The Radio Occultation Processing Package (ROPP) Overview

Version 9.1

30 June 2019

The ROM SAF Consortium
Danish Meteorological Institute (DMI)
European Centre for Medium-Range Weather Forecasts (ECMWF)
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Document Change Record

Issue/Revision	Date	By	Description
Version 1.0	21 Oct 2004	DO	First release version
Version 1.1	13 Jul 2005	DO	Release version for ROPP Beta1 (v0.8)
Version 1.2	4 Sep 2006	DO	Miscellaneous updates
Version 1.3	7 Nov 2006	DO	Release version for ROPP Beta2 (v0.9)
Version 1.4	15 Jan 2007	DO	Release version for ROPP-1 DRI
Version 1.5	20 Feb 2007	DO	Release version for ROPP-1 (v1.0)
Version 1.6	27 Feb 2008	DO	Release version for ROPP-1 (v1.1)
Version 1.7	18 Jul 2008	HL	Release version for ROPP-1 (v1.2)
Version 1.8	1 Nov 2008	DO,HL	Release version for ROPP-2 DRI
Version 2.0	1 Dec 2008	HL	Release version for ROPP-2 (v2.0)
Version 3.0	1 May 2009	HL	Release version for ROPP-3 DRI
Version 3.0.1	1 Jul 2009	DO	Release version for ROPP-3 (v3.0)
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Version 4.1	22 Apr 2010	HL	Release version for ROPP-4 (v4.1)
Version 5.0	27 Apr 2011	IC,DO	Release version for ROPP-5 DRI
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Version 5.1	30 Sep 2011	IC	Updated text appropriate to ROPP-5 (v5.1)
Version 6.0	31 Oct 2011	IC	Release version for ROPP-6 DRI
Version 6.1	31 Jan 2013	IC	Release version for ROPP-6 (v6.1); new template with ROM SAF logos
Version 7.0	31 Jul 2013	IC	Release version for ROPP-7 (v7.0)
Version 7.1	31 Dec 2013	IC	Release version for ROPP-7 (v7.1)
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Version 8.1	31 Dec 2015	IC	Release version for ROPP-8 (v8.1)
Version 9.0	28 Feb 2017	IC	Release version for ROPP-9 (v9.0)
Version 9.1	30 Jun 2019	IC	Update to ninth full release (v9.1)

ROM SAF

The Radio Occultation Meteorology Satellite Application Facility (ROM SAF) is a decentralised processing centre 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 Climate Data Records (CDRs) and Interim Climate Data Records (ICDRs) for users requiring a higher degree of homogeneity of the RO data sets. The CDRs and ICDRs 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 aid 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.

Intellectual Property Rights

Contents

Executive Summary

This document gives an overview description of the 'Radio Occultation Processing Package' (ROPP). ROPP is a key deliverable of the ROM SAF during its third Continuous Development and Operational Phase (CDOP-3, March 2017–February 2022).

ROPP is a package of software (as source code) and supporting build and test scripts, data files and documentation, which will aid users wishing to process, quality-control and assimilate radio occultation data into their NWP models. Whilst aimed at the GRAS instrument on METOP, as far as is practicable, the software is generic, in that it can handle any other GPS–LEO configuration radio occultation mission (COSMIC, CHAMP, GRACE, TerraSAR-X, TanDEM-X, C/NOFS, SAC-C , ROSA, PAZ, etc). Note, however, that LEO–LEO combinations are not yet supported.

ROPP is being developed in planned stages, and functionality will be enhanced with each major release. Intermediate minor versions will be released to correct bugs, add small enhancements to existing functionality and to extend portability.

This document describes the ROPP concept and development strategy and gives a high level view of the package content, notes the file interfaces which ROPP needs to handle and lists the main components of the software elements. It also lists the third-party software on which some components of ROPP rely.

This overview applies to the first update to the ninth full release version of ROPP (v9.1).

1 Introduction

1.1 Purpose of this document

This document gives an overview description of the 'Radio Occultation Processing Package' (ROPP). ROPP is a key deliverable of the ROM SAF during its third Continuous Development and Operational Phase (CDOP-3, March 2017–February 2022) [AD.1] as reflected in the Product Requirement Document [AD.2].

This document should be read in conjunction with the Product Requirements Document (PRD) [AD.2], the ROPP Architectural Design Document (ADD) [RD.1] and the ROPP User Guides [RD.2].

This document will be updated as the detailed content of the ROPP, and the actual software code implementation, is developed and released. **This overview applies to the first update to the ninth full release version of ROPP (v9.1).**

1.2 Applicable and reference documents

1.2.1 Applicable documents

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

[AD.1] Proposal for the Third Continuous Development and Operations Phase (ROM SAF CDOP-3) March 2017 – February 2022, as endorsed by Council 7th December 2016

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

[AD.3] ROPP User Licence. SAF/ROM/METO/LIC/ROPP/002

1.2.2 Reference documents

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

[RD.1] ROPP Architectural Design Document (ADD). SAF/ROM/METO/ADD/ROPP/001

[RD.2] The ROPP User Guides:

Overview. SAF/ROM/METO/UG/ROPP/001

ROPP_IO. SAF/ROM/METO/UG/ROPP/002

ROPP_PP. SAF/ROM/METO/UG/ROPP/004

ROPP_APPS. SAF/ROM/METO/UG/ROPP/005

ROPP_FM. SAF/ROM/METO/UG/ROPP/006

ROPP_1DVAR. SAF/ROM/METO/UG/ROPP/007

[RD.3] WMO FM94 (BUFR) specification for radio occultation data. SAF/ROM/METO/FMT/BUFR/001

[RD.4] Unidata netCDF website: http://www.unidata.ucar.edu/software/netcdf/

[RD.5] HDF Group website: http://www.hdfgroup.org/HDF5/

[RD.6] G95 Project website: http://www.g95.org

[RD.7] GFortran website: http://gcc.gnu.org/wiki/GFortran

[RD.8] Cygwin website http://www.cygwin.com

[RD.9] GRAS Level 1 Product Format Specification. EPS/MIS/SPE/97234

[RD.10] Development procedures for software deliverables. NWPSAF-MO-SW-002

[RD.11] ECMWF BUFR software website: https://software.ecmwf.int/wiki/display/BUFR

[RD.12] ECMWF GRIB_API software website: https://software.ecmwf.int/wiki/display/GRIB

[RD.13] ZLIB website http://www.zlib.net

[RD.14] EUMETSAT Radio Occultation Level 1 Product Format Specification. EUM/TSS/SPE/16/817861

[RD.15] IAU Standards of Fundamental Astronomy (SOFA) Libraries product. http://www.iausofa.org/

1.3 Acronyms and abbreviations

AC	Analysis Correction (NWP assimilation technique)
API	Application Programming Interface
Beidou	Chinese GNSS navigation system. Beidou-2 also known as COMPASS
BG	Background
BUFR	Binary Universal Format for data Representation
CASE	Computer Aided Software Engineering
CDR	Climate Data Record
CF	Climate and Forecasts (CF) Metadata Convention
CGS	Core Ground Segment
CHAMP	Challenging Mini–Satellite Payload
CLIMAP	Climate and Environment Monitoring with GPS–based Atmospheric Profiling (EU)
CMA	Chinese Meteorological Agency
C/NOFS	Communications/Navigation Outage Forecasting System (US)
CODE	Centre for Orbit Determination in Europe

