The GRAS SAF Radio Occultation Processing Intercomparison Project ROPIC

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Abstract Global Navigation Satellite System (GNSS) based radio occultation (RO) measurements promise to be valuable observations to supplement the data base used for numerical weather prediction, atmospheric process studies, and climate research. Especially in the latter case it is important to fully understand the influence of the particular processing (algorithms, implementations, and used parameters) on the quantities used for further studies. To assess the impact of different algorithms and implementations used to derive bending angles and refractivities and to identify possible systematic deviations three centers routinely processing RO data had been given an identical excess phase and orbit (Level 1a) CHAllenging Minisatellite Payload (CHAMP) data set comprising observations from two months. To probe the robustness and possible dependences of the processing results on atmospheric conditions the middle month of the winter and summer season 2005 had been chosen. The results after an external quality control indicate a good agreement of the data sets between 5 km to 40 km for bending angles and refractivity depending on latitude, although the Wegener Center for Climate and Global Change (WEGC) data set exhibits systematic deviations compared to Danish Meteorological Institute (DMI) and Deutscher Wetterdienst (DWD). At high altitudes, the different initialization strategies are visible in the processed data. The Radio Occultation Processing Center Intercomparison Campaign (ROPIC) was conducted by the Global Navigation Satellite System Receiver for Atmospheric Sounding (GRAS) Satellite Application Facility (SAF).

1 Introduction

Radio occultation (RO) proved to be a reliable technical concept meeting requirements like global coverage, all weather capability (the signals are not hampered by clouds and precipitation), *a priori* long term stability and self-calibration (Kursinski et al. 1997; Hajj et al. 2004) which favors RO data utilization within frameworks conducting climate studies (Foelsche et al. 2008; Löscher and Kirchengast 2008). The latter property, which distinguishes RO from most other space-borne observational techniques, should allow for rather easy inter-comparison and combination of data, offering the opportunity to get a comprehensive time series. Over the next decades, observations from different receivers and platforms (e.g., Constellation Observing System for Meteorology, Ionosphere, and Climate COSMIC (Rocken et al. 2000), or the Global Navigation Satellite System (GNSS) Receiver for Atmospheric Sounding (GRAS), a new state of the art GNSS based RO instrument (Loiselet et al. 2000; Luntama et al. 2008) onboard the Metop series of satellites operated by EUropean Organisation for the Exploitation of METeorological SATellites (EUMETSAT)) will be available.

Since RO data should serve as a climate benchmark the processing must be robust and deliver reproducible results, the GRAS Satellite Application Facility (SAF) located at the Danish Meteorological Institute (DMI) in Copenhagen, Denmark, initiated the Radio Occultation Processing Intercomparison Campaign (ROPIC). A similar project the Radio Occultation Sensor Evaluation (ROSE) had been conducted a while ago (Ao et al. 2003). The main finding had been a surprisingly small overlap of profiles processed by three different centers (University Cooperation for Atmospheric Research (UCAR), GeoForschungsZentrum Potsdam (GFZ), and Jet Propulsion Laboratory (JPL)) drawing from the same pool of raw data which lead to further investigations. The monthly mean of refractivity difference turned out to be less than 0.3 % with a standard deviation of 0.5 % in an altitude range of 10 km to 25 km. In the lower troposphere, the agreement was worse in the tropics than elsewhere, with the mean refractivity difference exceeding 1 % in the lower altitudes. Bending angles were not analyzed.

RO processing chains are composed of a number of algorithms which differ between the centers; even if the same underlying algorithm is used the specific implementations will be different thus slightly different results can be expected. As shown by von Engeln (2006a) this uncertainty cannot be neglected. This study serves to assess those variations by comparing the data products of different processing chains.

The intention is not the assessment of the absolute accuracy but to reveal possible inconsistencies and systematic deviations between different centers. This study should serve as a baseline to identify benefits from using certain algorithms and methods, which in turn could be used to optimize the processing chains. Most likely, the optimal processing method is complex (e.g., it may vary with altitude range and spatial location of the observation).

