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GRAS SAF
GRAS Meteorology

GRAS SAF Report 13

ROPP PP validation

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GRAS SAF Project

The GRAS SAF is a EUMETSAT-funded project responsible for operational processing of GRAS radio occultation data from the Metop satellites. The GRAS SAF delivers bending angle, refractivity, temperature, pressure, and humidity profiles in near-real time and offline for NWP and climate users. The offline profiles are further processed into climate products consisting of gridded monthly zonal means of bending angle, refractivity, temperature, humidity, and geopotential heights together with error descriptions.

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

The GRAS 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 project please go to http://www.grassaf.org.

1 Background

The Radio Occultation Processing Package (ROPP) software includes functionality for users to process radio occultation data to derive atmospheric bending angle and refractivity profiles. This report presents refractivity and bending angle profiles processed using the ROPP (v4.1) tool `ropp_pp_occ_tool`. This serves to illustrate the use of ROPP for occultation processing and validate its results. For further background and a full description of the `ropp_pp` processing and user options see GRAS SAF (2010).

Note that results presented here referring to ROPP-4 (v4.1) also apply to the ROPP-5 (v5.0) user release distribution.

The ROPP pre-processing module contains algorithms developed by Michael Gorbunov (GRAS SAF visiting scientist). The preprocessing code provided to users in ROPP is based on the OCC software code written by Michael Gorbunov. L1 and L2 bending angles are retrieved as a function of impact parameter from excess phase measurements with time and orbit position and velocity information. A wave optics algorithm (CT2) is used to obtain bending angles in the troposphere and lower stratosphere where multipath behaviour must be interpreted ($<$ 25 km) (Gorbunov and Lauritsen, 2004). Bending angles above 25 km are retrieved by geometric optics (Vorob'ev and Krasil'nikova, 1994). The atmospheric bending is computed from L1 and L2 channel bending angles by removing the ionospheric contribution (Gorbunov, 2002). A refractivity profile is then retrieved by inversion of the Abel integral.

Gorbunov et al. (2009) presented a statistical comparison of the results from OCC processing of COSMIC data with the UCAR (CDAAC) data products and ECMWF analyses. This report presents complementary results to demonstrate the consistency between results using ROPP and the OCC codes, and to validate the ROPP results against an independent processing system developed by UCAR (CDAAC) and meteorological information from ECMWF analyses. The UCAR processing chain is described by Kuo et al. (2004) and Sokolovskiy (2009).

1.1 Data

Post-processed COSMIC radio occultation data were provided by the COSMIC Data Analysis and Archival Center (CDAAC) http://cosmic-io.cosmic.ucar.edu/cdaac/ in the form of a '`atmPhs`' format file containing time, excess phase, amplitude and satellite positioning data during an occultation.

The `OCC` package (provided by Michael Gorbunov) was run as follows to generate profiles of L1 and L2 bending angles, ionospheric corrected bending angle (LC), statistically optimised corrected bending angle (opt), refractivity and dry temperature (Tdry). A `occ2ropp` conversion script was used to convert the OCC output results into a ROPP format output file `<atmPrf_OCC>`.

```
occ.x <atmPhs_file> -set=cosmic
occ2ropp <atmPhs_file>.inf -o <atmPrf_OCC>
```

To process the data using ROPP, the CDAAC `atmPhs` files were first converted to ROPP format netCDF using the `ucar2ropp` tool (provided in the `ropp_io` module).

The `ropp_pp_occ_tool` was then run as follows to generate L1, L2, LC and opt bending angles, refractivity and Tdry profiles.

```
ucar2ropp <atmPhs_file> -o <atmPhs_ROPP_file>
ropp_pp_occ_tool <atmPhs_ROPP_file> -o <atmPrf_ROPP> -c config/cosmic_pp.cf
```

Corresponding validation results were downloaded from CDAAC in the form of ’`atmPrf`’ format file containing corrected bending angles, refractivity and dry temperature profiles. In addition, ’`ecmPrf`’ files were obtained containing background meteorological profiles interpolated from an ECMWF analysis (ECMWG TOGA 2.5 degree Global Upper Air Analysis) onto 25 standard levels at the occultation time and location. The CDAAC format files were also converted to ROPP format netCDF for analysis.

```
ucar2ropp <atmPrf_file> -o <atmPrf_ROPP_file>.nc     #(for each file)
ucar2ropp <ecmPrf_file> -o <ecmPrf_ROPP_file>.nc     #(for each file)
```

One day of data were processed in this way, and then combined for analysis using the `ropp2ropp` tool (provided in the `ropp_io` module). A full resolution and thinned version were produced. The thinned version provides results on a standard set of 247 impact height levels (impact parameter minus radius of curvature) (GRAS SAF, 2009).

```
ropp2ropp <atmPrf_ROPP>* -m -o allROPP.nc
ropp2ropp <atmPrf_ROPP>* -m -p ropp_thin_log-247.dat -o allROPPthin.nc

ropp2ropp <atmPrf_OCC>* -m -o allOCC.nc
ropp2ropp <atmPrf_OCC>* -m -p ropp_thin_log-247.dat -o allOCCthin.nc


ropp2ropp <atmPrf_ROPP_file>* -m -o allCDAAC.nc
ropp2ropp <atmPrf_ROPP_file>* -m -p ropp_thin_log-247.dat -o allCDAACthin.nc

ropp2ropp <ecmPrf_ROPP_file>* -m -o allECM.nc
```

Data from 1 January 2009 and 25 August 2009 were selected for inclusion in this analysis.

