Atmos. Meas. Tech. Discuss., 8, 157–190, 2015
www.atmos-meas-tech-discuss.net/8/157/2015/
doi:10.5194/amtd-8-157-2015

Atmospheric Measurement Techniques Discussions
Open Access

The Radio Occultation Processing Package ROPP

I. D. Culverwell[1], H. W. Lewis[1], D. Offiler[1], C. Marquardt[2], and C. P. Burrows[1]

[1]Met Office, Exeter, UK
[2]EUMETSAT, Darmstadt, Germany

Received: 22 October 2014 – Accepted: 26 November 2014 – Published: 6 January 2015

Correspondence to: I. D. Culverwell (ian.culverwell@metoffice.gov.uk)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

This paper describes the Radio Occultation Processing Package, ROPP, a product of the EUMETSAT Radio Occultation Meteorology Satellite Application Facility (ROM SAF) developed by a large number of scientists over many years. A brief review of the concepts, functionality and structure of ROPP is followed by more detailed descriptions of its key capabilities. Example results from a full chain of processing using some of the ROPP tools are presented. Some current and prospective uses of ROPP are given. Instructions on how to access the code and its supporting documentation are provided.

1 Introduction

Radio Occultation (RO) observations are an increasingly important means of measuring the tropospheric and stratospheric refractivity, and, indirectly, tropospheric and stratospheric temperature and pressure, and tropospheric humidity (e.g., Kursinski et al., 1997; Anthes, 2011). Their high vertical resolution, freedom from significant bias, and global coverage are widely recognised (e.g., Anthes et al., 2008), and have led to the extensive use of RO data for atmospheric research, for assimilation in Numerical Weather Prediction (NWP) models and for climate monitoring. It follows that there is a need for widely available, well supported and fully documented software packages that provide the tools to undertake common RO data processing requirements. This paper describes one such package, ROPP.

The Radio Occultation Processing Package ROPP is provided by EUMETSAT's Radio Occultation Meteorology Satellite Application Facility (ROM SAF, known as the GRAS SAF before 2012). It comprises software (as source code) and supporting build and test scripts, data files and documentation, which are designed to help users wishing to process, quality-control and assimilate RO data into their NWP models. Facilities are provided for the full chain of RO data processing, from phase delays to bending an-

AMTD
8, 157–190, 2015

gles, to refractivities and dry temperatures, and finally to 1D-Var retrieved temperature and humidity profiles.

Although the software is aimed at the GRAS instrument on the Metop satellites, as far as is possible it is generic, in that it can handle any other GNSS[1]-LEO[2] configuration radio occultation mission (COSMIC, CHAMP, GRACE, C/NOFS, SAC-C, TerraSAR-X, TanDEM-X, PAZ, etc.). We note, however, that a LEO-LEO configuration is not currently supported.

Users can integrate a subset of ROPP code into their own software applications, individually linking modules to their own code. Alternatively, they can use the executable tools provided as part of each module as standalone applications for RO data processing.

This paper describes the status of ROPP-7 (v7.0), which was released in October 2013.

2 Overview of ROPP

2.1 Concept and strategy

ROPP should not be viewed as a "black box" processor, but as a suite of library functions and example applications (written in Fortran 95). The software was originally intended for users who wish to combine RO-specific routines with their own code, but by now ROPP has developed into a package which offers validated stand-alone tools for format conversion and RO data processing. Whichever way ROPP is used, users are welcome to modify or replace components in ROPP to suit their existing local systems.

Updates to ROPP, which include new science, modifications in response to new data or software dependencies, and bug-fixes, are regularly released by the ROM SAF after a period of review and beta-testing by interested parties.

[1]Global Navigation Satellite System.

[2]Low Earth Orbit.

AMTD
8, 157–190, 2015

ROPP functionality mirrors most aspects of the ROM SAF operational data production chain (i.e. the generation of NRT[3] refractivity profiles from bending angles), but will not be exactly the same code – although the operational chain will use some elements of ROPP and vice-versa. The publicly available version of ROPP also contains additional alternative algorithms as user-switchable options.

2.2 Main functionality

ROPP consists of a number of modules, some of which depend on others. Modules not only contain source code, but also build and test scripts, data, example test results and user documentation. The ROPP-7.0 modules and their headline functionalities are listed in Table 1, and the relations between them are indicated in Fig. 1. The main purpose and functionality of each module is discussed in the following Sections, but, in brief, the two service modules and three scientific modules of ROPP are as follows.

The utilities module of ROPP includes quality control and range-checking tools, and a variety of conversion routines, including co-ordinate transformations (between ECI and ECF co-ordinates, geopotential and geometric heights, etc.) and date/time and unit conversions.

The input and output module of ROPP provides access to a variety of data formats:

- EUMETSAT's EPS CGS[4] Level 1a NRT products (i.e., excess phase and POD[5] data as a function of time) in netCDF[6], and Level 1b NRT products (i.e., bending angles as a function of impact parameter) in BUFR[7];

- ROM SAF Level 2 NRT and offline products in netCDF and BUFR;

[3]Near Real Time.

[4]European Polar System Core Ground Segment.

[5]Precise Orbit Determination.

[6]Unidata's network Common Data Format.

[7]Binary Universal Format for data Representation.

- UCAR[8]/CDAAC[9] NRT atmPrf, atmPhs, sonPrf, ecmPrf, ncpPrf, gfsPrf products in netCDF, and bfrPrf products in BUFR;
- GFZ[10] NRT products in dat/dsc text file pairs;
- Gridded background field datasets in GRIB2[11] format.

ROPP handles these diverse data formats by converting them to its own well defined RO data structure (in netCDF).

The preprocessing module contains tools to undertake the staged preprocessing from excess phase (i.e., the phase accumulated by the carrier wave during transit of the atmosphere and ionosphere above that which would be accumulated along a straight line path in vacuo between the transmitter and receiver) to bending angle, through to refractivity and dry temperature. It also contains tools to diagnose tropopause heights from profiles of bending angle, refractivity, dry temperature or background model temperature.

The forward modelling module contains forward operators (including tangent linear, adjoint and gradient calculation code) for pressure-based, height-based and hybrid NWP model vertical grids, to generate refractivities and bending angles from model state variables. It also includes a 2-D bending angle calculation tool.

The 1D-Var module contains cost function minimisers that allow the retrieval of pressure/height, temperature and humidity profiles from refractivity or bending angle profiles, given colocated NWP model background profiles.

ROPP also includes sample reference data files and example output test files, as well as full user documentation. Further details of its contents and capabilities can be found in the ROPP Overview document at http://www.romsaf.org.