In our study, we focus on the assessment of the processing chains from excess phase level to bending angles and refractivities. Those are the quantities used in Numerical Weather Prediction (NWP) systems (Healy and Thepaut 2006) and are possibly the best candidates for long-term climate monitoring applications (Ringer and Healy 2007). Data even closer to the raw observation state might be even better but are not used yet. As a matter of fact it is difficult to quantify the uncertainties introduced by the different processing steps, thus it is an advantage to keep them at a minimum. Although for climate applications where mostly relative changes are of interest (Löscher et al. 2008) a possible bias for example is not posing a problem as long as it is stable in time (which is difficult to guarantee if it is not entirely clear where it stems from). Other quantities like suggested in Leroy et

Table 1 Definitions used for the same data level.

GFZ	GRAS-SAF	UCAR	EUMETSAT
Level 2	Level 1a	Level 2	Level 1a

al. (2006) might prove to be appropriate for climate applications too which still has to be studied in detail concerning its sensitivity to the processing.

As a common baseline a CHAllenging Minisatellite Payload (CHAMP) (Wickert et al. 2004) based data set had been compiled containing the occultation events from January and July 2005 covering the middle month of the Northern Hemisphere winter and summer season to represent different atmospheric conditions. The occultations had been processed from raw to excess phase and orbit data by GFZ Potsdam (Germany). The participating centers Deutscher Wetterdienst (DWD) in Offenbach (Germany), GRAS-SAF at DMI, and Wegener Center for Climate and Global Change (WEGC) in Graz (Austria) processed the common data set to bending angles, refractivities, and higher-level products like dry temperature. The activity was coordinated by the GRAS-SAF. We present here the results of the bending angle and refractivity intercomparison.

2 Data Set

To conduct the ROPIC campaign, a comprehensive set of phase delay and orbit data from CHAMP had been compiled for the participating processing facilities. This serves several purposes, it enables the participation of centers not capable of processing the data up to Level 1a (excess phase and orbit), it avoids that the overlap of processed profiles at that point is small as it happened in the ROSE campaign[1], and finally we are interested in investigating the processing from Level 1a to bending angles and refractivities thus respective effects are effectively isolated.

GFZ Potsdam provided the data of the CHAMP GPS radio occultation experiment, generated the phase delay data, and made the orbit data available for ROPIC. The GRAS-SAF edited the data and compiled the final ROPIC input data set including instructions. The package was distributed either in GFZ ASCII or ROPP (Radio Occultation Processing Package) NetCDF format via a dedicated web page.

To clarify the notation and avoid confusion Table 1 shows some data level definitions used for the excess phase (PD) and corresponding orbit data by different centers, in this paper the GRAS-SAF convention is used.

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[1] The overlap issue had been a bit relaxed meanwhile pers. communication J. Wickert

Table 2 ROPIC excess phase data set from GFZ.

	January	July	Total
GFZ Data	5246	5928	11174

Table 3 Processed ROPIC data set where the difference between passed profiles in Table 3 and raw data profiles in Table 2 is composed of profiles, which could not be processed to bending angles and profiles flagged as bad by the centers. Matches indicates profiles entering the analysis (matching DWD profiles and a mean tangent point location agreeing ≤ 50 km), QC refers to the quality control conducted by the centers.

	January		July		Total	
	Processed and Passed QC	Matches	Processed and Passed QC	Matches	Processed and Passed QC	Matches
DMI	4262	4142	5043	4944	9305	9086
DWD	4454	–	5066	–	9520	–
WEGC	3520	2939	4138	3398	7658	6337

The data set consists of two months (January and July 2005) to cover the atmospheric variability throughout the Northern Hemisphere summer and winter seasons providing a representative baseline. It comprises 5246 profiles from January 1, 2005 to January 31, 2005 and 5928 profiles from July 1, 2005 to July 31, 2005; in total 11174 profiles, a number, which allows to generate meaningful statistics. Due to problems in the attitude stabilization of CHAMP no precise orbits are provided from January 30, 22 UTC to January 31, 22 UTC, thus only a limited number of occultations could be processed.