COSMIC	Constellation Observing System for Meteorology, Ionosphere & Climate
DMI	Danish Meteorological Institute
DoD	US Department of Defense
EC	European Community
ECF	Earth–centred, Fixed coordinate system
ECI	Earth–centred, Inertial coordinate system
ECMWF	The European Centre for Medium-Range Weather Forecasts
EGM–96	Earth Gravity Model, 1996. (US DoD)
EOP	Earth Orientation Parameters
EPS	EUMETSAT Polar System
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre (ESA)
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EUMETCast	EUMETSAT's primary dissemination mechanism for the NRT delivery of satellite data and products
FY-3C/D	GNSS radio occultation receivers (CMA)
GALILEO	European GNSS constellation project (EU)
GCM	General Circulation Model
GFZ	GFZ Helmholtz Centre (Germany)
GLONASS	Global Navigation Satellite System (Russia)
GNOS	GNSS Occultation Sounder (China)
GNSS	Global Navigation Satellite Systems (generic name for GPS, GLONASS, GALILEO and Beidou)
GPL	General Public Licence (GNU)
GPS	Global Positioning System (US)
GPS/MET	GPS Meteorology experiment, onboard Microlab-1 (US)
GPSOS	Global Positioning System Occultation Sensor (NPOESS)
GRACE–A/B	Gravity Recovery and Climate Experiment (US/Germany)
GRACE–FO	GRACE Follow-on experiment (US/Germany)
GRAS	GNSS Receiver for Atmospheric Sounding (onboard Metop)
GUI	Graphical User Interface
GTS	Global Telecommunications System
HIRLAM	High Resolution Limited Area Model
ICDR	Intermediate Climate Data Record
IERS	International Earth Rotation Service
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
IGS	International GPS Service
ISRO	Indian Space Research Organisation
JPL	Jet Propulsion Laboratory (NASA)
KMA	Korean Meteorological Agency

KOMPSAT–5	GNSS radio occultation receiver (KMA)
LAM	Local Area Model (NWP concept)
LEO	Low Earth Orbited
LGPL	Lesser GPL (*q.v.*)
LOS	Line Of Sight
Megha-Tropiques	Tropical water cycle (and RO) experiment (India/France)
METOP	Meteorological Operational polar satellites (EUMETSAT)
MKS	Meter, Kilogram, Second
MPEF	Meteorological Products Extraction Facility (EUMETSAT)
MSL	Mean Sea Level
N/A	Not Applicable or Not Available
NASA	National Aeronautics and Space Administration (US)
NMS	National Meteorological Service
NOAA	National Oceanic and Atmospheric Administration (US)
NPOESS	National Polar-orbiting Operational Environmental Satellite System (US)
NRT	Near Real Time
NWP	Numerical Weather Prediction
OI	Optimal Interpolation (NWP assimilation technique)
Operational ROM SAF	Team responsible for the handling of GRAS data and the delivery of meteorological products during the operational life of the instrument
PAZ	Spanish Earth Observation Satellite, carrying a Radio Occultation Sounder
PFS	Product Format Specifications
PMSL	Pressure at Mean Sea Level
POD	Precise Orbit Determination
Q/C	Quality Control
RO	Radio Occultation
ROC	Radius Of Curvature
ROM SAF	The EUMETSAT Satellite Application Facility responsible for operational processing of radio occultation data from the Metop satellites. Leading entity is DMI; collaborating entities are UKMO, ECMWF and IEEC.
ROPP	Radio Occultation Processing Package
ROSA	Radio Occultation Sounder for Atmosphere (on OceanSat-2 and Megha-Tropiques)
RMDCN	Regional Meteorological Data Communication Network
SAC–C	Satelite de Applicaciones Cientificas – C
SAF	Satellite Application Facility (EUMETSAT)
SAG	Scientific Advisory Group
SI	Système International (The MKS units system)
TAI	Temps Atomique International (International Atomic Time)
TanDEM–X	German Earth Observation Satellite, carrying a Radio Occultation Sounder
TBC	To Be Confirmed
TBD	To Be Determined

TDB	Temps Dynamique Baricéntrique (Barycentric Dynamical Time)
TDT	Temps Dynamique Terrestre (Terrestrial Dynamical Time)
TDS	True–of–date coordinate system
TerraSAR–X	German Earth Observation Satellite, carrying a Radio Occultation Sounder
TP	Tangent Point
UKMO	United Kingdom Meteorological Office
UML	Unified Modelling Language
UT1	Universal Time-1 (proportional to the rotation angle of the Earth)
UTC	Universal Time Coordinated
VAR	Variational analysis; 1D, 2D, 3D or 4D versions (NWP data assimilation technique)
VT	Valid or Verification Time
WEGC	Wegener Center for Climate and Global Change
WGS–84	World Geodetic System, 1984. (US DoD)
WMO	World Meteorological Organization
WWW	World Weather Watch (WMO)

1.4 Definitions, levels and types

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, Offline, CDR or ICDR). The data levels and product types are defined below[1]. 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: (i) 3 hours after measurement (SAF Level 2 for EPS); (ii) 80 min after measurement (SAF Level 2 for EPS-SG Global Mission); (iii) 40 min after measurement (SAF Level 2 for EPS-SG Regional Mission).

[1] Note that the level definitions differ partly from the WMO definitions: http://www.wmo.int/pages/prog/sat/dataandproducts_en.php.

- **Offline product**: Data product delivered from less than 5 days to up to 6 months after measurement, depending on the requirements. The evolution of this type of product is driven by new scientific developments and subsequent product upgrades.
- **CDR**: Climate Data Record generated from a dedicated reprocessing activity using a fixed set of processing software[2]. The data record covers an extended time period of several years (with a fixed end point) and constitutes a homogeneous data record appropriate for climate usage.
- **ICDR**: An Interim Climate Data Record regularly extends in time a (Fundamental or Thematic) CDR using a system having optimum consistency with and lower latency than the system used to generate the CDR[3].

1.5 Structure of this document

Section 2 gives some basic background on the ROPP package: its purpose, history, structure, functionality, platform capabilities and user documentation. Section 3 explains in more detail the purpose and function of the routines and executables in the various 'modules' of ROPP. Section 4 explains the external depedency libraries (netCDF, BUFR etc) on which ROPP depends (or at least some of its tools depend), while Section 5 lists the most suitable versions for the latest release.

Appendices record useful ROPP and other ROM SAF documentation, list the principal authors of ROPP, and state the copyright information that applies to various parts of the code.

[2] (i) GCOS 2016 Implementation Plan; (ii) http://climatemonitoring.info/home/terminology/.
[3] http://climatemonitoring.info/home/terminology/ (the ICDR definition was endorsed at the 9th session of the joint CEOS/CGMS Working Group Climate Meeting on 29 March 2018).

2 Overview of ROPP

2.1 What is ROPP?

Objective: *To provide users with a comprehensive software package, containing all necessary functionality to preprocess RO data from Level 1a (Phase), Level 1b (Bending Angle) or Level 2 (Refractivity) files, plus RO-specific components to assist with the assimilation of these data in NWP systems.*

ROPP is a package of software (as source code) and supporting build and test scripts, data files and documentation, which will aid users wishing to process, quality-control and assimilate radio occultation data into their NWP models. The software is split into several modules. Users may wish to integrate a subset of ROPP code into their own software applications, individually linking modules to their own code. Alternatively, users may wish to use the executable tools provided as part of each module as standalone applications for RO data processing.