[8]University Corporation for Atmospheric Research.
[9]COSMIC Data Analysis and Archive Center.
[10]Helmholtz Centre, Potsdam.
[11]General Regularly distributed Information in Binary form, Ed 2.

AMTD
8, 157–190, 2015
Radio Occultation Processing Package
I. D. Culverwell et al.

3 Utility module

The ROPP UTILS module provides height- and date-conversion routines, and other general purpose library functions such as string handling, message output, array manipulation and basic mathematical routines. These are used by other ROPP modules and would probably not be called directly by users from their own programs. Table 2 lists some of the routines in this module.

ROPP is designed for terrestrial applications. If a user wished to develop RO tools appropriate to other planetary atmospheres, the ROPP UTILS module is where the bulk of the changes (to planetary radius, gravity, rotation rate etc.) would need to be made.

4 Input/output module

The ROPP IO module reads radio occultation data from a variety of sources (EUMETSAT, BUFR, UCAR, GFZ and, for background profiles, text and GRIB files) and converts them to ROPP's internal, netCDF-based, general format for radio occultation data. ROPP can also write out such data in BUFR format. Most of these data-reading tools use data thinning and range-checking routines which are themselves part of the module. Table 3 lists some of the routines and tools in the IO module.

Figure 2 shows the results of passing a rising COSMIC-1 "atmPhs" profile (20.3° W, 19.5° S, 01:02 UTC, 1 October 2012), containing excess phase and amplitude data, and downloaded from the CDAAC website, (CDAAC, 2014), through `ucar2ropp`. It also shows the background temperatures and humidities that result when GRIB2-formatted ECMWF analyses, downloaded from the ECMWF website, (ECMWF, 2014), are passed through `grib2bgrasc` and `bgrasc2ropp`.

AMTD
8, 157–190, 2015
Radio Occultation Processing Package
I. D. Culverwell et al.

5 Preprocessing module

The ROPP PP module has been largely adopted from the OCC code developed by Michael Gorbunov at the Institute for Atmospheric Physics, Moscow (Gorbunov et al., 2011).

ROPP PP provides routines to compute L1 and L2 bending angles from measured excess phase data by geometrical optics and wave optics methods. Ionospherically corrected bending angle profiles are derived by combining L1 and L2 bending angles linearly or in a statistically optimised way. Climatological bending angle profiles are appended above the corrected ones, in order that refractivity profiles can be calculated by means of an inverse Abel transform. Dry temperatures are generated from the refractivities. ROPP PP also contains code to calculate tropopause heights from a variety of fields in an RO profile. Table 4 lists some of the routines and tools in this module.

In more detail, the `ropp_pp` module tools do the following.

`ropp_pp_occ_tool` processes excess phase and amplitude data, as follows.

– Read "level 1a" data, i.e. satellite positions, L1 and L2 signal amplitudes and phases.

– Compute the occultation point and undulation (height of geoid minus height of ellipsoid).

– Filter, quality control and carry out mission-specific processing of amplitude and phase data (Gorbunov et al., 2006).

– Compute bending angles by geometric optics or wave optics (CT2) (Gorbunov and Lauritsen, 2004). By default, ROPP uses CT2 below 25 km and geometric optics above.

– Perform "linear combination" ionospheric correction (Vorob'ev and Krasil'nikova, 1994) and statistically optimised ionospheric correction (Gorbunov, 2002). The

AMTD
8, 157–190, 2015
Radio Occultation Processing Package
I. D. Culverwell et al.

latter requires a background bending angle profile, which is currently derived from the MSIS climatology (Hedin, 1991).

- Compute inverse Abel transform of the ionospherically corrected bending angle profile to generate a refractivity profile.
- Generate a dry temperature profile corresponding to this refractivity profile.
- Write results to the RO data structure and thence to the output file.

Figure 3 shows the output of `ropp_pp_occ_tool` when the unprocessed COSMIC excess phase data shown in Fig. 2 are passed through it. The derived bending angles are also displayed.

`ropp_pp_invert_tool` is almost the same as `ropp_pp_occ_tool`, but starts from "level 1b" L1 and L2 bending angles before generating linearly combined bending angles, statistically optimised bending angles, refractivities and dry temperature profiles, as before.

`ropp_pp_tph_tool` diagnoses tropopause heights, as follows.

- Read the bending angle, refractivity, dry temperature or background model temperature profile.
- Compute the covariance transform (COT) (Lewis, 2009) of the bending angle or refractivity, or the lapse rate (LRT) of dry temperature or temperature.
- Diagnose the tropopause height (TPH) in the appropriate vertical co-ordinate from the maximum of the COT or the value of the LRT. Also, within the tropics, diagnose the "cold point" tropopause height (CPT) for the temperature-based diagnostics.
- Diagnose and record a TPH quality control (QC) flag, based on confidence in the derived TPH.
- Write the TPH and its QC flag to the RO data structure and thence to the output file.

AMTD
8, 157–190, 2015

Figure 4 shows the tropopause heights for the COSMIC occultation and co-located/simultaneous ECMWF background profile used in this paper. All six are reasonably close, and the four "observationally" based TPHs are within 400 m after the impact altitude of the bending angle-based TPH has been converted to altitude by dividing by the refractive index at the tropopause (a downward shift of around 200 m).

6 Forward modelling module

The ROPP FM module contains forward operators which calculate refractivity and bending angle profiles from background model data on pressure-based, height-based and "hybrid" NWP model vertical grids. Tangent linear, adjoint and gradient codes of the forward operators are provided for use in assimilation processing. Table 5 lists some of the routines and tools in this module.

In more detail, the `ropp_fm` module tools do the following.

`ropp_fm_bg2ro_1d` forward models 1-D background fields, as follows.

- Read level 2b input model data (ECMWF pressure-based or Met Office height-based) and generate a "state vector" $\boldsymbol{x}$ of pressure p, temperature T and humidity q as functions of geopotential height Z.
- Read or define (if not in input file) the observation levels on which the output will be calculated.
- Compute the refractivity profile, $N(Z)$ (Kursinski et al., 1997).
- Calculate the bending angle profile, $\alpha(a)$, from the Abel transform of refractivity (Healy and Thepaut, 2006), restricted to non-super-refracting conditions.
- If desired, calculate the forward model gradients $\partial N_i/\partial x_j$ and $\partial \alpha_i/\partial x_j$.

The "innovation" curves (i.e. observation minus forward modelled background) in the top two panels of Fig. 5 show the bending angles and refractivities that result

AMTD
8, 157–190, 2015
Radio Occultation Processing Package
I. D. Culverwell et al.

from passing the background profiles in the bottom two panels of Fig. 2 through `ropp_fm_bg2ro_1d`.