2 Validation results

2.1 ROPP 4.0

The ROPP-4 (v4.0) release pre-processing software was developed based on the OCC code version 19.4.571. Figure 2.1 demonstrates the consistency between results processed using the OCC (v19.4) and ROPP (v4.0) codes for profiles from 1 January 2009. Results show excellent consistency, with mean differences between optimised bending angle, refractivity and dry temperature results all within 0.04%. Larger differences for a subset of profiles above 45 km result from selection of different best-fit MSIS climatology profiles used in the ionospheric correction (resulting from smaller differences between the input L1 and L2 bending angle profiles from OCC and ROPP used in the best-fit selection).

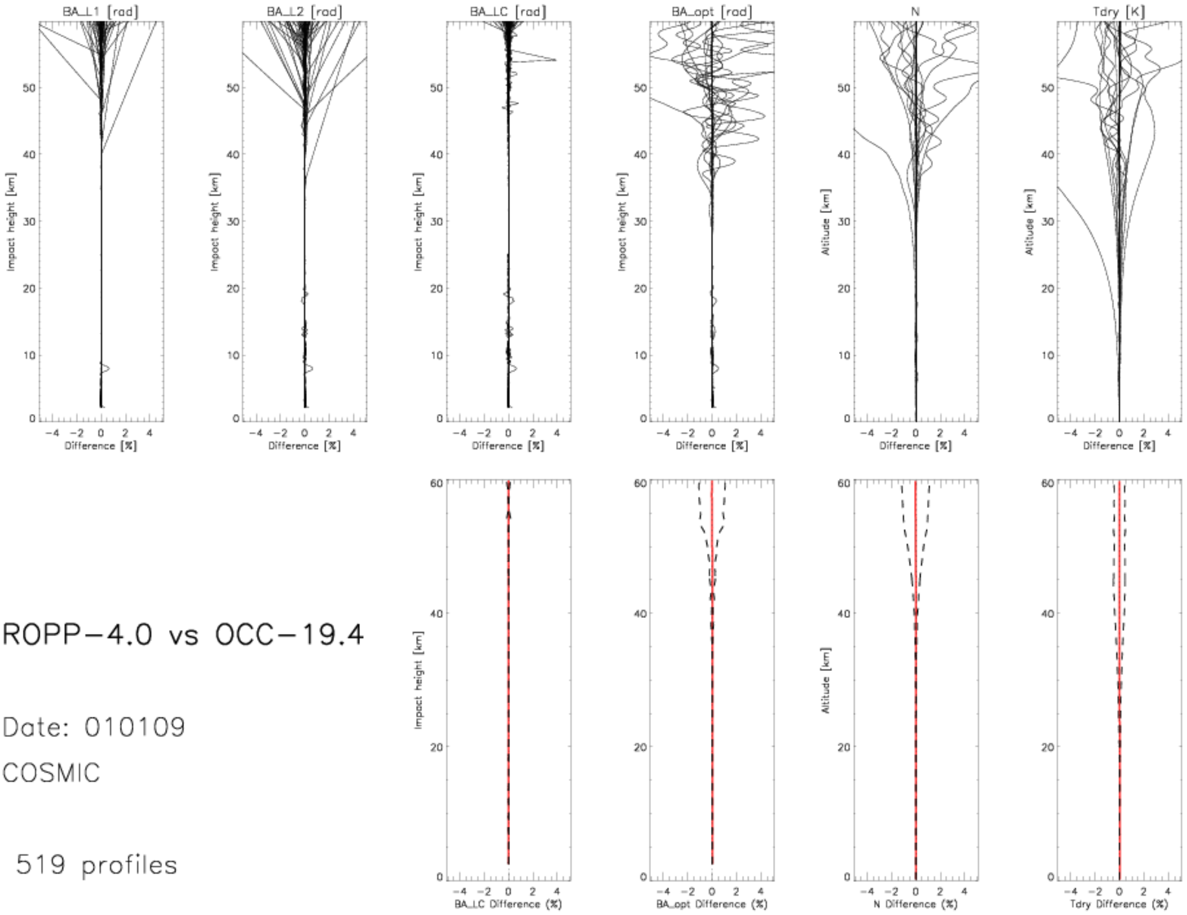

Figure 2.1: Differences between bending angle, refractivity and dry temperature results processed using the OCC (v19.4) and ROPP (v4.0) software codes. Top: Profile-by-profile differences. Bottom: The mean difference is plotted as the solid red line. The standard deviation about that mean is plotted as a black dashed line.

Figure 2.2 compares the ROPP (v4.0) processed results with the corresponding CDAAC processed profiles (as provided in '`atmPrf`' files). These results are consistent with those produced for OCC validation over a longer period by Gorbunov et al. (2009). Between 10 km and 30 km the agreement between the retrieved refractivity profiles is within 0.2%. The standard deviation of the differences between ROPP and CDAAC results increases above 40 km. Gorbunov et al. (2009) note that the CDAAC bending angle inversion is based on the NCAR climate model, whereas ROPP selects the best-fit profile from the MSIS climatology. Below about 8 km, there is a negative bias between ROPP and CDAAC results (ROPP bending angles and refractivity lower than CDAAC values), with a difference at the surface of -1%. The CDAAC wave optics processing is based on FSI after geometric optics back propagation to circular orbits, while ROPP uses the CT2 algorithm (Gorbunov and Lauritsen, 2004). It is known that the CDAAC bending angles (at version 2007.3200) are biased positive below 5 km due to a non-linear filter. The processing has since been improved to use a Phase Matching method (see http://cosmic-io.cosmic.ucar.edu/cdaac/status.html).