Whilst aimed at the GRAS instrument on METOP, as far as is practicable, the software is generic, in that it can handle any other GPS–LEO configuration radio occultation mission (COSMIC, CHAMP, GRACE, C/NOFS, SAC-C, TerraSAR-X, TanDEM-X, ROSA, PAZ, etc). The LEO–LEO configuration is not supported in the current ROM SAF CDOP, but in principle such support could be included at a future time if any mission with this configuration is likely to be launched.

ROPP is being developed in planned stages, and functionality will be enhanced with each release. Table 2.1 shows previous releases under CDOP and CDOP-2, and the intended major functionality over the foreseen releases during CDOP-3. Intermediate minor versions may be released to correct bugs, add small enhancements to existing functionality and to extend portability.

The ROPP concept, development strategy and overview of content is described in Section 2; Section 4 notes the file interfaces which ROPP will need to handle and Section 3 lists the main components of the software elements. For details of the package, the ROPP User Guides [RD.2] should be consulted. Finally, Section 5 lists the third-party software on which some components of ROPP rely.

ROPP contains support for a generic data format for radio occultation data (`ropp_io`), pre-processor routines (`ropp_pp`), application routines (`ropp_apps`), one- and two-dimensional forward models (`ropp_fm`), tools for quality control (immersed within the other modules, principally `ropp_1dvar`) and routines for the implementation of 1D–Var retrievals (`ropp_1dvar`). Utility routines used by some or all of the ROPP modules are provided in an additional module (`ropp_utils`). This structure (Figure 2.1) reflects the various degrees of interdependence of the difference ROPP modules. For example, the subroutines and functions in `ropp_io` and `ropp_fm` modules are mutually indepdendent, whereas routines in `ropp_1dvar` depend on `ropp_fm`. Sample standalone implementations of `ropp_pp`, `ropp_fm` and `ropp_1dvar` (which then require `ropp_io` for file interfaces, reading and writing data) are provided with those modules and documented in the relevant User Guides.

Release	Date	Main additional functionality
ROPP-1	Mar 2007	File I/O format conversions (text, netCDF, BUFR); profile thinning; forward models for bending angle and refractivity; 1D–Var retrieval (on pressure- and height-based levels).
ROPP-2	Dec 2008	Preprocessing from bending angles to refractivity; Abel and inverse-Abel transforms. Generic support for writing ROPP formatted text files removed.
ROPP-3	Jun 2009	Preprocessing from Doppler to bending angle; additional file conversions and profile thinning options. Code validated with pre-operational GRAS data.
ROPP-4	Dec 2009	2D forward operators for bending angles. Code validated with operational GRAS data.
ROPP-5	Jun 2011	Option for non-ideal gas law and new refractivity coefficients in the forward model. Optional interface with ECMWF BUFR library instead of the Met Office BUFR library. Support for new NRT RO data sources such as C/NOFS, SAC-C and TanDEM-X.
ROPP-6	Feb 2012	Science, algorithm and technical improvements. Code consolidation.
ROPP-7	Sep 2013	Introduce tropopause height diagnostic.
ROPP-8	Dec 2014	Introduce forward modelling and retrievals of L1 and L2 bending angles; improved vertical interpolation scheme.
ROPP-9	Feb 2017	Introduce planetary boundary layer height diagnostic; introduce wave optics propagator.
ROPP-10	Dec 2019	RO reflection flag; ionospheric data generators.
ROPP-11	Dec 2021	Asphericity code; further ionospheric data generators.

Table 2.1: Main functionality of ROPP major releases during CDOP and CDOP-2, and those planned for CDOP-3.

2.2 Concept and strategy

- ROPP is not a 'black box' end-to-end processor;
- It is a suite of library functions and example applications (Fortran 95 source code) from which users can 'pick and mix' with their own (possibly distributed) code;
- Users may modify or replace components in ROPP to suit existing local operational infrastructure;
- ROPP is delivered in phases with a beta-testing programme involving interested users;
- ROPP functionality mirrors aspects of the ROM SAF operational data production chain, but will not be the same code (though the operational chain will use some elements of ROPP and vice-versa);
- Level 1a to Level 2 processing algorithms will be similar — but not necessarily identical — to those in the ROM SAF operational and offline processors and alternative algorithms may be provided as user- switchable options;
- Bit-compatibility between ROM SAF Level 2 data and ROPP-processed equivalents is not to be expected, though they will have very similar statistical properties.

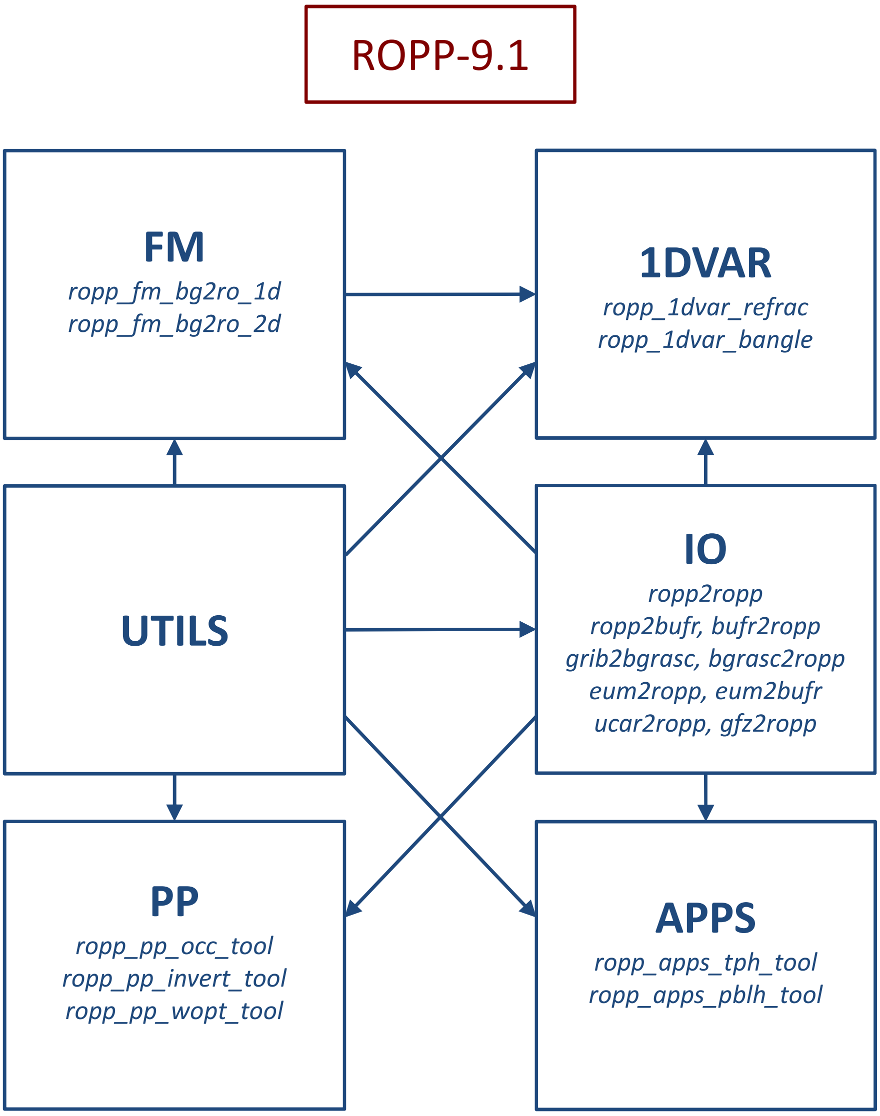

Figure 2.1: The **modules** and *tools* within ROPP-9.1. The module at the head of an arrow depends directly on the module at its tail.