`ropp_fm_bg2ro_2d` extends the forward modelling of `ropp_fm_bg2ro_1d` by accounting for variation of the refractivity across the occultation plane, rather than just in the vertical at the tangent point. This has been found to have a beneficial effect on O–B differences in the lower troposphere (Healy et al., 2007). It works as follows.

- Read 2-D level 2b input model data (ECMWF pressure-based or Met Office height-based) and generate a 2-D "state vector" $\boldsymbol{x}$ of pressure p, temperature T and humidity q as functions of geopotential height Z and (uniformly spaced) horizontal angle θ.
- Read or define (if not in input file) observation levels on which the output will be calculated.
- Compute the refractivity section, $N(Z,\theta)$ (Kursinski et al., 1997).
- Calculate the bending angle profile, $\alpha(a)$, by 4th order Runge–Kutta integration of the 2-D ray equations (Rodgers, 2000).
- Compute the set of 1-D bending angle profiles at each horizontal location, using the Abel transform method of `ropp_fm_bg2ro_1d`, for comparison.

7 1D-Var retrieval module

The ROPP 1DVAR module provides quality control, minimisation and diagnostic routines for the retrieval of pressure, geopotential height, temperature and humidity profiles from profiles of refractivity or bending angle and (colocated, simultaneous) NWP background profiles, together with error covariance matrices of the observation and background. Table 6 lists some of the routines and tools in this module.

In more detail, the `ropp_1dvar` module tools do the following.

`ropp_1dvar_bangle` carries out a 1D-Var minimisation of the usual cost function J, where

$$2J(\boldsymbol{x}) = (\boldsymbol{x}-\boldsymbol{b})^T \mathbf{B}^{-1}(\boldsymbol{x}-\boldsymbol{b}) + (\boldsymbol{o}-\mathcal{H}(\boldsymbol{x}))^T \mathbf{O}^{-1}(\boldsymbol{o}-\mathcal{H}(\boldsymbol{x})) \quad (1)$$

where $\boldsymbol{x}$ is the state vector, $\boldsymbol{b}$ is the background state vector, $\boldsymbol{o}$ is the vector of bending angle observations, $\mathcal{H}$ is the (non-linear) forward model (Sect. 6), $\mathbf{B}$ is the background error covariance matrix and $\mathbf{O}$ is the covariance matrix of the combined measurement and forward model error. It works as follows.

- Read input model data (ECMWF pressure-based or Met Office height-based) and generate the background state vector $\boldsymbol{b}$ of temperature T and humidity q as functions of geopotential height Z.
- Read the background error matrix $\mathbf{B}$. The correlations usually come from an auxiliary file. The diagonal elements, the variances, can also be supplied externally, or profile-by-profile in the background file.
- Read the bending angles on impact parameters to generate the observation vector $\boldsymbol{o}$.
- Read the bending angle error covariance matrix $\mathbf{O}$. The correlations usually come from an auxiliary file. (The bending angle correlation matrix is usually assumed to be the identity.) The diagonal elements, the variances, can also be supplied externally, or profile-by-profile in the observation file.
- Carry out quality control based on range-checking, O–B (i.e. $\boldsymbol{o}-\mathcal{H}(\boldsymbol{b})$) and probability of gross error, and generate diagnostics if desired.
- Minimise the cost function in Eq. (1), either using an ROPP-specific minimiser based on a quasi-Newton method (Nocedal, 1980) or a Levenberg-Marquardt minimiser (Marquardt, 1963). The “solution” $\boldsymbol{a}$ equals $\boldsymbol{x}$ at the minimum J.

AMTD
8, 157–190, 2015

– Forward model bending angles from solution state vector $\boldsymbol{a}$.

– Generate O–A (i.e. $\boldsymbol{o} - \mathcal{H}(\boldsymbol{a})$) and analysis error covariance matrix **A**.

– Write to RO data structure and thence to output file.

Figure 5 shows the result of passing the (LC) bending angle profile shown in Fig. 3 and the colocated ECMWF background profile shown in Fig. 2 through `ropp_1dvar_bangle`. The retrieval has generally pulled the background towards the observations, as expected. Temperature increments of around 1 K and specific humidity increments of around 1 $\mathrm{g\,kg^{-1}}$ near the surface result.

`ropp_1dvar_refrac` does the same as `ropp_1dvar_bangle` but uses refractivity observations instead of bending angles. Naturally, different observation background errors **O** are needed.

The O–B and O–A profiles of a retrieval based on the refractivities generated (automatically) by `ropp_pp_occ_tool` by inverse Abel transform of the bending angles of Fig. 3, are shown in the top right element of Fig. 5. Again, the 1D-Var retrieval procedure has drawn the background to the observations. (Note that the temperature and humidity increments in this figure come from the bending angle retrieval.)

8 Testing module

The ROPP TEST module comprises a comprehensive suite of test routines, and associated test datasets, which can be run on a range of compilers and platforms. This "Test Folder" is one of the main ways of formally validating the ROPP code prior to public release of a new major version of the package. Table 7 lists some of the elements of this module.

Note that the complete `ropp_test` suite is not intended for users but for internal validation of the ROPP code, although some functionality of `ropp_test` is included in `ropp_io`, `ropp_pp`, `ropp_fm` and `ropp_1dvar` for users to verify that the code has been correctly built.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

AMTD

8, 157–190, 2015

Radio Occultation Processing Package

I. D. Culverwell et al.

9 Required and optional third party software

Full implementation of ROPP requires some standard third party software packages. These are all non-commercial ("freeware") and thus freely available, and (apart from the Met Office BUFR package) can easily be downloaded from internet resources. (The Met Office BUFR package is available without charge but has some licence restrictions. As from v5.0, ROPP may instead interface with the ECMWF BUFR library, which is freely available under the GNU LGPL[12].)

The ROPP documentation clearly indicates which packages are needed by which modules.

The third party packages used in ROPP7.0 are shown in Table 8. Naturally, as ROPP develops, the relevant, tested dependency packages may also change. Users are advised to consult the ROPP download page on the ROM SAF website to see which packages, and which versions, are relevant for the release they are using.

All third-party code or packages used by ROPP are, by definition, classed as "pre-existing software" and all rights remain with the originators. Separate rights licenses may be part of these distributions, and such licences must be adhered to by end-users.

To build ROPP and the dependency packages, standard Unix-type tools such as `make`, `ar` etc., plus ISO-compliant Fortran 95 and ANSI C compilers are required. Should users wish to modify the ROPP code for their own purposes, freely available tools such as `autoconf`, `automake`, and `m4` are recommended. The bash shell is needed to run the optional package build utility scripts. Optionally, IDL and an EPS[13] file viewer are used to generate and display results of some user-validation tests as part of the build.