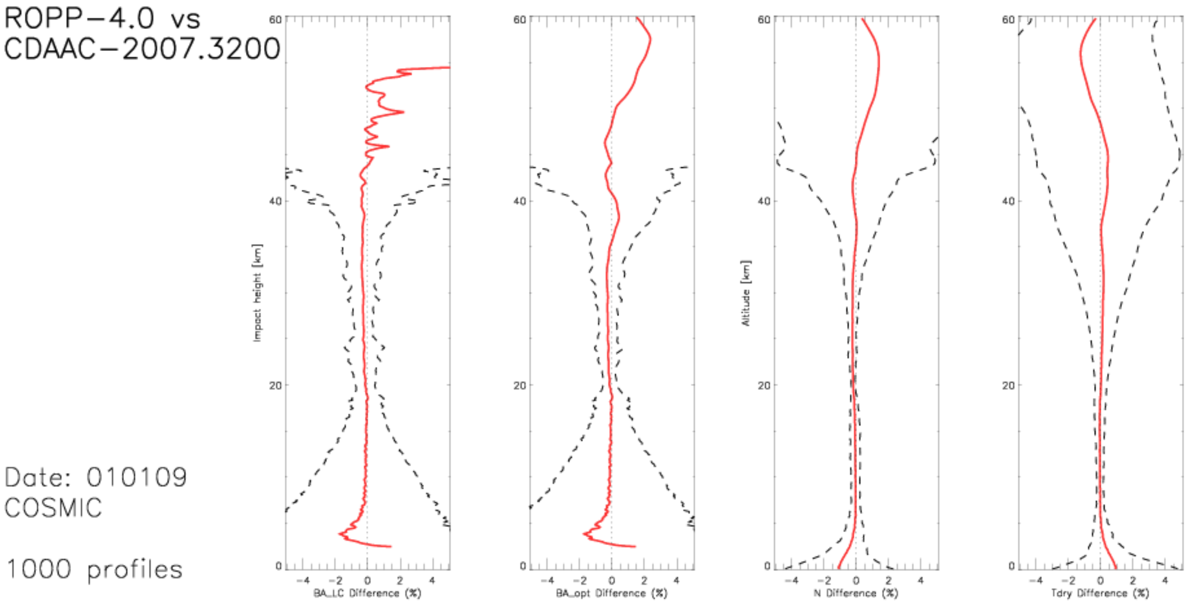

Figure 2.2: Differences between bending angle, refractivity and dry temperature results processed using ROPP (v4.0) and as processed by CDAAC (2007.3200).

Figure 2.3 compares the ROPP retrieved refractivity with forward-modelled refractivity profiles from co-located ECMWF analyses. Differences of up to 2% are evident in the near-surface multi-path region. Also shown in Figure 2.3 is a comparison between the ROPP dry temperature results and the ECMWF temperature analyses. Note that dry temperatures are strongly biased relative to the atmospheric temperature in the lower troposphere where humidity is significant. There is good agreement between processed dry temperature and ECMWF temperature (within 1 K) between heights of 10 and 20 km however.

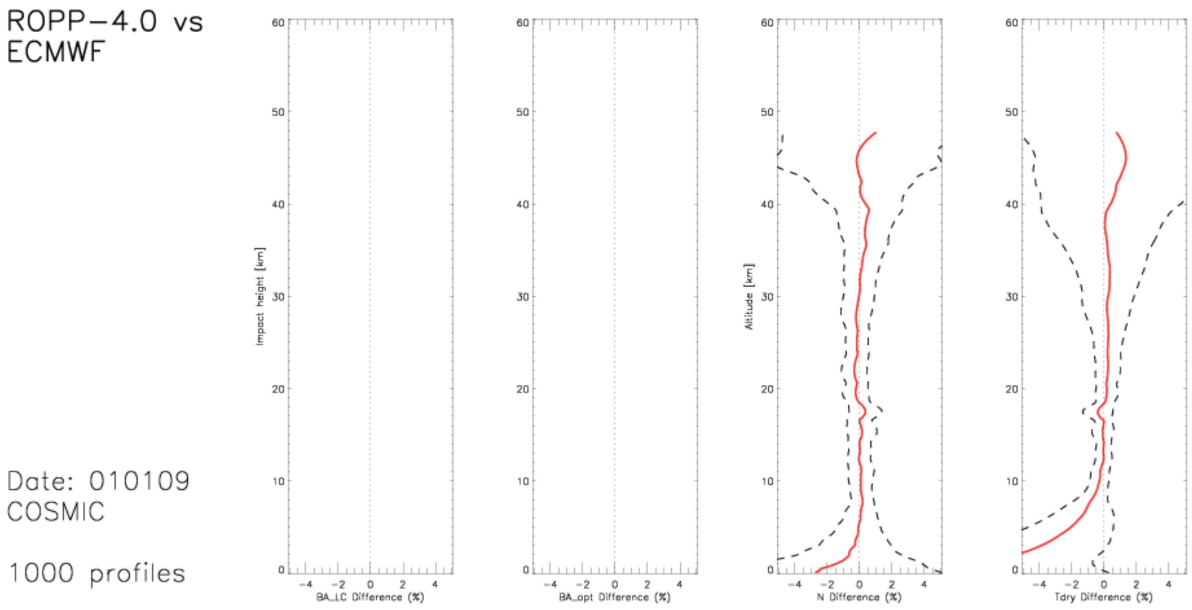

Figure 2.3: Differences between refractivity and dry temperature results processed using the ROPP (v4.0) software and ECMWF analyses (as provided by CDAAC).