2.3 Main functionality

ROPP can read:

- CGS Level 1a NRT products in netCDF;
- CGS Level 1b NRT products in BUFR disseminated via EUMETCast;
- SAF Level 2 NRT products in BUFR disseminated via the GTS or EUMETCast;
- SAF Level 2 NRT in products in netCDF via EUMETCast;
- SAF Level 2 offline products in netCDF or BUFR;

- UCAR/CDAAC NRT atmPrf, atmPhs, sonPrf, ecmPrf, ncpPrf, gfsPrf products in netCDF and bfrPrf products in BUFR;
- GFZ NRT products in dat/dsc text file pairs;
- Gridded background datasets in ECMWF GRIB format.

It also provides support for flexible netCDF I/O of RO data via simple interfaces with a file management/conversion tool.

ROPP offers the following processing facilities:

- Support for flexible netCDF I/O of RO data via simple interfaces with a file management/conversion tool;
- Staged preprocessing from excess phase up to refractivity and dry temperature;
- Forward operators (including tangent linear, adjoint and gradient code) for pressure- and height-based and hybrid NWP model vertical grids, and for both refractivity and bending angle simulation, as vertical profiles and 2D planes;
- 1D–Var and minimiser for retrieval of pressure/height, temperature and humidity profiles from a refractivity or bending angle profile, given an NWP background profile;
- Tropopause height and planetary boundary layer height diagnostics;
- Further support for NWP models and climate applications;
- Quality control and range checks;
- Data filtering / smoothing / interpolation / thinning;
- Co-ordinate transformations (ECI/ECF coordinates, geopotential/geometric heights, etc);
- Date/time and other unit conversions;
- Observation covariance matrices for different latitude bands and seasons;
- Standalone test harnesses (including test input and example output files);
- BUFR encoder and decoder application tools;
- Low level utility routines (providing simplified interfaces, etc);
- Configuration, build scripts and support files for a variety of POSIX-compliant platforms with built-in support for a number of common F95 and C compilers;
- Sample reference data files and example output test files;
- Full user documentation.

Module	Content
ROPP_UTILS	Utility tools; units conversion, low level interfaces, etc.
ROPP_IO	Support for file reading and writing of RO files; RO internal data structure and interfaces; BUFR encoder/decoder tools; import RO data from non-ROPP files; extraction of background profiles from GRIB files; profile thinning; file management.
ROPP_PP	Preprocessing (from excess phase through to refractivity and dry temperature); wave optics propagator.
ROPP_FM	Forward models (and tangent linear, adjoints and gradients), 1D and 2D versions.
ROPP_1DVAR	1D–Var (user-callable subroutines and standalone applications).
ROPP_APPS	Applications (diagnosis of tropopause height and planetary boundary layer height).
ROPP_TEST	Standalone test harness for ROPP modules. Not a user module, although subsets of the test system are included with ROPP_IO, ROPP_PP, ROPP_FM and ROPP_1DVAR.

Table 2.2: ROPP-9 modules and their main content

ROPP is implemented as a number of modules, each module containing a set of related functions; some modules use other modules. Modules not only contain source code, but also build and test scripts and data, example test results and user documentation for that module. ROPP is implemented in a phased approach, and not all of the above functionality will be available in this current release. The ROPP-9 modules and their main content are listed in Table 2.2 and their inter-relationships are indicated in Fig 2.1. The main functions of each module are discussed in Sec 3.

2.4 Development

- ROPP is developed incrementally from scientifically validated prototype code, with a phased release programme until the required functionality is achieved. Current and future functionality will be validated using operational GNSS-RO data.
- Each major release will undergo a formal beta-testing, delivery readiness inspection (DRI) review and release procedure, following the established NWP SAF model [RD.10].
- The first full release (ROPP-1 v1.0) was in April 2007 with limited functionality, concentrating on NWP assimilation support (e.g. 1D–Var with forward operators for Refractivity and Bending Angle, file I/O interfaces and support tools), as indicated in Table 2.2. An update (ROPP-1 v1.1) was released in March 2008, mainly relating to the ROPP_IO module to improve performance and robustness against poor quality RO data. ROPP-1 v1.2 (September 2008) was a further update, mainly relating to the ROPP_FM and ROPP_1DVAR modules. The forward operator architecture was simplified and support was added for height-based model levels. An ROPP-specific minimisation algorithm was written to replace the third-party M1QN3 code. A number of redundant utility libraries were removed from ROPP_UTILS and the dependence on third-party libraries and pre-existing software in all modules was generally reduced by recoding certain functions.

- A second release package (ROPP-2 v2.0) with extended and improved functionality was released in December 2008. The main change in ROPP-2 was the inclusion of a new ROPP_PP (preprocessor) module containing basic tools for processing Bending Angle data through to Refractivity. Routines to perform ionospheric correction and forward and inverse Abel integrals were introduced.

- A third release package (ROPP-3 v3.0) with further extended and improved functionality was released in July 2009. The main new element in ROPP-3 was to include advanced pre-processing algorithms for Excess Phase through to Bending Angle (e.g. Geometric optics, FSI/CT2). ROPP-3 was validated against pre-operational Level 1b and Level 2 GRAS data.

- A fourth release package (ROPP-4 v4.0) contained extended 2-dimensional forward models for NWP systems that can employ this feature. Use of 2D FM can improve the assimilation in areas of high horizontal gradients in the troposphere (fronts etc). ROPP-4 was validated with fully operational GRAS Level 1b and Level 2 data and released in December 2009, though the ROPP_PP module remained at pre-operational status pending investigation into a compiler dependency in a low level ROPP_PP routine. An update v4.1 was released in July 2010 to correct this problem, allowing this module to also have operational status.

- A fifth release package (ROPP-5 v5.0, June 2011) extended the functionality of the forward model and 1D–Var tools to account for non-ideal gas (compressibility) effects. In addition, the configure/build and BUFR encoder/decoder applications were updated to use either the Met Office BUFR kernel library or the ECMWF equivalent. Encoding to BUFR Edition 4 standard was made default. NRT data from newly available and future RO missions such as C/NOFS, SAC-C, TanDEM-X, ROSA and PAZ supported.

- A sixth full release (ROPP-6 v6.0, February 2012) focused on reconciling the preprocessing package (ROPP_PP) with its original source code ('OCC'), as well as a series of minor modifications in response to ROPP tickets, and a general tidying of the code.

- An update to the sixth full release (ROPP-6 v6.1, February 2013) provided a tool to extract background profiles from gridded fields in GRIB format, and the tools to read 'grouped' RO data in netCDF4 files. The dry temperature was also retrieved and output by default (as a level 2a quantity).