[12] Lesser General Public Licence.

[13] Encapsulated PostScript.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

AMTD

8, 157–190, 2015

Radio Occultation Processing Package

I. D. Culverwell et al.

10 Uses of ROPP

It is important to realise that ROPP is designed to be used both as a research tool and for operational processing.

The following organisations use, or shortly intend to use, ROPP in their operational systems, where its main use is in the assimilation of RO data.

- The ROM SAF uses ROPP algorithms to generate operational refractivity profiles from bending angles provided by EUMETSAT, and code based on ROPP to generate retrieved temperature and humidity profiles from those refractivities (Lauritsen et al., 2011). ROPP is also used in the ROM SAF's offline operational processing of gridded climate products, which starts from excess phase and amplitude data (ROMSAF, 2014).

- The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) uses ROPP for validation and monitoring of GRAS[14] data. The ROPP FM module is used to forward model ECMWF background data to bending angles, and the ROPP IO module is used to put GRAS and COSMIC[15] data in the same format. EUMETSAT will also use ROPP for the generation of BUFR data in the next operational processor (A. von Engeln, personal communication, 2014).

- The Naval Research Laboratory (NRL-Monterey, USA) implemented the ROPP bending angle forward model in the operational variational assimilation system run by the Fleet Numerical Meteorology and Oceanography Center (FNMOC) (B. Ruston, personal communication, 2014).

- The Japanese Meteorological Agency (JMA) use ROPP operationally to assimilate bending angles (H. Owada, personal communication, 2014).

[14] GNSS Receiver for Atmospheric Sounding.

[15] Constellation Observing System for Meteorology, Ionosphere and Climate.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

AMTD

8, 157–190, 2015

Radio Occultation Processing Package

I. D. Culverwell et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀ ▶
Back Close
Full Screen / Esc

Printer-friendly Version
Interactive Discussion

- The Korea Institute of Atmospheric Prediction Systems (KIAPS) intend to use ROPP to assimilate bending angles into their new data assimilation system (H. Kwon, personal communication, 2014).
- The Centro de Previsão de Tempo e Estudos Climáticos (CPTEC, Brazil) use ROPP's forward modelling and quality control tools for the assimilation of refractivities in their research data assimilation system. They hope to start pre-operational testing soon (L. Sapucci, personal communication, 2014).
- The Chinese Academy of Sciences (CAS) are considering whether to use ROPP in the preprocessing of data from the GNOS instrument (W. Bai, personal communication, 2014).

Forward models based on the implementations in ROPP are also used operationally at the Met Office and ECMWF (S. Healy, personal communication, 2014).

Although ROPP is used extensively within the ROM SAF as a research tool, it is beginning to be used more widely, as in the following examples.

- Zhang et al. (2010) used ROPP to examine the effect of ionospheric correction on radio occultation measurements over Australia.
- Zin et al. (2012) investigated the properties of the ROSA GNSS receiver with ROPP.
- Ringer and Healy (2008) investigated climatological trends in bending angle using the ROPP forward model algorithms.
- von Engeln et al. (2009) compared bending angle observations made by the GRAS instrument to ECMWF forecasts which were forward modelled with (effectively) ROPP.

As ROPP is developed, new functionality will be introduced, which, it is hoped, will be of interest to researchers in a range of areas.

AMTD
8, 157–190, 2015

11 Where to get ROPP

Prospective users can obtain ROPP from the "ROPP software" link of the ROM SAF home page (ROMSAF, 2014). An ROPP overview, user guides, release notes, a log of the changes from the last release, and the BUFR specification for RO data are provided. Users need to accept the software licence which is presented. They can download the entire ROPP distribution, or individual modules. Fully documented build scripts are provided. A helpdesk is available, and should be the first point of contact for users in need of advice and information. Support for ROPP is restricted to the current release, and the previous two.

12 Conclusions

This paper has given a brief overview of the Radio Occultation Processing Package ROPP. Its structure and functionality have been briefly described, before details of its key software tools have been given. Results have been shown of a "full chain" of ROPP processing, from COSMIC data files and ECMWF background fields to ionospherically corrected bending angles and refractivities, to 1D-Var retrievals of temperature and humidity. Example tropopause height diagnostics of the resulting profiles have also been shown. Figure 6 summarises the full data flow.

Past, present and future examples of the use of ROPP have been given. The intention of this paper is to encourage other Radio Occultation scientists to use ROPP to process their data.

Further information on the use of ROPP within the ROM SAF can be found from the "Publications" link of the ROM SAF home page (ROMSAF, 2014). This page also has links to ROM SAF reports, conference proceedings, articles and other publications of interest to those in the field of radio occultation.

AMTD
8, 157–190, 2015

Acknowledgements. This work was carried out as part of EUMETSAT's Radio Occultation Meteorology Satellite Application Facility (ROM SAF), which is a decentralised operational RO processing centre under EUMETSAT. IDC, DO and CPB are members of the ROM SAF.

We thank UCAR/CDAAC for providing the COSMIC excess phase data and ECMWF for the gridded background fields that were used in the ROPP data processing example.

Many people, inside and outside the ROM SAF, have contributed to the development of ROPP. The principal authors are listed in Table 9. The ROM SAF extends its sincere appreciation for their efforts.

References

Anthes, R. A.: Exploring Earth's atmosphere with radio occultation: contributions to weather, climate and space weather, Atmos. Meas. Tech., 4, 1077–1103, doi:10.5194/amt-4-1077-2011, 2011. 158

Anthes, R. A., Bernhardt, P. A., Chen, Y., Cucurull, L., Dymond, K. F., Ector, D., Healy, S. B., Ho, S.-P., Hunt, D. C., Kuo, Y.-H., Liu, H., Manning, K., McCormick, C., Meehan, T. K., Randel, W. J., Rocken, C., Schreiner, W. S., Sokolovskiy, S. V., Syndergaard, S., Thompson, D. C., Trenberth, K. E., Wee, T.-K., Yen, N. L., and Zeng, Z.: The COSMIC/FORMOSAT-3 Mission: Early Results, B. Am. Meteorol. Soc., 3, 313–333, 2008. 158

COSMIC Data Analysis and Archive Center: http://cdaac-www.cosmic.ucar.edu/cdaac (last access: 27 November 2014), 2014. 162

European Centre for Medium-Range Weather Forecasts: http://www.ecmwf.int (last access: 27 Novenber 2014), 2014. 162