2.2 ROPP 4.0 to ROPP 4.1 update

A number of upgrades were implemented to the `ropp_pp` processing between user releases ROPP v4.0 and ROPP v4.1, in addition to the additional functionality to process GRAS raw sampling data. Code updates to ROPP v4.1 were implemented based on the OCC code version 20.6.688. The main changes implemented were:

- Updated the MSIS model phase calculation used in the open-loop data processing
- Increased the amount of data used by decreasing data cut-off limits.
- Radio-holographic filtering of phase data is no longer applied, only to the CT2 amplitude.
- Other minor algorithm updates and bugfixes.

Figure 2.4 shows the differences between results processed using ROPP-4 (v4.0) and ROPP-4 (v4.1) for COSMIC data from 1 January 2009. The largest differences are in the near-surface multipath region, where the mean bending angles difference is up to 1%. This is a result of the less restrictive data cut-off criteria, use of unfiltered phase data in the CT2 wave optics calculation and use of a modified MSIS phase model in the open loop data correction. The MSIS data are also used to correct degraded L2 observations (see GRAS SAF (2010) for details), so there are some differences in the L2 bending angle results below 25 km. Above 25 km, where bending angles are retrieved using geometric optics, results from ROPP v4.0 and v4.1 processing show also differences, but about a zero mean.

These results demonstrate the significant sensitivity of a particular retrieved profile to the available algorithm and configuration choices. The most sensitive profiles are those which include most noise. Further investigation and demonstration of the sensitivities to each part of the processing chain would be very instructive, particularly for understanding data quality and the application of radio occultation data for long-term climate monitoring.

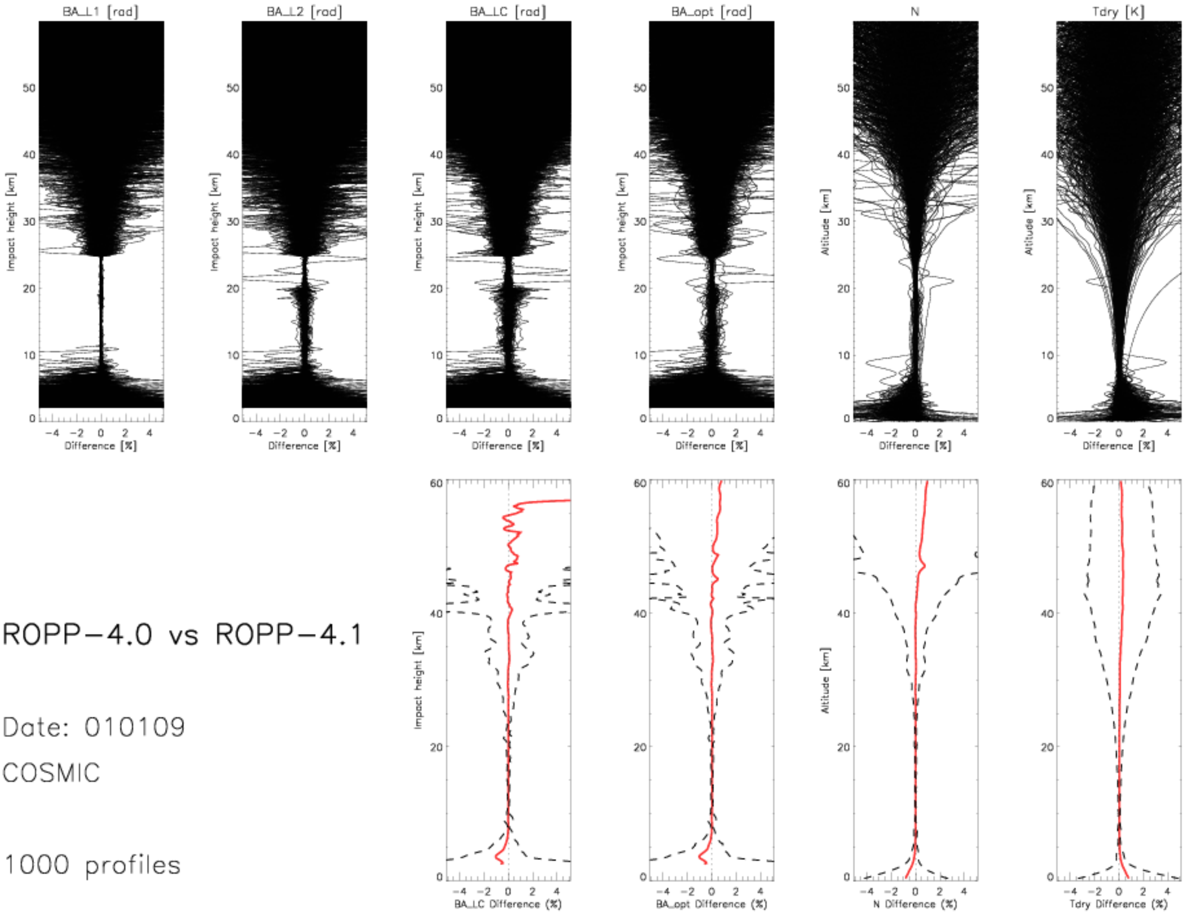

Figure 2.4: Differences between bending angle, refractivity and dry temperature results processed using the ROPP (v4.0) and ROPP (v4.1) software codes. Other details are as in Figure 2.1.