The space based single differencing technique had been used to eliminate the CHAMP satellite clock error and to derive the atmospheric excess phase data for ROPIC (which is not equal to the GFZ standard data stream where the double differencing technique is employed). The GPS clock errors are corrected by using 5 min clock solutions, provided by the GFZ orbit processing facility (König et al. 2005). The use of the single differencing technique seems to introduce no significant deviations compared to the operational double differencing. Details concerning the GFZ RO data processing using the single differencing technique are given by Wickert et al. (2002). Further references related to the derivation of the atmospheric excess phase from GPS RO data are, e.g., Schreiner et al. (1998) and Hajj et al. (2002).

The DWD reference data (especially the ray-traced bending angles which are usually not available) proved to be essential for quality control. For all data sets, the mean tangent point had been recalculated as in Section 3 described (except for the WEGC data, since the tangent point track was not provided the given coordinates had been used). Since the aim of this project is to assess the relative deviations between different retrieval procedures, the processing chains of the centers are treated as “black boxes” in a first step. The delivered profiles are assumed to be the quality controlled standard output. A next step will be to analyze where differences originate which will call for a close look at the specific implementations.

The DMI and DWD processing chains are based on the same underlying algorithm (a combination of geometric optics (GO) and wave optics, where the Canonical Transform 2nd Type (CT2) is used). The WEGC data was retrieved with the Occultation Processing System version OPSv5.3, an enhanced version of OPSv5.2 (Foelsche et al. 2007) based on the heritage of the CHAMPCLIM retrieval (Foelsche et al. 2005). This retrieval is a dry air retrieval based on geometric optics.

More subtle differences exist concerning quality control, initialization methods, smoothing, and implementation particularities, which cause differences in the output. Details on the processing applied by DMI cf. Gorbunov (2005), Gorbunov and Lauritsen (2006), Gorbunov et al. (2006), by DWD cf. Gorbunov (2002), Gorbunov and Lauritsen (2002), Gorbunov (2005) and by WEGC cf. Gobiet et al. (2007), Foelsche et al. (2007).

The ROPIC data consists of Level 1a, bending angle, refractivity profiles, and data processed to a higher level like dry temperature including the respective (ECMWF) reference data (collocated reference profiles of temperature, specific humidity, pressure including the derived refractivity, surface pressure, and for the DWD data set the derived bending angles).

To ease processing and general handling all data sets had been converted to the ROPP[2] (Radio Occultation Processing Package) NetCDF format in a pre-processing step. To filter outliers, which would spoil the statistics, quality control procedures are executed as part of the analysis. The quality controls are based on external data (bending angles and refractivities) which rules are as follows: Any profile, which deviates from the respective reference between 10 km and 20 km more than 10 % is considered an outlier and flagged as failed. From 10 km down every level of a profile is checked against the respective reference and if the deviation exceeds 20 % the first time the value at that level and all consecutive levels is set to missing values. The same procedure is applied to all levels from 20 km up.

As reference data the DWD provided collocated ray-traced bending angles and reference refractivities, both derived from ECMWF data, are used. If a profile is flagged as outlier in bending angle space, it is not carried on to the refractivity analysis.

Those procedures are empirical and proved to be reliable measures to account for outliers and un-physical values, which seem to appear in a few profiles on a random base. Since the observations are compared to the DWD derived reference profiles in the analysis only profiles with a difference of $\leq$ 50 km in the mean tangent point location with respect to DWD enter the calculations.

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[2] For instructions to download the ROPP-Package go to
http://www.grassaf.org/ROPP_package.php

Careful quality control at all stages of the analysis proved to be essential to reliably remove outliers in bending angle and refractivity space, which would spoil the statistics, where one has to be careful not to exclude too many observations from the analysis. Sensitivity tests using different percentage thresholds for data filtering suggest that the method used here provides a simple but reliable quality monitoring framework. The complication for standard RO data products is the in general missing bending angle reference.