- A seventh full release (ROPP-7 v7.0, Sep 2013) included various diagnoses of the tropopause height, derived from bending angle, refractivity, dry temperature or background model temperature.

- An internal update to the seventh full release (ROPP-7 v7.1, December 2013) provided the facility to model L1 and L2 bending angles directly in the forward model and the 1D–Var modules, as well as the option to use an improved interpolation scheme in the forward model.

- The eighth full release (ROPP-8 v8.0, December 2014) consolidated the changes in ROPP-7.1, and included improvements to the error handling, improved automatic testing when building ROPP, developments to the background profile extraction tool, better output levels definitions in the 1D forward model, developments to the EUMETSAT-format level 1a data reader, and numerous other changes.

- An internal update to the eighth full release (ROPP-8 v8.1, December 2015) provided the tools to diagnose planetary boundary layer heights from various profiles of radio occultation data.
- The ninth full release (ROPP-9 v9.0, February 2017) incorporated a large number of changes to the data reading routines, especially those of EUMETSAT level 1a data, as well as the first version of a wave optics propagator. This tool calculates the excess phases that would be incurred by RO signals propagating through a given spherically symmetric neutral refractivity field. It does so by scattering the radio wave through a set of refractivity 'screens', before propagating the signal at the final screen to the LEO. Numerous other small changes were also incorporated.
- An update to the ninth full release (ROPP-9 v9.1, December 2018) provides tools to ingest data from the GNOS instrument on FY-3C, some new reference frame transformations to match those used by EUMETSAT, some accounting for the effects on single frequency bending angles of a finite electron density at the LEO, minor developments to the wave optics propagator, and numerous small improvements.
- Minor releases will be made as required (bug fixes, extending portability, improving functionality to existing modules, etc.) inbetween major releases.

2.5 Platform support

The ROPP program code is written as far as is practical in ISO-compliant Fortran 95 and tested to work on a variety of operating systems and compiler combinations, but limited to those available to the SAF consortium and beta-test users. Some components of the package will require the use of freely available file I/O interface libraries such as netCDF — see Sec 5.

Specifically:

1. ROPP is developed, tested, and fully supported on Linux (currently Red Hat Enterprise Release 6.8) with Intel ('ifort' v12 and v16), NAG ('nagfor' v5.2), Portland Group ('pgf95' v15), SUN ('sunf95' v8) and GNU ('gfortran' v4.4.7) Fortran 95 compilers. Third-party dependency packages employing C-language code is compiled with GNU C ('gcc' v4.4.7) compilers.
2. ROPP-1 v1.0 was successfully tested on HP-UX 11 with NAG f90/95 ('f95' v4) and an HP-UX version of the GNU G95 ('hpg95') — and C ('gcc') compilers for third-party libraries. However, due to the withdrawal of MetO HP hardware since that release, practical testing on this platform is no longer possible. The ROPP build system continues to technically support this platform, but the ROM SAF does not guarantee to fix problems found only with HP-UX.
3. ROPP-1, ROPP-2 and ROPP-3 were successfully tested on a NEC IA64-based front-end with NEC ('efc') Fortran-95 — and with NEC C ('ecc') for third-party libraries — supercomputing environment. This system was replaced by the IBM Power-6 system in mid-2009, which was upgraded to Power-7 in 2012.
4. ROPP-5 and ROPP-6 have been successfully tested on IBM Power-6 HPC system with AIX Fortran Compiler ('xlf95' v12.1), and ROPP-6.1, ROPP-7 and ROPP-8 on IBM Power-7 HPC with

'xlf95' v12.1. Since the replacement of these machines with a Cray XC40, however, support for these compilers can no longer be guaranteed.

5. ROPP has been built, and has undergone user-level testing, under Cygwin on Microsoft Windows with GNU G95 ('g95') GFortran ('gfortran') (and GNU C ('gcc')). Support for building the package will only be under the Cygwin [RD.8] environment, which provides Linux-like shell and build tools under Windows. It has not proved practical to build the dependency packages using Windows native compilers (Intel, Salford, etc) since their command line syntax is not compatible with the packages' POSIX- standard configure systems. Hence these compilers are not supported for ROPP. As from ROPP-8, the g95/Cygwin combination is no longer supported.

6. ROPP will be tested on other (non-SAF) POSIX-compliant platforms and compiler combinations under the beta-testing programme and where there has been feedback from users for release versions (see below). Beta-test platforms are generally Linux-based.

7. Building and installation is not supported for non-POSIX platforms such as OpenVMS, though the program code can be expected to (manually) compile and run correctly with minimal changes e.g. related to file syntax differences. There is no support in the ROPP or dependency packages for EBCDIC-based systems, such as IBM/MVS.

Note that the above details are subject to change should alternative platforms and/or specific compilers become available (or cease to be available) to the Development Team during the project.

'Support' includes:

1. Supplied facilities to build and install the package components (e.g. configure scripts to generate and run 'make' files) and example standalone applications and reference test data and results;

2. Correction of bugs or other deficiencies (in software or documentation) noted by users;

3. Investigation of workarounds, with users, for problems found in compiling the code due to compiler 'oddities' for platforms not explicitly supported (see above);

4. Continuous development of the code in response to user feedback in terms of improved functionality and efficiency;

5. Release of minor update versions as necessary, to include bug fixes, robustness against non-nominal input data, improve portability etc, as for example ROPP-1 v1.1, v1.2, ROPP-4 v4.1 and ROPP-6 v6.1.

Users requiring support of the ROPP Development Team should in the first instance contact the ROM SAF Helpdesk at http://www.romsaf.org > Helpdesk > New Enquiry. Development and support for ROPP will continue under the third Continuous Development and Operational Phase (CDOP-3) of the ROM SAF ([AD.2], March 2017 to February 2022) and beyond that, assuming formal extension agreements are put in place. The ROPP User Licence [AD.3] gives formal details.

Required:

1. The configuration system will allow the compilation, installation and testing of the software on generic Unix-like (POSIX-compliant) platforms, provided ANSI/ISO-compliant Fortran 95 and C compilers and standard shells and development tools (bash, make, ar, m4, automake, etc) are available. Third-party libraries may rely on additional tools.
2. Some elements of the ROPP software require the use of third party code, which should be pre-installed by the user before attempting to build the ROPP applications — see Sec 5.
3. Specific support and guidance on the use of optimising compiler switches will be provided for the operating systems and compilers available to the SAF consortium. Users are encouraged to provide the SAF with similar settings for other platforms, which can then be included (but not formally supported by the SAF) in a subsequent release of the package.

2.6 User documentation

A full list of user documentation is provided in Tables A.1, A.2 and A.4. These documents are available via the ROM SAF website at http://www.romsaf.org.

The ROPP distribution website has a Release Notes file in the root directory which provides a 'Quick Start' guide to the package. This should be read before downloading the package files. Also included is a record of the changes between the latest ROPP release and the previous one. Detailed build and install instructions are contained in the release notes of the individual ROPP software modules and the ROPP User Guide [RD.2]. Detailed build and install instructions are contained in the release notes of the individual ROPP software modules.