2.3 ROPP 4.1 [ROPP 5.0]

Figure 2.5 demonstrates the consistency between ROPP (v4.1) and OCC (v20.6.688) retrieved bending angle, refractivity and dry temperature profiles from 1 January 2009. As in Figure 2.1, there is good consistency between ROPP and OCC results. A small number of profiles show near-surface differences for those profiles where the number of data used after applying the cut-off criteria may be marginally different between the two processing implementations. Mean differences are within 0.1% everywhere however.

Figures 2.6 and 2.7 show validation of the ROPP v4.1 results against CDAAC processed occultations and ECMWF analyses. Comparing with Figures 2.2 and 2.3 demonstrates that the updated processing in ROPP v4.1 significantly reduces the lower tropospheric biases. The mean bias between ROPP v4.1 and CDAAC refractivity is only 0.5% for example, while

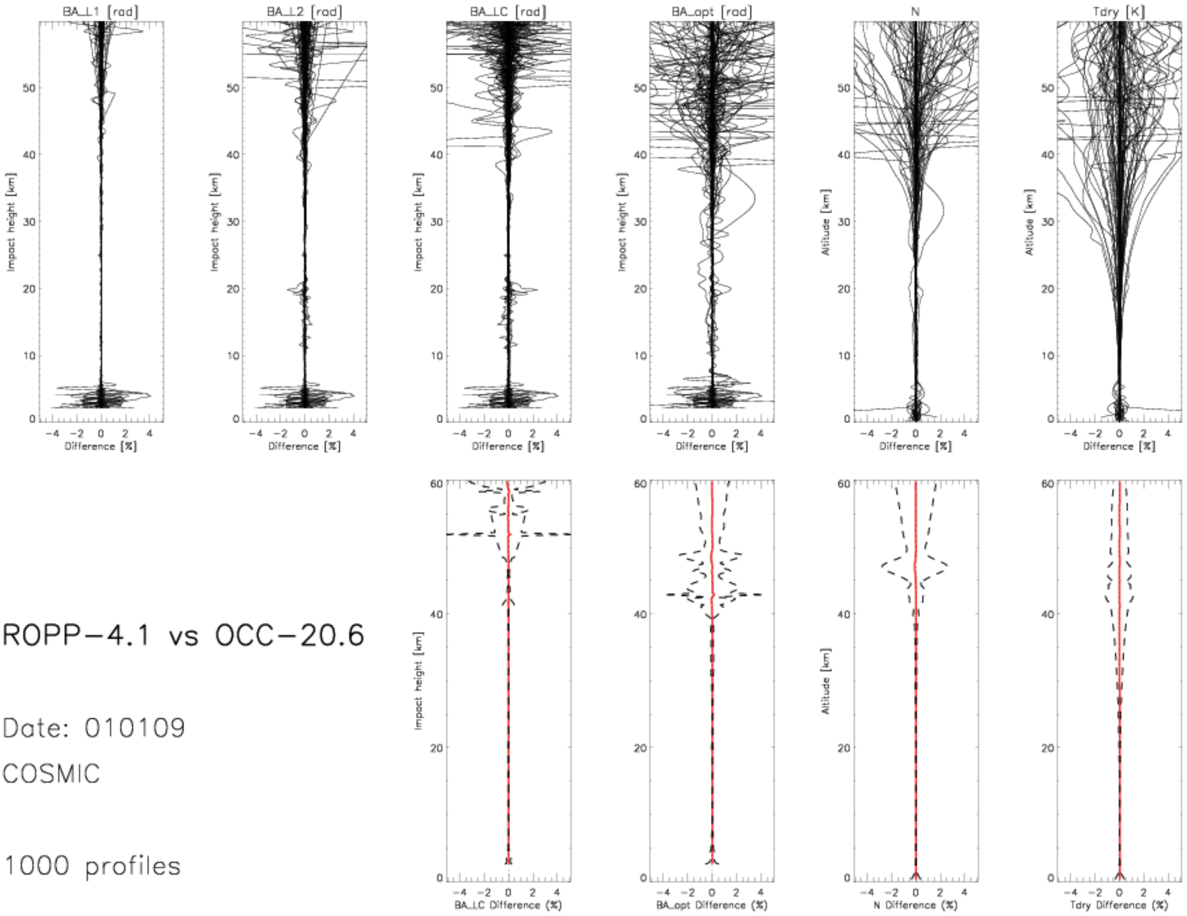

Figure 2.5: Differences between bending angle, refractivity and dry temperature results processed using the OCC (v20.6) and ROPP (v4.1) software codes. Other details are as in Figure 2.1.

the excellent consistency between 10 km and 30 km is maintained. The near-surface negative bias between ROPP retrieved refractivity and ECMWF analyses is also reduced from -2.75% using v4.0 to -1.75% using v4.1. This is also consistent with the results presented by Gorbunov et al. (2009), who suggest that the bias against ECMWF may be due to systematic loss of cycles when tracking low-level noisy occultations.