Gorbunov, M. E.: Ionospheric correction and statistical optimization of radio occultation data, Radio Sci., 37, 1084, doi:10.1029/2000RS002370, 2002. 163

Gorbunov, M. E. and Lauritsen, K. B.: Analysis of wave fields by Fourier Integral Operators and their application for radio occultations, Radio Sci., 39, RS4010, doi:10.1029/2003RS002971, 2004. 163

Gorbunov, M. E., Lauritsen, K. B., Rhodin, A., Tomassini, M., and Kornblueh, L.: Radio holographic filtering, error estimation, and quality control of radio occultation data, J. Geophys. Res., 111, D10105, doi:10.1029/2005JD006427, 2006. 163

AMTD

8, 157–190, 2015

Radio Occultation Processing Package

I. D. Culverwell et al.

Gorbunov, M. E., Shmakov, A. V., Leroy, S. S., and Lauritsen, K. B.: COSMIC Radio Occultation Processing: Cross-Center Comparison and Validation, J. Ocean. Atmos. Technol., 28, 737–751, doi:10.1175/2011JTECHA1489.1, 2011. 163
Healy, S. B. and Thepaut, J.-N.: Assimilation experiments with CHAMP GPS radio occultation measurements, Q. J. Roy. Meteor. Soc., 132, 605–623, doi:10.1256/qj.04.182, 2006. 165
Healy, S. B., Eyre, J. R., Hamrud, M., and Thepaut, J.-N.: Assimilating GPS radio occultation measurements with two-dimensional bending angle observation operators, Q. J. Roy. Meteor. Soc., 133, 1213–1227, doi:10.1002/qj.63, 2007. 166
Hedin, A. E.: Extension of the MSIS thermosphere model into the middle and lower atmosphere, J. Geophys. Res., 96, 1159–1172, 1991. 164
Kursinski, E. R., Hajj, G. A., Schofield, J. T., Linfield, R. P., and Hardy, K. R.: Observing earth's atmosphere with radio occultation measurements using the Global Positioning System, J. Geophys. Res., 102, D19, 23429–23465, 1997. 158, 165, 166
Lauritsen, K. B., Syndergaard, S., Gleisner, H., Gorbunov, M. E., Rubek, F., Sørensen, M. B., and Wilhelmsen, H.: Processing and validation of refractivity from GRAS radio occultation data, Atmos. Meas. Tech., 4, 2065–2071, doi:10.5194/amt-4-2065-2011, 2011. 170
Lewis, H. W.: A robust method for tropopause altitude identification using GPS radio occultation data, Geophys. Res. Lett., 36, L12808, doi:10.1029/2009GL039231, 2009. 164
Marquardt, D.: An Algorithm for Least-Squares Estimation of Nonlinear Parameters, SIAM J. Appl. Math., 11, 431–441, 1963. 167
Nocedal, J.: Updating Quasi-Newton Matrices with Limited Storage, Math. Comput., 35, 773–782, 1980. 167
Ringer, M. A. and Healy, S. B.: Monitoring twenty-first century climate using GPS radio occultation bending angles, Geophys. Res. Lett., 35, 1944–8007, doi:10.1029/2007GL032462, 2008. 171
Rodgers, C. D.: Inverse Methods for Atmospheric Sounding: Theory and Practice, World Scientific Publishing, Singapore, New Jersey, London, Hong Kong, 2000. 166
The Radio Occultation Meteorology Satellite Application Facility: http://www.romsaf.org (last access: 27 November 2014), 2014. 170, 172
von Engeln, A., Healy, S., Marquardt, C., Andres, Y., and Sancho, F.: Validation of operational GRAS radio occultation data, Geophys. Res. Lett., 36, 1944–8007, doi:10.1029/2009GL039968, 2009. 171

AMTD
8, 157–190, 2015
Radio Occultation Processing Package
I. D. Culverwell et al.

Vorob'ev, V. V. and Krasil'nikova, T. G.: Estimation of the Accuracy of the Atmospheric Refractive Index Recovery from Doppler Shift Measurements at Frequencies Used in the NAVSTAR System, Physics of the Atmosphere and Ocean, 29, 602–609, 1994 (English translation). 163

Zhang, K., Le Marshall, J., Norman, R., Wang, C.-S., Fu, E., Li, Y., and Kuleshov, Y.: A study on the relationship between ionospheric correction and data control for GPS radio occultation in Australia, in: Proceedings of Geoscience and Remote Sensing Symposium (IGARSS), Honolulu, Hawaii, 25–30 July 2010, 2940–2943, doi:10.1109/IGARSS.2010.5650216, 2010. 171

Zin, A., Zago, S., Mangolini, E., Landenna, S., Marradi, L., Notarpietro, R., Radicella, S., Nava, B., and Catalano, V.: The ROSA radio occultation project, in Proceedings of Satellite Navigation Technologies and European Workshop on GNSS Signals and Signal Processing, (NAVITEC), Nordwijk, the Netherlands, 5–7 December 2012, 1–8, doi:10.1109/NAVITEC.2012.6423096, 2012. 171

AMTD

8, 157–190, 2015

Radio Occultation Processing Package

I. D. Culverwell et al.

Table 1. ROPP-7.0 modules and their main functionalities.

Module	Content
UTILS	Utility tools; units conversion, low level interfaces, etc.
IO	Support for file reading and writing of RO files; RO internal data structure and interfaces; BUFR encoder/decoder tools; importation of RO data from non-ROPP files; extraction of background profiles from GRIB2 files; profile thinning; file management.
PP	Preprocessing (from excess phase through to refractivity and dry temperature); tropopause height diagnostics.
FM	Forward models (and tangent linear, adjoints and gradients), 1-D and 2-D versions.
1DVAR	1D-Var (user-callable subroutines and standalone applications).
TEST	Standalone test harness for ROPP modules. Not a user module, although subsets of the test system are included with the IO, PP, FM and 1DVAR modules.

AMTD
8, 157–190, 2015

Table 2. SUBROUTINES in the ROPP UTILS module.

Name	Purpose
GEOMETRIC2GEOPOTENTIAL	Converts geometric heights (wrt ellipsoid) to geopotential heights (wrt geoid).
GEOPOTENTIAL2GEOMETRIC	Converts geopotential heights (wrt geoid) to geometric heights (wrt ellipsoid).
DATE_AND_TIME_UTC	Calculates current date/time from system clock, adjusted to UTC, from the system time.
CALTOJUL	Converts Julian Day to calendar date and clock time, and vice-versa.
TIMESINCE	Converts Julian Day (or calendar date and clock time) to the time since some epoch.
DATUM_HMSL	Converts the height of a point wrt the WGS-84 ellipsoid to the height above the EGM96 geoid.
DATUM_TRANS	Translates (lon, lat, ht) or (x, y, z) between different Earth system co-ordinates.