Module-specific user guides for the input/output (ROM SAF, 2019d), preprocessor (ROM SAF, 2019e), applications (ROM SAF, 2019b), forward model (ROM SAF, 2019c) and 1D–Var (ROM SAF, 2019a) modules describe the algorithms and routines used in those modules. These provide the necessary background and descriptions of the ROPP software for users to process radio occultation data from excess phase to bending angle or refractivity, and to perform 1D–Var retrievals of radio occultation data and implement ROPP in their own applications.

More detailed Reference Manuals are also available for each module for users wishing to write their own interfaces to the ROPP routines, or to modify the ROPP code. These are provided in the associated module distribution files.

Further documentation can be downloaded from the ROPP section of the ROM SAF web site http://www.romsaf.org. The full user documentation set is listed in Table A.1.

In addition to these documents, most of the standalone application programs have Unix-style 'man page' help files which are installed during the build procedures. All such programs have summary help information which is available by running the command with the `-h` switch.

Any comments on the ROPP software should in the first instance be raised via the ROM SAF Helpdesk at http://www.romsaf.org.

References

ROM SAF, The Radio Occultation Processing Package (ROPP) 1D–Var module User Guide, SAF/ROM/METO/UG/ROPP/007, Version 9.1, 2019a.

ROM SAF, The Radio Occultation Processing Package (ROPP) Applications module User Guide, SAF/ROM/METO/UG/ROPP/005, Version 9.1, 2019b.

ROM SAF, The Radio Occultation Processing Package (ROPP) Forward model module User Guide, SAF/ROM/METO/UG/ROPP/006, Version 9.1, 2019c.

ROM SAF, The Radio Occultation Processing Package (ROPP) Input/Output module User Guide, SAF/ROM/METO/UG/ROPP/002, Version 9.1, 2019d.

ROM SAF, The Radio Occultation Processing Package (ROPP) Pre-processor module User Guide, SAF/ROM/METO/UG/ROPP/004, Version 9.1, 2019e.

3 Software functions

The ROPP software is split into several modules for specific purposes. Users may wish to integrate a subset of ROPP code into their own software applications, individually linking modules to their own code. Alternatively, users may wish to use the executable tools provided as part of each module as standalone applications for RO data processing.

In this section we list the main software subcomponents of ROPP. This list is limited to the higher level, user-callable routines and standalone tools. Several of these will call lower level routines, which would not normally be accessed directly by the user (but will be fully documented in the relevant ROPP Reference Manuals). The list is by grouping of major function (module) and each sublist gives the following information:

Name: the name of the routine. This is a tag and is not necessarily the name of the implemented subroutine, function or main program. Uppercase names refer to user callable (API) routines; lowercase names are standalone (executable) application tools.
Purpose: a short description of what the routine or program does.
Input: the main inputs to the routine. This is not a full argument or command line list.
Output: the main outputs from the routine. This is not a full argument or output list.
RV: the Release Version number when this routine was first, or will be, included.
P/S: 'P' for Pre-Existing Software (not developed under the ROM SAF contract) or 'S' for SAF (developed within and for the SAF).

ROPP is developed in planned stages and not all functionality was available in the early releases. Functionality which is not yet provided in the latest ROPP release, but to be added in future releases, are listed in italics.

The ROPP User Guides [RD.2] provide the details of the package, its dependencies and how to build and test the package components. The ROPP Reference Manuals (one per module) give the interface and functional details of each and every routine in the package.

3.1 Utility module, ropp_utils

The UTILS module provides height and date conversion routines, and other general purpose library functions such array manipulation, string handling, message output and basic mathematical routines. These are used by other ROPP modules and are not intended to be called directly by user applications. The following is just a small subset of the routines in this module.

Name	Purpose	Input	Output	RV	P/S
GEOMETRIC2 GEOPOTENTIAL	Geopotential height conversion	Geometric heights (wrt ellipsoid)	Geopotential heights (wrt geoid)	1.0	S
GEOPOTENTIAL2 GEOMETRIC	Geometric height conversion	Geopotential heights (wrt geoid)	Geometric heights (wrt ellipsoid)	1.0	S
DATE_AND_TIME_UTC	Current date/time from system clock, adjusted to UTC	System time	Year, Mon, Day, Hour, Min, Sec, Msec, Time Zone (UTC)	4.0	P
CALTOJUL	Convert between Julian Day and calendar date and clock time for absolute time calculations	Year, Mon, Day, Hour, Min, Sec, Msec (or Julian Day)	Julian Day (or Year, Mon, Day, Hour, Min, Sec, Msec)	4.0	P
TIMESINCE	Convert between absolute (calendar) date/time and time since some epoch	Calendar date/time (or relative time)	Relative time (or calendar date/time)	5.0	P
DATUM_HMSL	Height above mean sea level	Lat, lon, ht of point wrt ellipsoid (WGS-84)	Height of point above geoid (EGM96)	3.0	P
DATUM_TRANS	Earth coordinate system transforms	3D location of point in system 1 (lat/lon/ht or x,y,z)	3D location of point in system 2 (lat/lon/ht or x,y,z)	3.0	P

Table 3.1: SUBROUTINES in the `ropp_utils` module.

3.2 Input/Output module, ropp_io

The IO module provides support for a generic data format for radio occultation data. Routines are provided for flexible netCDF I/O of RO data via simple interfaces with a file management/conversion tool and BUFR encoder and decoder application tools. Tools to convert from UCAR and GFZ format data files are also included. Most of these tools employ data thinning and range checking routines contained in the module.

Name	Purpose	Input	Output	RV	P/S
ROPP_IO	API definitions	n/a	n/a	1.0	S
ROPP_IO_TYPES	Data/structure definitions	n/a	n/a	1.0	S
ROPP_IO_READ	Read RO data	netCDF file	RO data structure	1.0	S
ROPP_IO_WRITE	Write RO data	RO data structure	netCDF file	1.0	S
ROPP_IO_INIT	Initialise data	RO data structure	RO data structure	1.0	S
ROPP_IO_THIN	Profile thinner	RO data structure	RO data structure	1.0	S
ROPP_IO_RANGECHECK	Range-check/validate all ROPP parameters	RO data structure	RO data structure	1.1	S
ropp2ropp	File manager/converter	netCDF file	netCDF file	1.0	S
ropp2bufr	BUFR encoder	netCDF file	BUFR file	1.0	S
bufr2ropp	BUFR decoder	BUFR file	netCDF file	1.0	S
ucar2ropp	UCAR file converter	UCAR netCDF file	netCDF file	1.0	S
gfz2ropp	GFZ file converter	GFZ text file pair	netCDF file	1.1	S
test2ropp	Test data generator	n/a	netCDF file	1.2	S
grib2bgrasc	Extract GRIB data	GRIB file	ASCII file	6.1	S
bgrasc2ropp	ASCII data converter	ASCII file	netCDF file	6.1	S
eum2ropp	Read netCDF4 RO data	netCDF4 file	netCDF file	6.1	S
eum2bufr	Encode netCDF4 RO data	netCDF4 file	BUFR file	6.1	S

Table 3.2: SUBROUTINES and standalone executables in the ropp_io module.

3.3 Preprocessing module, ropp_pp

The PP module provides routines to compute L1 and L2 channel bending angles from measured excess phase data by geometrical optics and wave optics methods. Ionospheric correction of L1 and L2 bending angles is applied to derive corrected bending angle and refractivity profiles by combining measured data with climatological bending angle profiles. The module also includes an Abel transform (and its inverse) to calculate bending angle from refractivity (and vice versa). Dry temperatures are also generated.