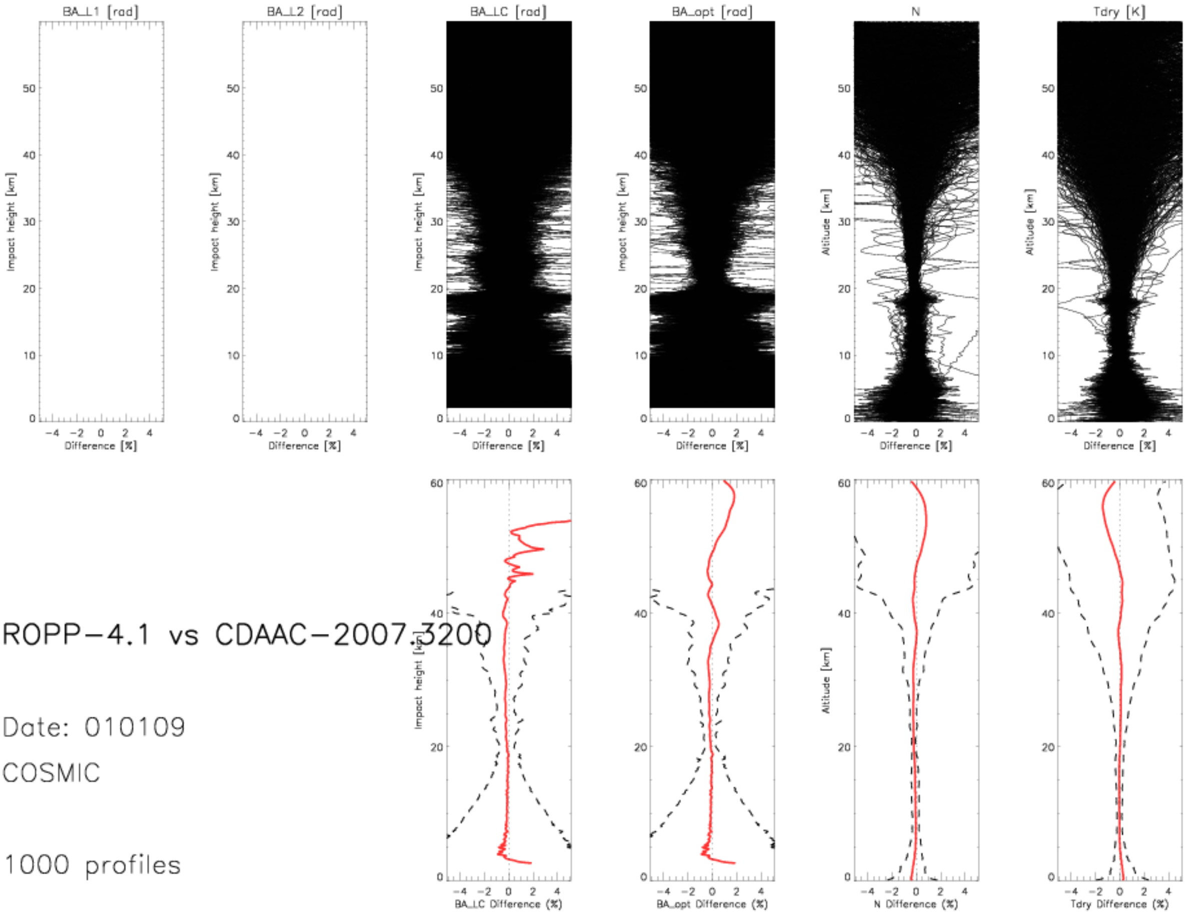

Figure 2.6: Differences between bending angle, refractivity and dry temperature results processed using ROPP (v4.1) and as processed by CDAAC (2007.3200).

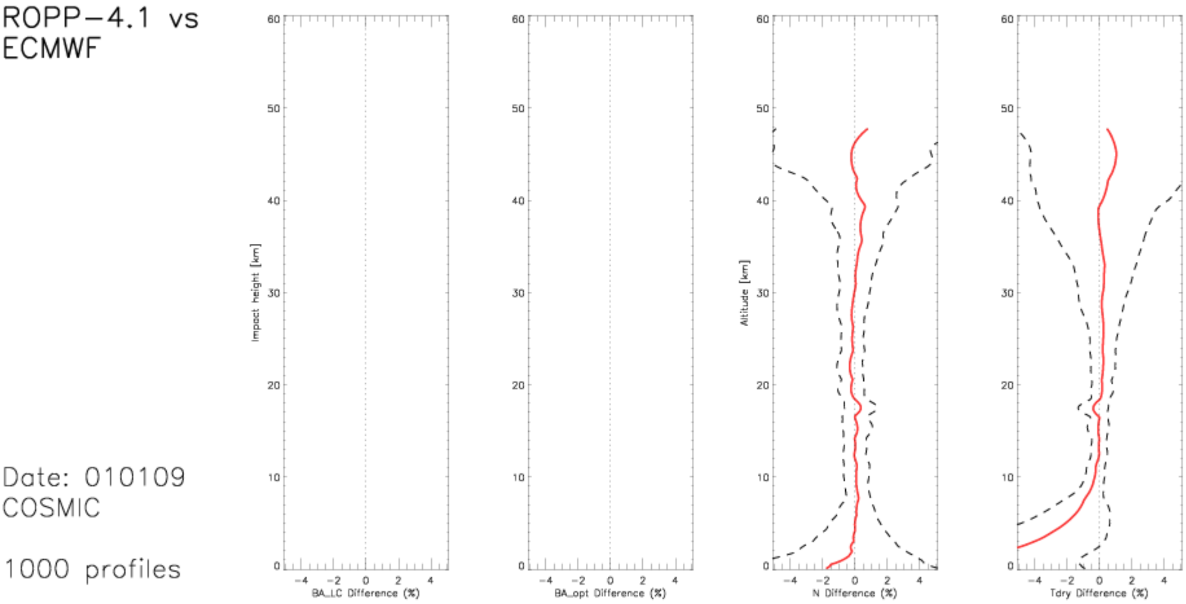

Figure 2.7: Differences between refractivity and dry temperature results processed using the ROPP (v4.1) software and ECMWF analyses (as provided by CDAAC).