3 Baseline of the Comparison

The baseline of the comparison are bending angles as function of 247 fixed impact heights (impact parameter minus radius of curvature) up to ~60 km and refractivities at an equidistant 200 m grid above ellipsoid (WGS-84) covering an altitude range from 0 km to 45 km (226 vertical levels). This data is complemented by collocated ECMWF profiles (at the profile's mean tangent point location) and the respective derived refractivities (plus the ray-traced bending angles for DWD). The mean tangent point is calculated as the average of the tangent point track of the observations from the lowermost 20 km of a profile. By doing so, the mean tangent point is effectively weighted towards lower altitudes (von Engeln 2006a). The ECMWF collocated profiles are derived from operational analysis fields retrieved at a 1° by 1° spatial resolution comprising 60 vertical levels, which are interpolated to the comparison grid. The time layer (of four available per day) closest (in time) to the profile had been used.

DWD provided beside the ECMWF derived reference refractivity two sets of reference bending angle data sets, based on an Inverse Abel procedure and ray-tracing. Since the DWD data set contains most profiles, which enter the comparison (cf. Table 2) the ray-traced bending angles and consequently the respective reference refractivities have been used as data to compare against. Still one has to keep in mind that in our comparison the differences between the retrieved results are most important, although the comparison to ECMWF (in bending angle and refractivity space) provides some added value to the analysis.

To analyze the data, basic statistical quantities like bias, median, standard deviation, and variance had been used. First assessments indicated the presence of outliers or unphysical values in the data set. This assumption had been verified by comparing the median (median of the differences to the reference) of the deviations against the bias. After introducing the quality control procedures (cf. Section 2), both values agree well indicating the successful removal of corrupted profiles and data points, although the agreement between the different centers is still slightly better using the median in refractivity space. That indicates that a few profiles influence the statistics disproportionately. The calculations had been performed for each set of profiles separately where first the matches with the DWD data set had been determined. The analysis was then performed based on differ

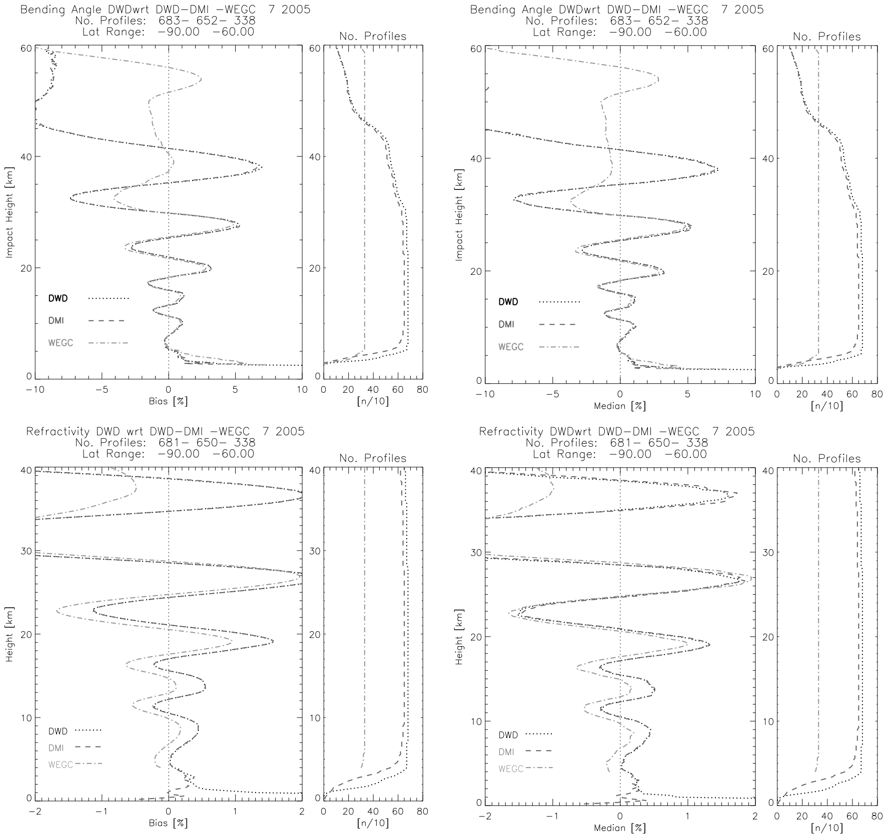

Fig. 1 This panel shows bending angle and refractivity bias to the left and the respective median of difference profiles between 60° and 90° south from July 2005 on the right (different vertical and horizontal axes for bending angle and refractivity).

