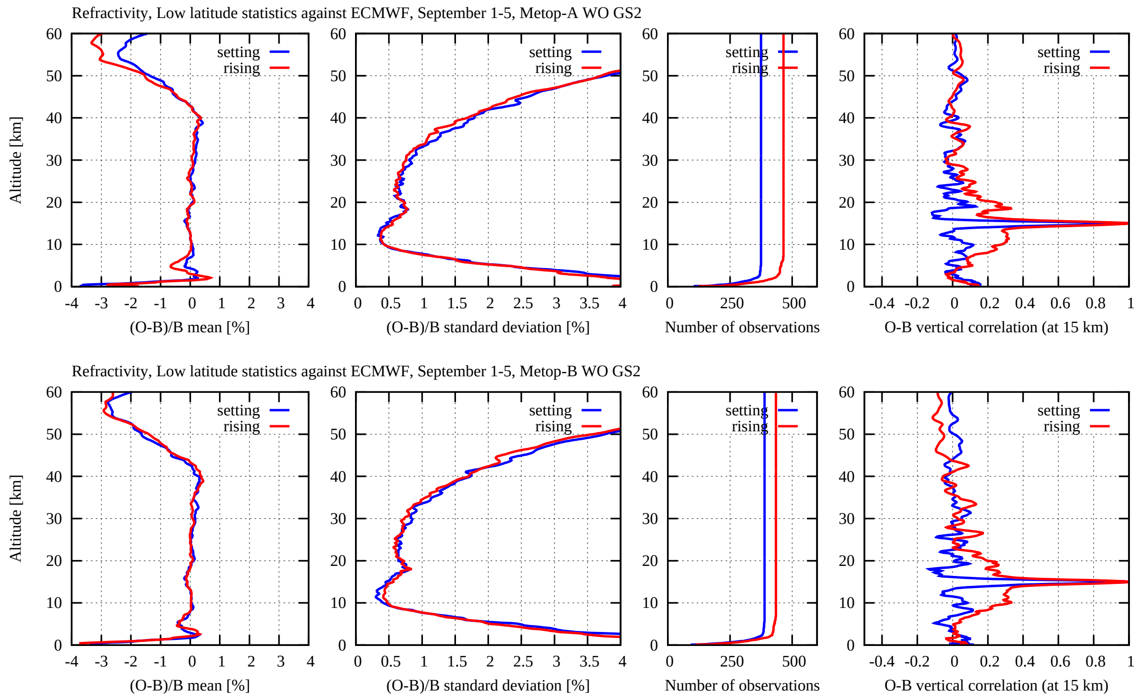

Figure 3.2: *Low latitude statistics. Otherwise same as Figure 3.1.*

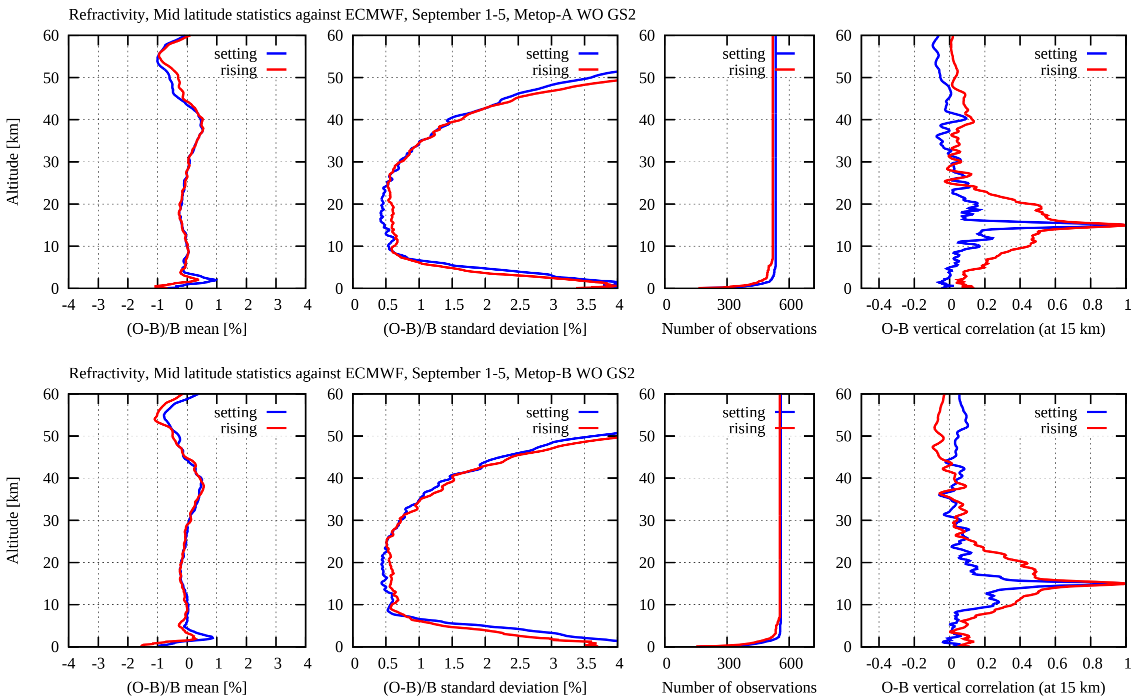

Figure 3.3: *Mid latitude statistics. Otherwise same as Figure 3.1.*

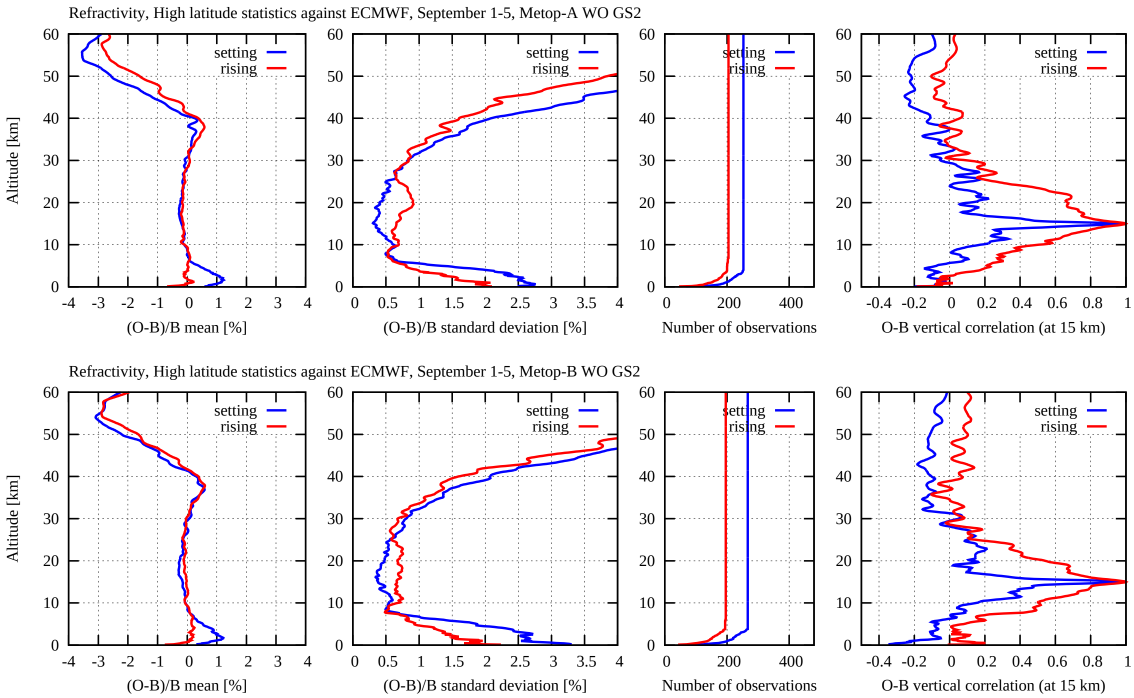

Figure 3.4: *High latitude statistics. Otherwise same as Figure 3.1.*

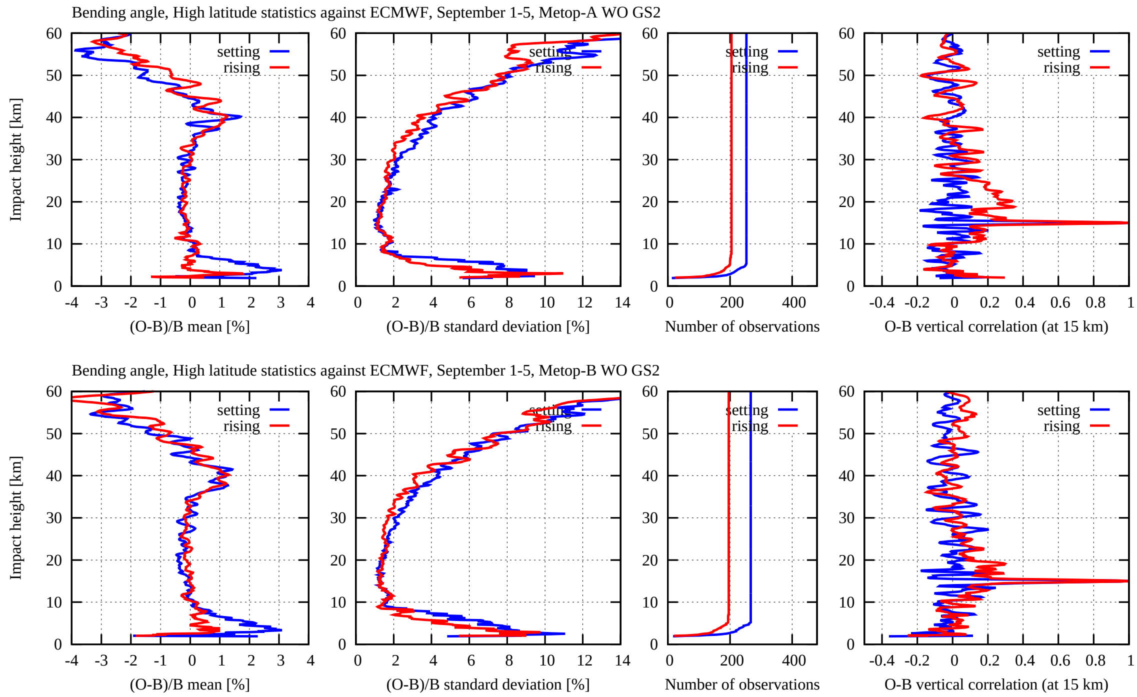

Figure 3.5: *High latitude statistics comparing the EUMETSAT bending angle to corresponding profiles from ECMWF forecasts. To be compared with Figure 3.4.*

3.4 Compliance with requirements

The formal requirements for the ROM SAF data products are stated in the Products Requirements Document (PRD) [AD.3]. The particular requirements applicable to the level 2a refractivity products are here reiterated in Table 3.1.

Disregarding the results below 8 km, Figure 3.6 shows that the mean plus/minus the standard deviation of the refractivity products is close to or within the target requirement, for both rising and setting occultations, and for both Metop-A and Metop-B. Below 8 km compliance with the PRD in terms of the target is not possible, but compliance in terms of the threshold is.

Table 3.1: *Threshold, Target, and Optimal accuracies according to the PRD [AD.3].*

Threshold	Target	Optimal
0–5 km: 1.8%–6% 5–30 km: 1.8% 30–50 km: 0.09 N-units	0–5 km: 0.6%–2% 5–30 km: 0.6% 30–50 km: 0.03 N-units	0–5 km: 0.3%–1% 5–30 km: 0.3% 30–50 km: 0.02 N-units

3.5 Service specifications

The Service Specifications [AD.4] describes the commitments by the ROM SAF related to the services and products provided to the users. These commitments include a set of operational accuracy targets that should be met by the level 2a refractivity products, and which is monitored regularly and documented as part of normal operations.