2.4 25 August 2009

Further validation results, using COSMIC occultation data from 25 August 2009 are plotted in Figures 2.8, 2.9 and 2.10. Results are consistent with those shown in Figures 2.5, 2.6 and 2.7, which indicates that those validation results are representative of processing quality at different times of the year.

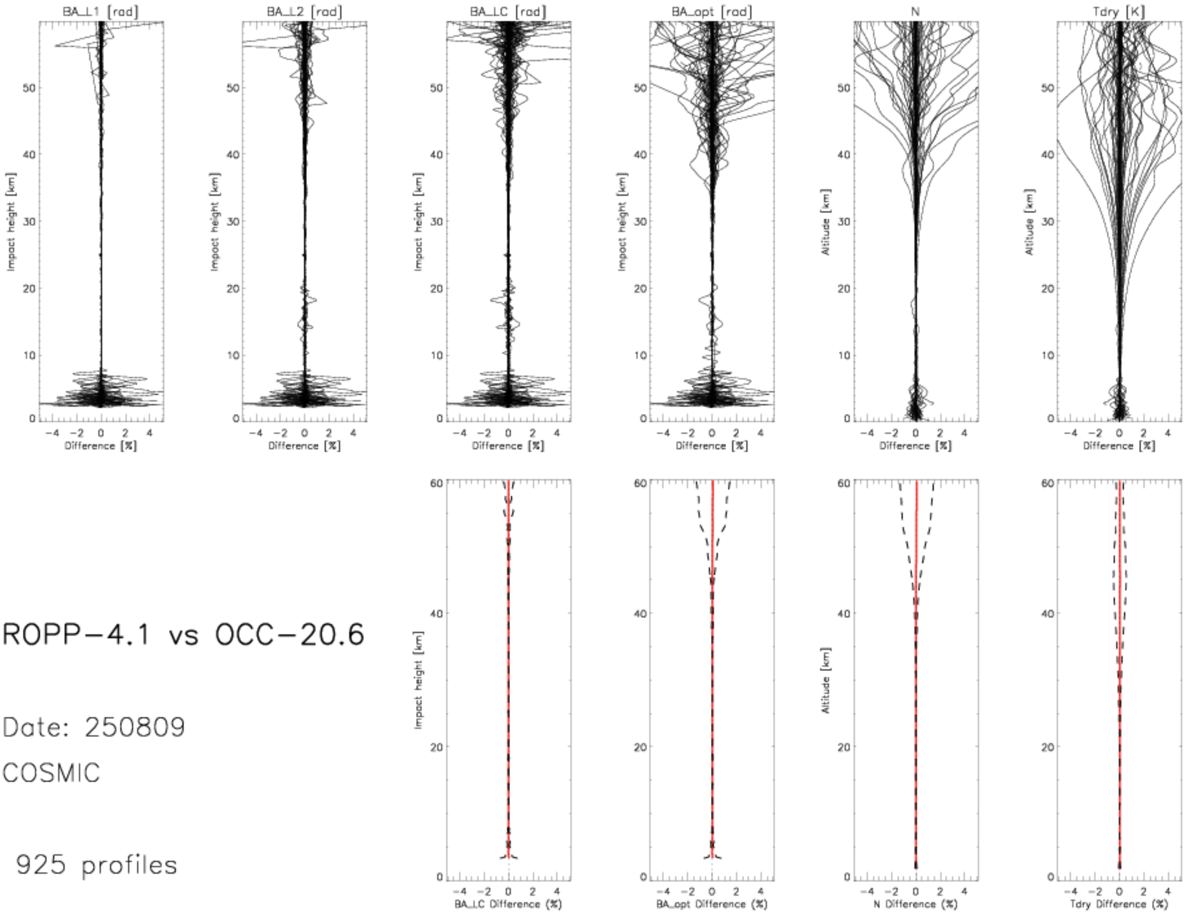

Figure 2.8: Differences between bending angle, refractivity and dry temperature results processed using the OCC (v20.6) and ROPP (v4.1) software codes.