ences to the DWD reference data as common baseline. One has to notice that DWD is compared against its own provided reference in contrast to WEGC and DMI. Since the relative differences between the centers are the focus of this study, no side effects are expected to be introduced due to that fact.

A different number of profiles per center enters the analysis thus the sample sizes are different. To assess if this approach has any implications the analysis was performed a second time only taking profiles into consideration, which are present in each data set, thus the sample size was equal for each center. The differences are negligible proving that our approach to maximize the number of analyzed profiles does not introduce any sampling error.

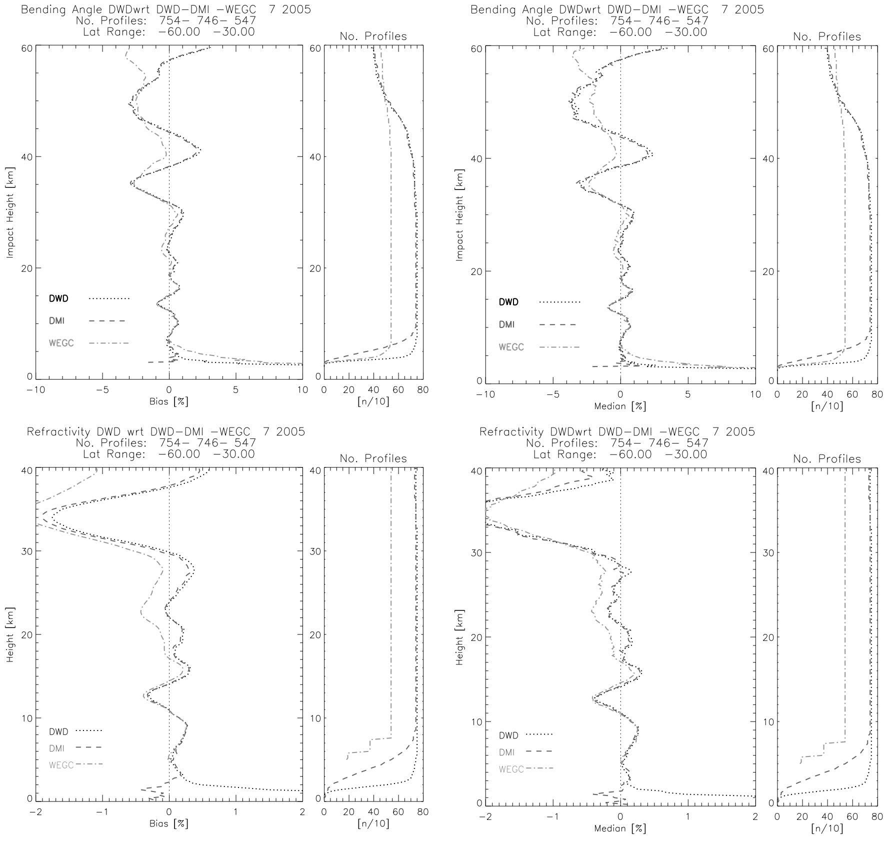

Fig. 2 This panel shows bending angle and refractivity bias to the left and the respective median of difference profiles between 30° south and 60° south from July 2005 on the right (different vertical and horizontal axes for bending angle and refractivity).

4 Results

To illustrate the results a subset of plots based on the differences between profiles and respective references is shown. We focus here on the low, mid, and high latitude Southern Hemisphere for July as exemplary cases. The high latitude Southern Hemisphere case demonstrates the level of consistency between the different data sets concerning the pronounced increments (Gobiet et al. 2005) present during the Antarctic winter in the ECMWF analyses 2005.