AMTD
8, 157–190, 2015

Table 3. SUBROUTINES and standalone `executables` in the ROPP IO module.

Name	Purpose
ROPP_IO_READ	Reads ROPP-formatted RO data.
ROPP_IO_WRITE	Writes ROPP-formatted RO data.
ROPP_IO_INIT	Initialises data input and output.
ROPP_IO_THIN	Thins profiles.
ROPP_IO_RANGECHECK	Range-checks and validates all ROPP parameters.
`ropp2ropp`	Copies/renames/reformats/range-checks/thins/orders/ splits/concatenates ROPP files.
`ropp2bufr`	Converts ROPP-formatted data file to BUFR format.
`bufr2ropp`	Converts BUFR-formatted data file to ROPP format.
`ucar2ropp`	Converts UCAR-formatted data file to ROPP format.
`gfz2ropp`	Converts GFZ-formatted data file pair to ROPP format.
`grib2bgrasc`	Extracts Fortran namelist of background model data from GRIB2-formatted gridded dataset.
`bgrasc2ropp`	Converts Fortran namelist to ROPP format.
`eum2ropp`	Converts netCDF4-formatted ROPP data to standard ROPP format.
`eum2bufr`	Converts netCDF4-formatted ROPP data to BUFR format.

AMTD
8, 157–190, 2015

Radio Occultation Processing Package

I. D. Culverwell et al.

Table 4. SUBROUTINES and standalone `executables` in the ROPP PP module.

Name	Purpose
ROPP_PP_IONOSPHERIC_CORRECTION	Make ionospheric corrections to L1 and L2 signal.
ROPP_PP_INVERT_REFRACTION	Calculate refractivity profile (inverse Abel transform).
ROPP_PP_ABEL	Calculate bending angle profile (Abel Transform method).
ROPP_PP_BENDING_ANGLE_GO	Calculate bending angle profile (geometrical optics method).
ROPP_PP_BENDING_ANGLE_WO	Calculate bending angle profile (wave optics method).
ROPP_PP_TDRY	Calculate dry temperature.
`ropp_pp_occ_tool`	Process excess phase data to bending angle to refractivity and dry temperature.
`ropp_pp_invert_tool`	Process bending angle data to refractivity and dry temperature.
`ropp_pp_tph_tool`	Calculate tropopause height from a bending angle, refractivity, dry temperature or background temperature profile.

AMTD
8, 157–190, 2015

Table 5. SUBROUTINES and standalone `executables` in the ROPP FM module.

Name	Purpose
ROPP_FM_REFRAC_1D	Forward model state vector to refractivity.
ROPP_FM_BANGLE_1D	Forward model 1-D state vector to bending angle.
ROPP_FM_BANGLE_2D	Forward model 2-D state vector to bending angle.
`ropp_fm_bg2ro_1d`	Standalone tool to map 1-D model profile into bending angle and refractivity profile.
`ropp_fm_bg2ro_2d`	Standalone tool to map 2-D model section into bending angle profile.

AMTD
8, 157–190, 2015

Table 6. SUBROUTINES and standalone `executables` in the ROPP 1DVAR module.

Name	Purpose
ROPP_1DVAR_SOLVE	Quasi-Newton cost function minimiser.
ROPP_1DVAR_LEVMARQ	Levenberg-Marquardt cost function minimiser.
`ropp_1dvar_refrac`	Standalone 1D-Var retrieval application using refractivity observations.
`ropp_1dvar_bangle`	Standalone 1D-Var retrieval application using bending angle observations.

AMTD
8, 157–190, 2015

Table 7. ELEMENTS of the ROPP TEST module.

Name	Purpose
CC	Compile and link all modules on a variety of compilers and platforms.
IO	Convert between various RO data formats; compare against references.
PP	Test consistency between Abel and inverse Abel transforms; compare ROPP-generated refractivities and bending angles against NRT profiles; check processing of raw sampling data. Compare calculated TPHs with reference values.
FM	Forward model ECMWF and Met Office backgrounds; compare to GRAS, CHAMP and COSMIC observations. FASCOD/ducting examples. Test 2-D operator.
1DVAR	Test refractivity and bending angle retrieval tools by analysing O–A and O–B.

AMTD
8, 157–190, 2015
Radio Occultation Processing Package
I. D. Culverwell et al.

Table 8. Third party software packages used with ROPP-7 (v7.0).

Name	Purpose
For all supported platforms:	
netCDF	I/O interface library to a platform-independent, self-documenting binary file data format. Required by the IO module (and hence all others).
MOBUFR	Met Office BUFR kernel library. Only needed if building the BUFR encoder/decoder tools from the IO module. (Available on request to the Met Office via the ROPP Development Team.)
ECBUFR	Alternative ECMWF BUFR kernel library. Only needed if building the BUFR encoder/decoder tools from the IO module.
GRIB_API	The ECMWF Fortran interface to a WMO-standard format for gridded data. Only needed if background profiles are to be extracted from such datasets, using the IO module.
HDF5	Software suite which underpins netCDF-4. Only needed if "grouped" EUMETSAT-style RO data are to be read. Not required for the classic netCDF model used for the standard ROPP data format.
ZLIB	Compression library used by HDF5.
For windows platform only:	
Cygwin	Linux-style environment for building dependency packages and ROPP on Microsoft Windows platforms. N.B. Only required for implementation of ROPP on Microsoft Windows platforms (WinXP or later).

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
AMTD
8, 157–190, 2015

Table 9. Contributors to ROPP.

Name	Current institute	Contribution
Christian Marquardt	EUMETSAT	Author of majority of ROPP-1 code in UTILS, IO, FM and 1DVAR modules, and much personal, pre-existing software.
Huw Lewis	Met Office	1st ROPP Development Manager, FM and 1DVAR extensions. PP module.
Dave Offiler	Met Office	ROPP Project Manager, IO application code and IO extensions, BUFR format/template.
Sean Healy	ECMWF	Original 1-D FM code, 2-D FM operator code, introduction of compressibility factors.
Michael Gorbunov	Russian Academy of Sciences	Original PP code.
Axel von Engeln	EUMETSAT	Author of original Test Folder system and of EUMETSAT-formatted RO data reader.
Stig Syndergaard	DMI	Original spectral version of MSIS model (expansion in spherical harmonics and Chebychev polynomials), PP module developments.
Ian Culverwell	Met Office	2nd ROPP Development Manager. Documentation, testing, consolidation, IO development, GRIB2 reader, implementation of tropopause height diagnostics.
Carlo Buontempo	Met Office	Savitzky-Golay thinner code.
Michael Rennie	ECMWF	1st ROPP Test Manager. Test folder developments.
Kjartan Kinch	DMI	Elements of ropp_pp.
Hans Gleisner	DMI	Elements of ropp_pp, prototype GRIB2 reader.
Torsten Schmidt	GFZ	Guidance on tropopause height diagnostics.
Chris Burrows	Met Office	2nd ROPP Test Manager. Test folder developments.
Kent Bærkgaard Lauritsen	DMI	Code reviews; liaison with EUMETSAT (licences, beta tester contracts).