Name	Purpose	Input	Output	RV	P/S
ROPP_PP	Interface definitions	n/a	n/a	2.0	S
ROPP_PP_IONOSPHERIC_CORRECTION	Ionospheric corrections to L1 and L2 signal	Uncorrected L1 and L2 bending angle profiles	Corrected bending angle profile	2.0	S
ROPP_PP_INVERT_REFRACTION	Calculate refractivity profile (Abel Transform method)	Corrected Bending angle as function of impact parameter	Refractivity as function of geometric height AMSL	2.0	S
ROPP_PP_ABEL	Calculate BA profile (Abel Transform method)	Refractivity as function of geometric height AMSL	Bending angle as function of impact parameter	2.0	S
ROPP_PP_BENDING_ANGLE_GO	Calculate bending angle profile (Geometrical Optics method)	Excess Doppler time series	Bending angle as function of impact parameter	3.0	S
ROPP_PP_BENDING_ANGLE_WO	Calculate bending angle profile (Wave optics method)	Excess Doppler and amplitude time series	Bending angle as function of impact parameter	3.0	S
ROPP_PP_TDRY	Calculate dry temperature	Refractivity	Dry temperature	3.0	S
`ropp_pp_occ_tool`	Process excess phase data	L1 and L2 excess phase data	Ionospherically corrected bending angle, refractivity and dry temperature	3.0	S
`ropp_pp_invert_tool`	Process bending angle data	L1 and L2 ionospherically corrected bending angle	Refractivity and dry temperature	3.0	S
`ropp_pp_wopt_tool`	Wave optics propagator	1D neutral refractivity profile	Excess phase data	9.0	S

Table 3.3: SUBROUTINES and standalone `executables` in the `ropp_pp` module.

3.4 Applications module, ropp_apps

The APPS module provides routines to diagnose tropopause height (TPH) and planetary boundary layer height (PBLH) from a range of profiles of radio occultation data (bending angles, refractivities, background temperatures etc). The TPH routines were introduced in the `ropp_pp` module at version 7.0; they were transferred to the new module `ropp_apps` at version 8.1.

Name	Purpose	Input	Output	RV	P/S
ROPP_APPS	Interface definitions	n/a	n/a	8.1	S
ROPP_APPS_TPH_BANGLE (etc)	Calculate TPH from bangle (etc) profile	(bending angle, impact parameter)	Tropopause height	7.0	S
ROPP_APPS_PBLH_BANGLE (etc)	Calculate PBLH from bangle (etc) profile	(bending angle, impact parameter)	Planetary boundary layer height	8.1	S
ROPP_APPS_COV_TRANSFORM	Calculate covariance transform	General profile	Covariance transform	7.0	S
ROPP_APPS_CALC_ GEOP	Calculate geopotential	T, q, Ak, Bk for ECMWF profile	Geopotential height	7.0	S
ROPP_APPS_CALC_ TDRY	Calculate dry temperature	Refractivity profile	Dry temperature	8.1	S
ROPP_APPS_IMPACT2GEOM	Convert impact param to geom height	Impact param and refractivity	Geometric height	8.1	S
`ropp_apps_tph_tool`	Calculate tropopause height	Bending angle, refractivity, dry temperature or temperature	Impact param, geom. height, geom. height or geopotential of tropopause, resp.; processing flags.	7.0	S
`ropp_apps_pblh_tool`	Calculate planetary boundary layer height	Bending angle, refractivity, dry temperature, background temperature, background specific humidity, background relative humidity	Height of boundary layer above surface; processing flags.	8.1	S

Table 3.4: SUBROUTINES and standalone `executables` in the `ropp_apps` module.

3.5 Forward modelling module, ropp_fm

The FM module provides forward operators to compute vertical refractivity and bending angle profiles from background data on pressure- and height-based and hybrid NWP model vertical grids. Tangent linear, adjoint and gradient codes to the forward operators are provided for use in assimilation processing.

Name	Purpose	Input	Output	RV	P/S
ROPP_FM	Interface definitions	n/a	n/a	1.0	S
ROPP_FM_REFRAC_1D	Map model state vector to refractivity	Model P,T,q vs geop ht profile	Refractivity vertical profile as fn of geopotential height or pressure	1.0	S
ROPP_FM_BANGLE_1D	Map model 1D state vector to bending angle	Model P,T,q (ionospheric parameters) vs geop ht profile	Bending angle vertical profile as fn of impact parameter or pressure	1.0	S
ROPP_FM_BANGLE_2D	Map model 2D state vector to bending angle	Model P,T,q vs geop ht profiles at points along the ray path	Bending angle vertical profile as fn of impact parameter or pressure	4.0	S
TL/AD/GRAD	Tangent linear, adjoint and gradient codes of above forward models			1.0	S
`ropp_fm_bg2ro_1d`	Standalone tool to map 1D model profile into refractivity profile	ROPP file containing model background P,T,q vs geop ht profile(s)	ROPP file containing model-equivalent bending angle and refractivity profile(s)	1.0	S
`ropp_fm_bg2ro_2d`	Standalone tool to map 2D model section into bending angle profile	ROPP file containing model background P,T,q vs geop ht and horizontal distance	ROPP file containing model-equivalent bending angle profiles	4.0	S

Table 3.5: SUBROUTINES and standalone `executables` in the `ropp_fm` module.

3.6 1D–Var retrieval module, ropp_1dvar

The 1DVAR module provides 1D–Var and minimiser routines for retrieval of pressure/height, temperature and humidity profiles from a refractivity or bending angle profile, given an NWP background profile, observation and background covariance matrices. Perform data quality control checks.

Name	Purpose	Input	Output	RV	P/S
ROPP_1DVAR	Interface definitions	n/a	n/a	1.0	S
ROPP_1DVAR_SOLVE	Quasi-Newton cost function minimiser	Background T,q,p profiles, observed refractivity or bending angle profile, b/g and ob error covariance matrices	Solution vector, forward modelled b/g and solution, cost function and other diagnostics	1.0	S
ROPP_1DVAR_LEVMARQ	Levenberg-Marquardt cost function minimiser	Background T,q,p profiles, observed refractivity or bending angle profile, b/g and ob error covariance matrices	Solution vector, forward modelled b/g and solution, cost function and other diagnostics	1.0	S
`ropp_1dvar_refrac`	Standalone 1D–Var retrieval application (supporting ECMWF-type pressure-based and Met Office height-based model levels)	Profile(s) of refractivity, model background, b/g and ob error covariance matrices	Retrieved profiles of T,q,geop ht on pressure levels	1.2	S
`ropp_1dvar_bangle`	Standalone 1D–Var retrieval application (supporting pressure-based and height-based levels)	Profile(s) of bending angle, model background, b/g and ob error covariance matrices	Retrieved profiles of T,q,geop ht on pressure levels	1.2	S

Table 3.6: SUBROUTINES and standalone `executables` in the `ropp_1dvar` module.

3.7 Testing module, ropp_test

The TEST module provides a comprehensive suite of test routines and associated test datasets which can run via an IDL top level control tool on several local or networked platforms with a variety of compilers, together with a web-based result reporting system. This suite is known as the 'Test Folder' and is one of the main validation tools for formal review of ROPP prior to open release of a new major version of the package.