The overall agreement between the bending angles derived by the different centers is good up to an altitude of 30 km at southern high, 35 km at mid respectively up to 40 km at low latitudes. The agreement gets worse within the last few kilome-

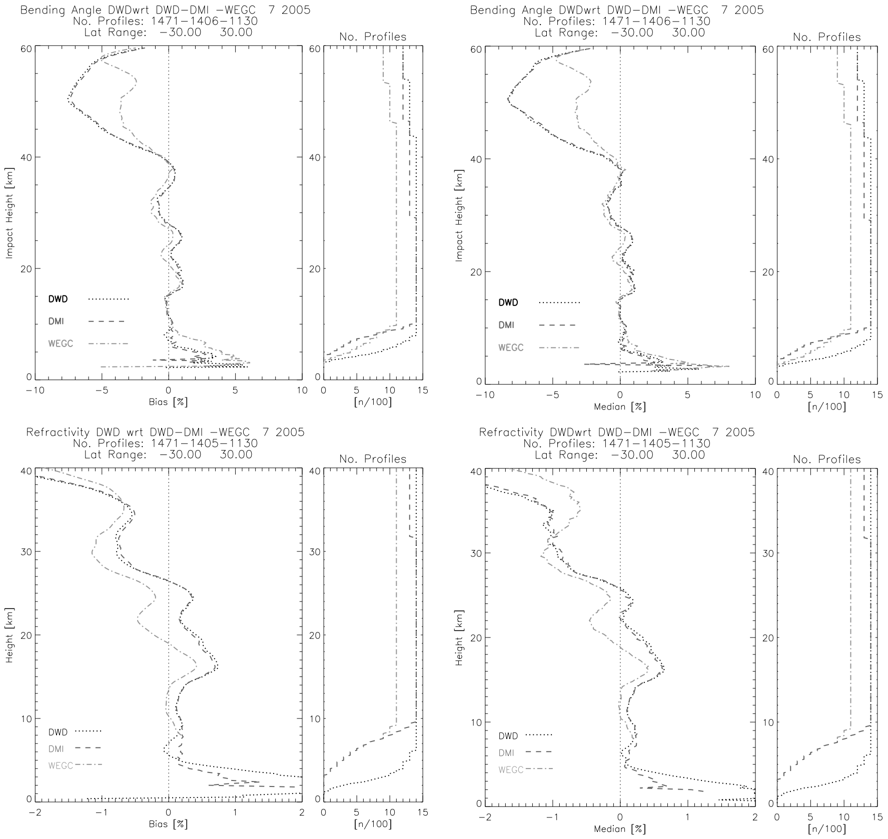

Fig. 3 This panel shows bending angle and refractivity bias to the left and the respective median of difference profiles between 30° south and 30° north from July 2005 on the right (different vertical and horizontal axes for bending angle and refractivity).

ters above the ground but as can be seen in the plots the number of profiles equally declines (WEGC profiles terminate at 4 km for high, at 5 km for mid and at 8 km for low latitudes in refractivity space) although WEGC exhibits a systematic deviation compared to DWD and DMI. The atmospheric increments compared to ECMWF at southern high latitudes are captured by all data sets consistently. At high altitudes WEGC derived values start to deviate from the other two centers at 30 km in the high, 35 km in the mid, and 40 km at low latitudes whereas DWD and DMI still agree with each other. This effect most likely stems from the different high altitude initialization where DMI and DWD are using the MSISE-90 (Mass Spectrometer Incoherent Scatter) model (Hedin 1991). The fit to (and selection of) MSISE is done in the range from 40 km to 60 km in a dynamical way for each occultation. The actual transition from measurement to MSISE is on average done between 30 km and 50 km such that MSISE represents 0 % at 30 km and 100 % at 50 km in the results (this description applies for DMI, DWD uses similar procedures). The WEGC bending angle profile is statistically optimized between 30 km and 120 km, at the lower part with co-located ECMWF profiles and above ~60 km with profiles from the MSISE-90 climatology.