AMTD
8, 157–190, 2015

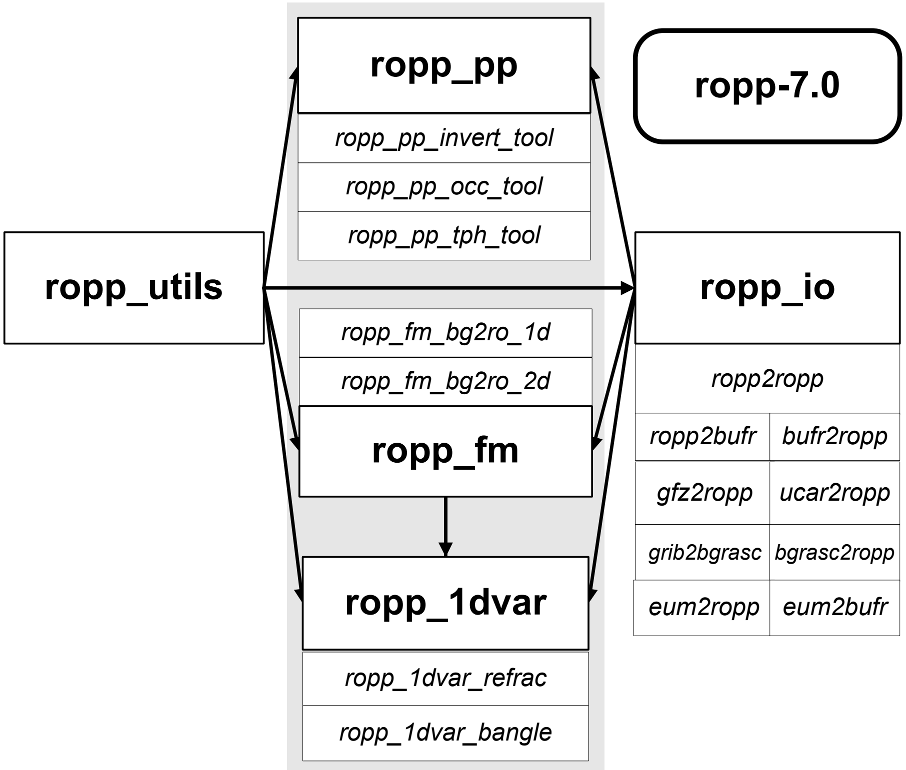

Figure 1. The **modules** and *tools* within ROPP-7.0. The module at the head of an arrow depends directly on the module at its tail.

AMTD
8, 157–190, 2015

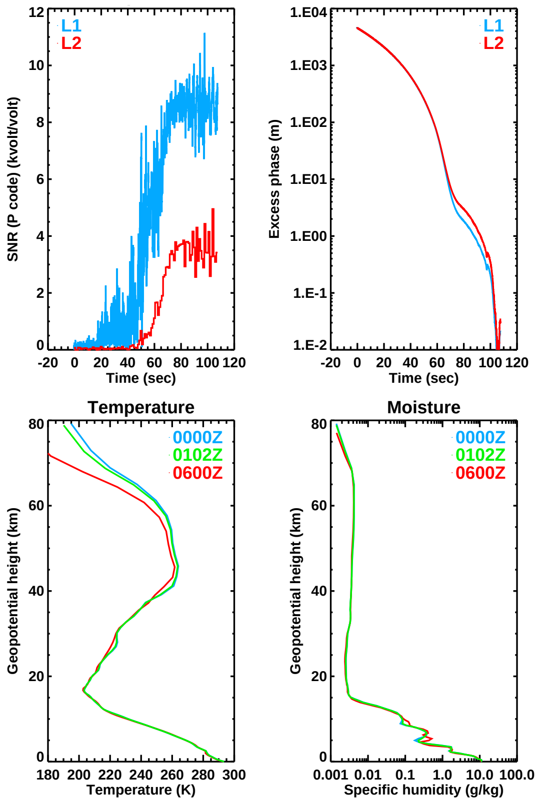

Figure 2. The results of passing "raw" COSMIC data through some of the tools in the `ropp_io` module. Top left: L1 and L2 signal-to-noise ratios (unprocessed); top right: L1 and L2 excess phases (unprocessed); bottom left: colocated background temperatures extracted from ECMWF analysis/forecast at 00:00 and 06:00 UTC, and the resulting simultaneous profile, obtained by linearly interpolating in time between them, as produced by `grib2bgrasc` and `bgrasc2ropp`; bottom right: as bottom left but for specific humidity.

AMTD
8, 157–190, 2015
Radio Occultation Processing Package
I. D. Culverwell et al.

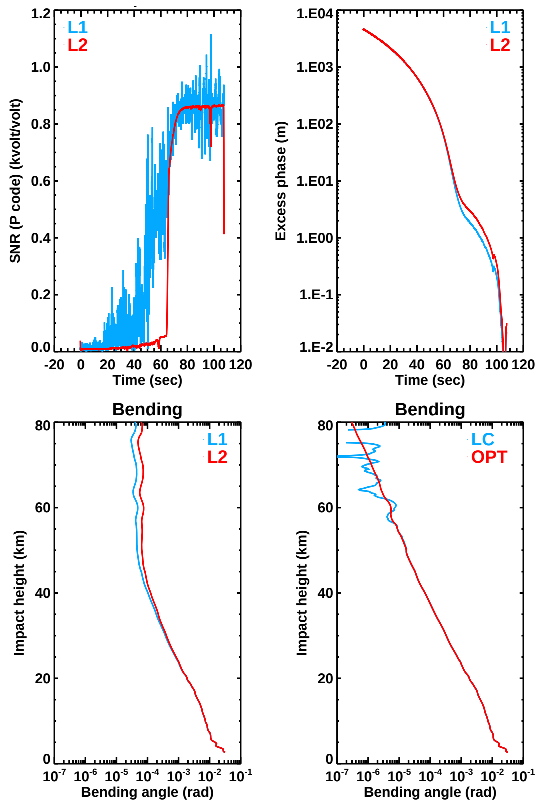

Figure 3. The results of passing the "raw" COSMIC phase/amplitude data of Fig. 2 through `ropp_pp_occ_tool`. Top left: L1 and L2 signal-to-noise ratios (preprocessed); top right: L1 and L2 excess phases (preprocessed); bottom left: resulting L1 and L2 bending angles; bottom right: "linearly combined" (LC) and "statistically optimised" (OPT) ionospherically corrected bending angles.