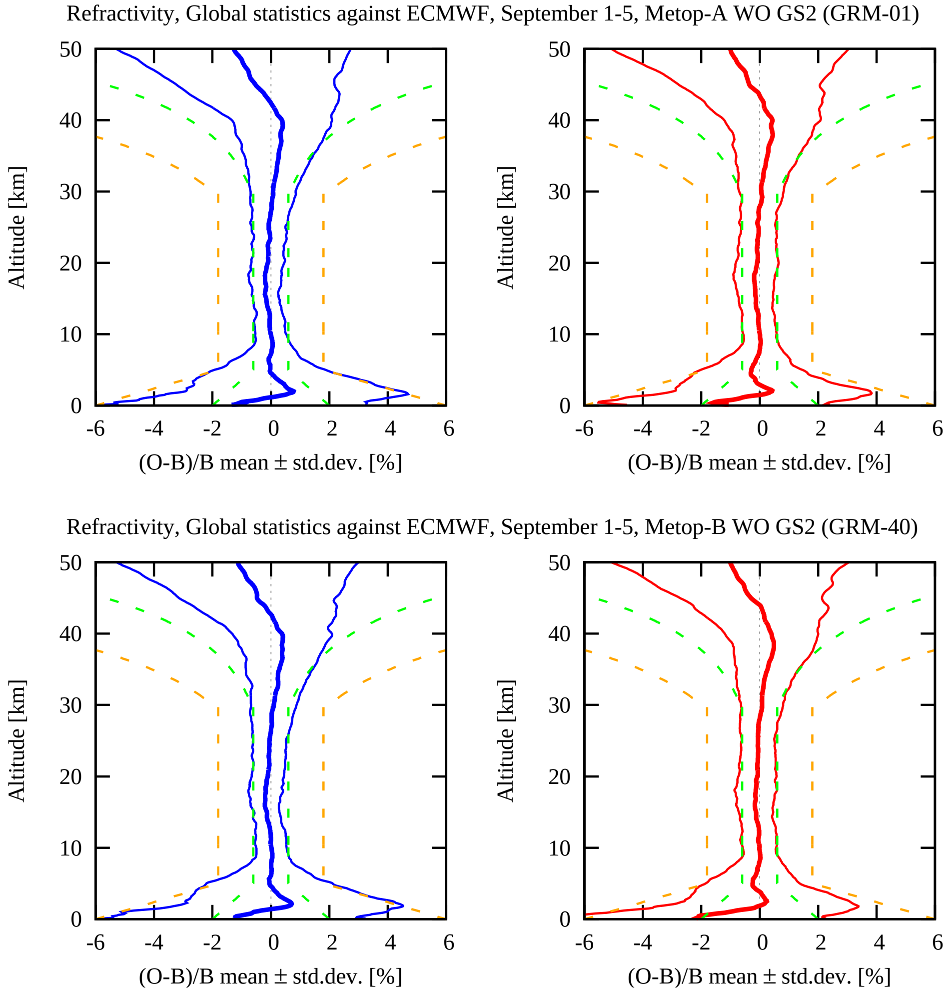

Figure 3.6: *Mean plus/minus standard deviation relative to ECMWF forecasts. Top: Metop-A. Bottom: Metop-B. Left: Setting. Right: Rising. Dashed lines superimposed indicates the target (green) and threshold (orange) accuracies for NRT refractivity according to the PRD [AD.2].*

Even though these targets should be consistent with the PRD [AD.3], they are not necessarily identical to the PRD requirements. The accuracy targets defined in the service specifications for the level 2a refractivity products GRM-01 and GRM-40 are listed in Table 3.2.

Table 3.2: *Service specifications according to the Service Specifications document [AD.4].*

	$<(O-B)/B>$ bias	$<(O-B)/B>$ standard deviation
0–8 km	1.0% (global)	4.0% (global)
8–30 km	0.2% (global)	0.8% (global)
30–40 km	0.4% (global)	2.0% (global)
40–50 km	1.5% (global)	6.0% (global)
Verification/Validation Methods	Vertical averages of absolute deviations from ECMWF short-term forecasts	

The target accuracy in a given altitude interval in Table 3.2 should be understood as an average over that interval. Compliance to the service specifications of the operational products is reported in biannual operations reports (e.g., [RD.6]). The validation results shown in this chapter indicate that the GRM-01 and GRM-40 products meet the service specifications accuracy.

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 Quality control and processing failures

The current QC flags about 25% of all processed profiles as non-nominal. Additionally, about 5% of profiles that are initially flagged as nominal by EUMETSAT fails the processing to refractivity at the ROM SAF and no refractivity profile is produced. Technically, the profiles fail when the bending angle differs too much from the background bending angle profile used for the statistical optimization.

There are basically two different reasons why the bending angle differs too much from the background bending angle profile. One is ionospheric scintillations at high altitudes, which is responsible for about half of the failures [RD.6]. The other reason is the erroneous oscillations discussed in Section 2.3; the largest of these are responsible for the other half of the failures. Additionally, we implemented a new QC check at high altitudes to catch many more of these cases with erroneous oscillations, such that users can still have confidence in the refractivity products at high altitudes. This is QC check number 8, which flags about 14% of all profiles (cf. Table 2.1).