This explains the rapid decrease in the number of the accepted profiles in the DWD and DMI cases at altitudes of ~45 km and above (QC threshold 20 % relative deviation from reference) since the difference between MSISE-90 and the observed atmosphere can be significant.

These results give a hint that we have here one example of parametric uncertainty caused by auxiliary information introduced during the processing. This information leaves a signature in the data, which in theory exponentially decreases with altitude (in the case of high altitude initialization) but still might influence observations in the atmospheric domain of interest. That is important if the data is used within a climate context and non static (in time) auxiliary data is present in the processing. What can be observed in bending angle space is to a certain extend translated to refractivity space where WEGC seems to be drawn to the reference at altitudes above 30 km. WEGC's systematic deviations to DMI and DWD apparent in all plots are somewhat reduced in the median compared to the bias. The altitude dependent pattern of the deviation is significantly different in the high, mid, and low latitudes thus it is very unlikely that they are caused by a single effect; the pattern appears in a reduced height interval in the mid latitudes.

One can notice the decrease of penetration depth of profiles towards the tropics in Fig. 1 to Fig. 3 (refractivity space) which can be clearly related to the moist atmosphere, which is still a challenge for the processing algorithms. In any latitude band DWD profiles exhibit the best penetration performance, in the WEGC data set observations are completely absent from a certain altitude which increases from the poles towards the equator in refractivity space. This can be attributed to the used GO processing which cannot cope with the strong refractivity gradients present in moist dense atmospheric regimes, wave optics methods are performing better in such an environment. That is reflected in bending angles, which apparently cannot be processed to refractivities.

Another interesting feature to note is that the median seems to move the DMI and DWD results a bit away from the reference compared to the deviations visible in the bias plots, an effect which appears at high altitudes.

The results suggest that all retrieval chains capture the same atmospheric features below 30 km to 40 km depending on latitude, but the systematic differences relative to each other show that those features are captured at different magnitude. This behavior had been confirmed for the rest of the data set not presented here. The indication is that outliers can be ruled out as possible cause of the remaining deviations (as the median suggests).

5 Conclusion

The ROPIC campaign serves to assess the level of independence RO data exhibits concerning the used processing chain. Not surprising DMI and DWD derived results agree very well with each other since the underlying processing chains are based not only on the same theory (combination of geometrical optics at high altitudes and CT2 at lower altitudes) but also exhibit similar initialization strategies and partly share the same code base. WEGC is using a different approach (only geometrical optics processing) but still the results agree reasonably well in the altitude domain of interest concerning the representation of atmospheric features. Nevertheless, the data still exhibits systematic deviations, which are latitude dependent. This behavior should be assessed further; the deviations apparent at high altitudes most likely stem from the different initialization strategies. If this assumption is correct, it would illustrate an example for parametric uncertainty of RO processing.

These results highlight the potential of RO data for climate applications on one hand but also indicate the need of close cooperation between the different centers to consolidate their processing, to identify systematic deviations, and improve overall robustness. The output of more independent processing chains is needed to better quantify the bandwidth of variations (DMI and DWD processing chains are not strictly independent) and to realistically estimate the magnitude of structural uncertainty.

Agreement should be reached on open issues like a common definition of the mean tangent point or discretization schemes making it easier to relate differently processed data to each other. Since agreement on internal processing procedures is not expected to be reached, I would suggest to provide at least the tangent point track as a standard data product.

Another important step would be the development of reliable quality standards for data products in an ideal case relying on methods for filtering based purely on observed quantities not dependent on auxiliary reference data.

This first assessment should provide a starting point for further investigations, which should have a thorough look at the different processing strategies and auxiliary data used. In an ideal scenario, the current data set would be supplemented by more independently derived data sets to have a better chance of estimating the performance envelope of RO defined by structural and parametric uncertainty.

Especially for climate applications which can rely on the monitoring of relative changes instead of the absolute values the auxiliary data used should be static (static in the sense of not changing as a function of time). In that case, any systematic deviation introduced by the auxiliary data is static too and relative changes are not masked by their variation.

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