AMTD
8, 157–190, 2015

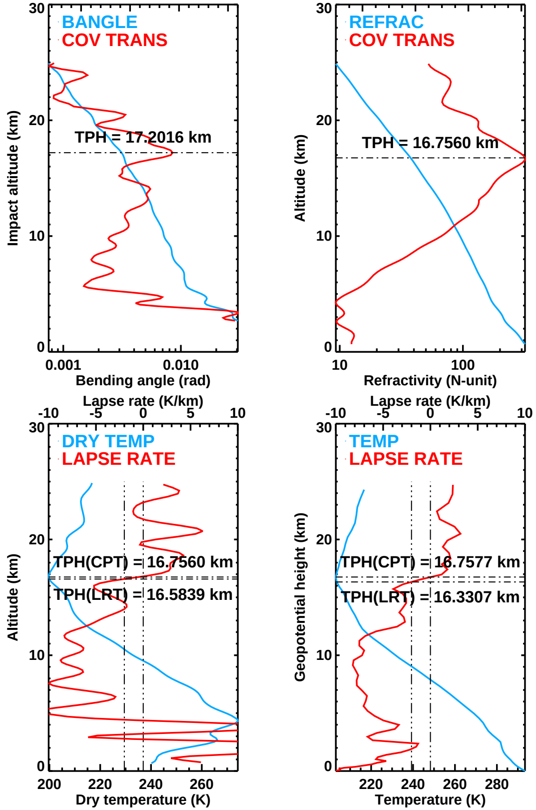

Figure 4. Tropopause heights for the COSMIC occultation of Figs. 2 and 3. Top left: bending angle and its covariance transform. Top right: refractivity and its covariance transform. Bottom left: dry temperature and its lapse rate. Bottom right: background temperature and its lapse rate from colocated and simultaneous ECMWF background.

AMTD
8, 157–190, 2015
Radio Occultation Processing Package
I. D. Culverwell et al.

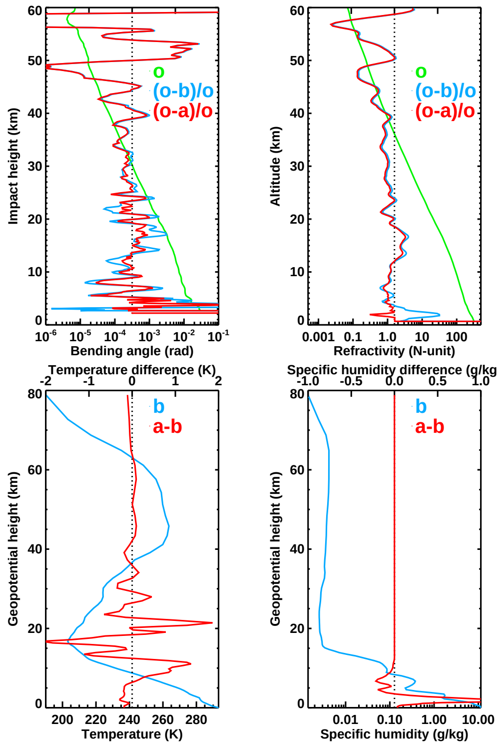

Figure 5. The results of passing COSMIC bending angles and refractivities, and the colocated/simultaneous ECMWF background fields, through `ropp_1dvar_bangle` and `ropp_1dvar_refrac` respectively. Top left: observed bending angle profile ***o***, as generated by `ropp_pp_occ_tool` (see Fig. 3), and its fractional difference from the background ***b*** and 1D-Var solution ***a***, after forward modelling (effectively) by `ropp_fm_bg2ro_1d`. Top right: same but for refractivity. Bottom left: background temperatures, as generated by `gras2bgrasc` and `bgrasc2ropp` (see Fig. 3) and the difference from the solution temperatures, as returned by `ropp_1dvar_bangle`. Bottom right: as bottom left but for specific humidities.

AMTD
8, 157–190, 2015

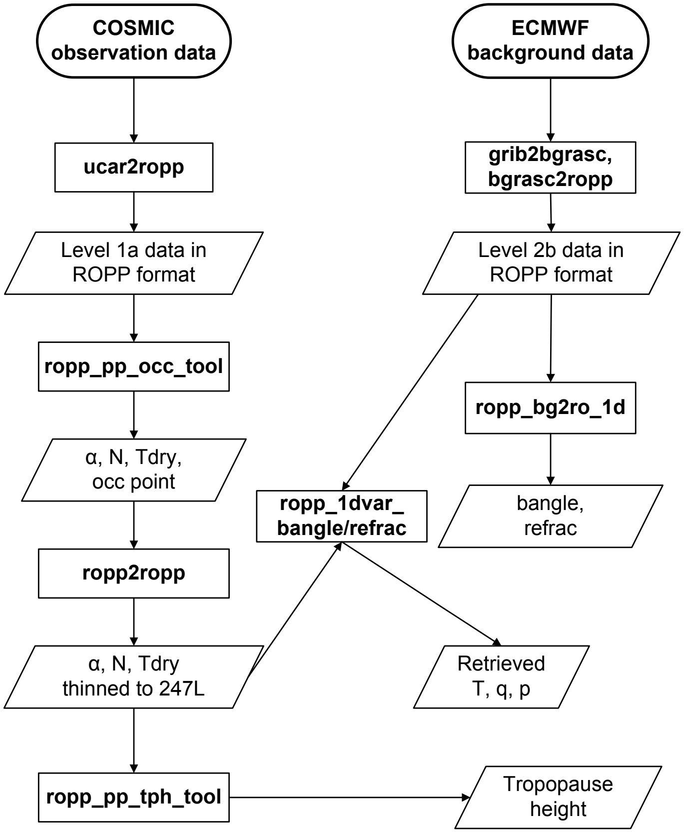

Figure 6. Data flow in the "full chain" of processing described in this paper. Analogous flowcharts would apply if starting from, for example, CHAMP RO data from GFZ and background data from the Met Office NWP model. For brevity, α and "bangle" denote bending angle, while N and "refrac" denote refractivity.

AMTD
8, 157–190, 2015