While it is difficult to mitigate the effects of ionospheric scintillations, it should be possible to avoid the erroneous oscillations, as they did not appear in earlier versions of the EUMETSAT data. Thus, there is reason to believe that the number of both failed and non-nominal profiles can be significantly reduced in future versions of the refractivity products.

Also, in a future version of the processing software at the ROM SAF, the ROM SAF will strive to process all profiles, such that all those profiles where the bending angle differs too much from the background bending angle profile, are just marked as non-nominal.

4.2 Processing in the lower troposphere

Although the data provided by EUMETSAT is based on open loop tracking (raw sampling mode) in the lower troposphere, and processed using a wave optics method, there are a number of cases were the refractivity and the bending angle are quite different from the corresponding ECMWF forecasts, and where the bending angle gradient (and corresponding refractivity and dry temperature) becomes suspiciously large below 8 km. This prompted the implementation of a new QC in the troposphere, which marks about 4% of all profiles as non-nominal. Still, there are suspicious cases left that are marked nominal, and there are also differences in the bias and standard deviation between rising and setting occultations that are not well understood. The ROM SAF is working with EUMETSAT to fully understand these issues, and possibly the data quality will improve in future versions of the processors at EUMETSAT and the ROM SAF.

4.3 L2-extrapolation

The L2-extrapolation implemented at EUMETSAT gives rise to a larger refractivity standard deviation for rising occultations at altitudes 10–20 km, which is accompanied by broad vertical error correlations (cf. Fig 3.1–3.4). The reason that this affects mostly rising occultations is because the L2 signal tracking for rising occultations only starts at around 20 km SLTA; the L2 signal tracking for setting occultations usually ends at a lower SLTA. Earlier investigations have shown that there is a trade-off in the instrument performance between the number of data gaps in closed loop tracking and the tracking of the L2 signal in the UTLS (which prevents the raw sampling tracking). Possibly EUMETSAT will make new investigations and revise the tracking strategy for rising occultations in relation to the launch and commissioning phase of the Metop-C satellite.

4.4 Use of new climatology

The ROM SAF is working to improve the statistical optimization by using a new climatology called BAROCLIM, which eventually will replace the current MSIS-90 bending angle climatology. Together with other adjustments of the statistical optimization, this will result in higher accuracy and smaller standard deviation at high altitudes (above 40 km). BAROCLIM has already been implemented for ROM SAF off-line and reprocessing products, but later also the NRT products will benefit from the anticipated improvements.

4.5 Biases at high altitudes

It has long been recognized that the ECMWF model has a positive refractivity bias around 40 km. When ECMWF upgraded their model in June, 2013, the bias was reduced significantly when compared to GRM-01 and GRM-40 products (evident from the ROM SAF operations reports). Still a small bias compared to the GRM-40 and GRM-01 products is present in the figures in this report (e.g., Figure 3.6). It is possible that the remaining bias around 40 km is primarily a bias in the ECMWF model, and that the GRM-01 and GRM-40 products are less biased than per se around this altitude and above.

5 Conclusions

On a daily basis, the GPAC successfully processes about 1270 EUMETSAT bending angle profiles into refractivity profiles. Of these, about 75% pass a number of QC checks and are flagged as nominal.

The statistical comparisons presented in this report (using only nominal profiles) show that the quality of GRAS/Metop-B refractivity (GRM-40) is on par with that of GRAS/Metop-A (GRM-01). Differences in the statistics (against ECMWF forecasts) in the period investigated exist, but are on a level comparable to or smaller than day-to-day variations in the statistics from either of the satellites.

The standard deviation (against ECMWF forecasts) between 10 and 20 km for rising occultations is significantly larger than for setting occultations, for both GRM-01 & GRM-40 products. This is due to the L2-extrapolation of rising occultations, which typically starts at around 20 km (going downwards), and is accompanied by a broader vertical error correlation.

The mean difference and standard deviation (against ECMWF forecasts) below 8 km for setting occultations is significantly larger than for rising occultations, in particular at high latitudes. Generally, the mean difference is positive between 2 and 5 km and negative close to the surface. Possibly, the difference between rising and setting occultations is related to the deeper tracking of setting occultations (C. Marquardt, personal communication, 2016).