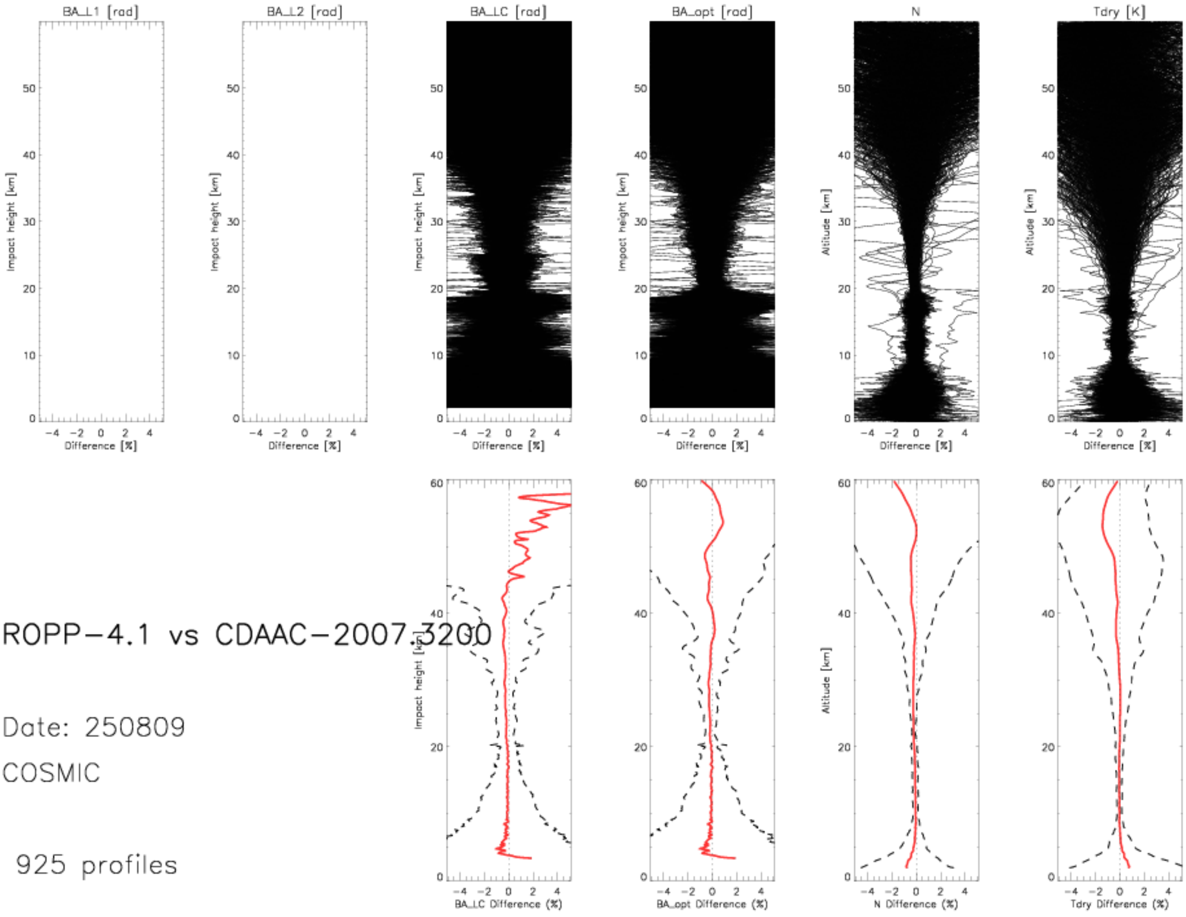

Figure 2.9: Differences between bending angle, refractivity and dry temperature results processed using ROPP (v4.1) and as processed by CDAAC (3200).

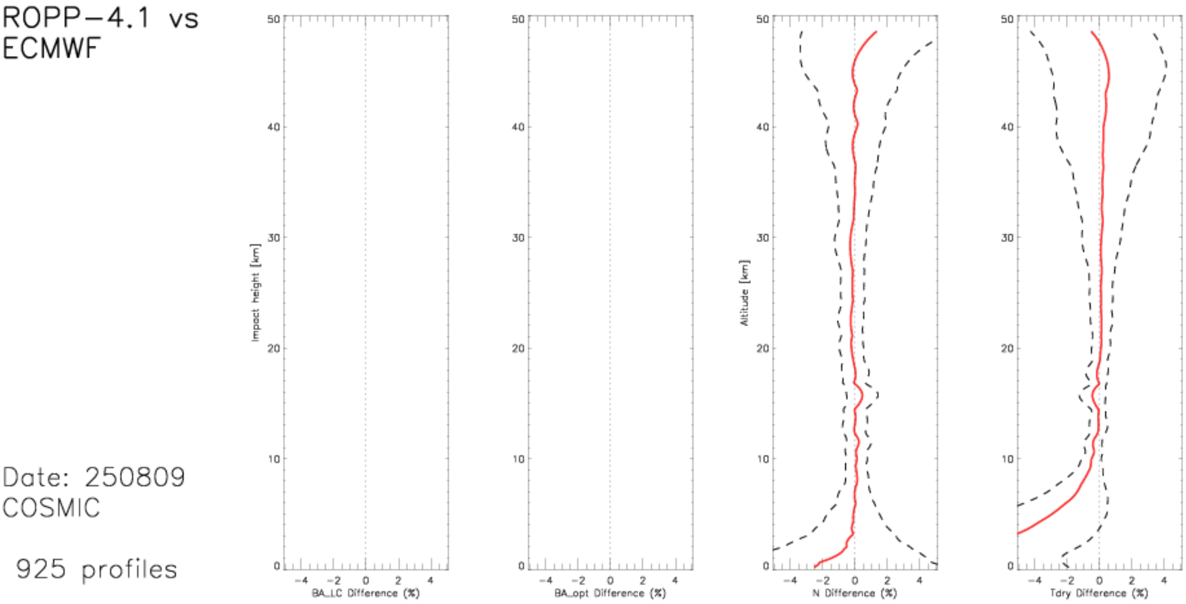

Figure 2.10: Differences between refractivity and dry temperature results processed using the ROPP (v4.1) software and ECMWF analyses (as provided by CDAAC).

2.5 Summary

ROPP provides tools and routines to process radio occultation data from excess phase and amplitude measurements to L1 and L2 bending angles, ionospheric corrected bending angles, optimised bending angles, refractivity and dry temperature. The software can be applied to data from any radio occultation mission, including GRACE, CHAMP, COSMIC and GRAS.

This analysis has demonstrated the application of ROPP to generate retrieved profiles from COSMIC observations. There good consistency between the ROPP software with other radio occultation processing and ECMWF analyses. Above 5 km, biases in retrieved refractivity are of the order 0.1%, increasing to about 2% towards the surface. Results from the latest ROPP release version show better agreement with validation data than results from earlier versions. Results are generally similar between the winter and summer case shown, and are considered representative of longer-term validation exercises based on a larger number of occultations.

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