Name	Purpose	Input	Output	RV	P/S
`ropp_test`	CC tests. Build (compile and link)	Source code and dependency libraries	ROPP module object libraries and executable code built with no recorded errors	–	S
	IO standalone test harness	RO observation files (subset supplied with ROPP) and randomly generated RO data	RO data validated against input data	–	S
	PP standalone test harness (also implicitly tests UTILS and IO modules)	RO Level 1a/b observation files	Derived refractivity profiles	–	S
	APPS standalone test harness (also implicitly tests UTILS and IO modules)	RO Level 1b/2a/2b files	Derived TPHs and PBLHs	–	S
	FM standalone test harness (also implicitly tests IO and UTILS modules)	NWP background files (subset supplied with ROPP)	Refractivity and bending angle profile	–	S
	1D–Var standalone test harness (also implicitly tests FM, IO and UTILS modules)	RO observation files, NWP background files (subset supplied with ROPP)	Derived T,q,P vs h (or T,q,h vs P) profile files	–	S

Table 3.7: Elements of the `ropp_test` module.

NB: the complete ropp_test suite is not intended for users but for internal validation of the ropp code. 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, and generates output consistent with provided reference files.

3.8 Ground-based GNSS module, ropp_gbg

The long-awaited GBG module of ROPP has instead been transplanted into a standalone software package, 'GBGP', which provides a set of library routines and application tools that support file conversions and quality-control checking of ground-based GNSS data (principally delay and integrated water vapour, initially using the plain-text so-called 'COST-format' files and potentially in netCDF later). GBGP source code and full documentation can be found at http://www.romsaf.org/gbgp/

4 External file interfaces

It is necessary that ROPP is able to interface with a number of diverse file formats employed by the suppliers of RO data. Those foreseen for GRAS data are noted below. Examples of those formats which are currently supported can be found in the `ropp_io/data` directory of the distribution, wherein a README file gives details.

4.1 netCDF

Files produced by the ROM SAF at Level 2 and disseminated via EUMETCast or via an FTP server. These files also contain a subset of the Level 1b scientific data from the PFS files. See the ROPP User Guide [RD.2]. This is the 'native' ROPP file type supported by the ROPP_IO module at API level and standalone tools in other modules.

EUMETSAT take advantage of the 'data grouping' facility in netCDF-4 in their level 1a datasets ([RD.14]). This library requires the use of the HDF5 and, optionally, the ZLIB libraries. Since the reading of such 'netCDF-4' data is an increasingly common use of ROPP, the decision has been taken to drop build support for 'classic' netCDF-4 (netcdf-3 mode) from ROPP9.0. Thus, the netCDF libraries recommended for use with ROPP now require HDF5 and (optionally) ZLIB.

4.2 BUFR

Files produced by EUMETSAT containing a subset (thinned profiles) of the PFS Level 1b data and disseminated via EUMETCast. Files produced by the ROM SAF at Level 2 and disseminated via GTS and EUMETCast. These files will contain a subset of the scientific Level 1b and Level 2 data from the netCDF files. The Level 1b data will be identical to the equivalent data in the EUMETSAT BUFR products. UCAR produce BUFR files to the same template specification containing NRT COSMIC, C/NOFS and (before failure of the satellite) SAC-C data. GRACE-B and TerraSAR-X & TanDEM-X (and previously CHAMP and GRACE-A) RO data processed by GFZ — and encoded using ROPP — are also available in the same BUFR template via the GTS. See the RO BUFR Template specification at [RD.3]. The ROPP_IO module supports the encoding and decoding of BUFR files from/to ROPP netCDF files by a pair of application tools.

4.3 GRIB

Files in GRIB format, typically produced by operational NWP centres, containing level 2b-2d background field data, can be read and converted into ASCII or standard ROPP format. See the GRIB_API at [RD.12] for specification of the GRIB file format, and for information on how to download the libraries.

4.4 Other

Non-GRAS data from other missions (COSMIC, CHAMP, GRACE-A/B, TerraSAR-X, TanDEM-X, C/NOFS, SAC-C, ROSA, PAZ, etc) may be provided to users in arbitrary file formats. Where the WMO-standard BUFR template for RO data is used, the existing ROPP tools will handle these data. Other formats may be provided by the suppliers (UCAR, GFZ, ...); where possible, ROPP will support these formats by providing tools to convert them to the ROPP netCDF specification so that downstream applications are as far as possible mission-independent insofar as file reading is concerned. UCAR 'atmPrf', 'atmPhs', 'sonPrf', 'ecmPrf', 'ncpPrf', 'gfsPrf' files, and GFZ 'dat/dsc' file pairs, can be converted using tools supplied with ROPP_IO.

Support for interfacing to other file formats may be provided within the ROPP_IO module in later releases.

5 Required and optional third-party software

To fully implement ROPP, the SAF deliverable code uses some standard third party packages. These are all non-commercial ('freeware') and thus freely available as source code, 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.

Use of these non-SAF packages and their source, is clearly signposted in the ROPP documentation. Some third party code is only needed with certain ROPP modules, so are optional if those modules are not required by the user. For instance, implementing just the forward model module in an NWP assimilation system will probably not require the netCDF or BUFR libraries.

Where licensing terms allow (in most cases), the SAF will provide, alongside the ROPP distribution, a version of the third party code distribution, which has been successfully integrated with ROPP. This may not be the most recent distribution, so links will be provided to the original provider so that latest versions can be used if desired. In this case, the user is responsible for correct installation and retesting of the ROPP component. The ROM SAF would welcome feedback on the successful use of newer distributions.

Currently used third party packages (latest version supported by ROPP-9 (v9.0) are shown in Table 5.1. The ROM SAF provides the packages listed here alongside the ROPP distribution on the ROPP download webpage via http://www.romsaf.org.

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.

In addition to the above, as previously noted, in order 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', 'm4' and 'robodoc' are recommended. Reference Manual documentation is principally in LaTeX. The bash shell is needed to run the optional package build utility scripts. Optionally, IDL and an EPS file viewer are used to generate and display results of some user-validation tests as part of the build, although validation of the integrity of the build does not require these facilities: results are compared to reference data numerically (with effect from ROPP-8).

Name	Version	Purpose	Original source
For all supported platforms:			
ZLIB	1.2.8	Compression library used by HDF5.	[RD.13]
HDF5	1.8.16	Software suite which underpins netCDF4.	[RD.5]
netCDF-Core	4.4.0	netCDF-Core library	[RD.4]
netCDF-Fortran	4.4.3	netCDF-Fortran library	[RD.4]
MOBUFR	24.0.2	Met Office BUFR kernel library. Only needed if building the BUFR encoder/decoder tools from the ROPP_IO module.	On request to the Met Office via the ROPP Development Team
ECBUFR	000387	Alternative ECMWF BUFR kernel library. Only needed if building the BUFR encoder/decoder tools from the ROPP_IO module.	[RD.11]
GRIB_API	1.14.5	A WMO-standard format for gridded data. Only needed if background profiles are to be extracted from such datasets, using the tool in the ROPP_IO module.	[RD.12]
SOFA	20160503_c	IAU astronomical standards library. Only needed if very accurate transformations between reference frame are desired.	[RD.15]
For windows platform only:			
Cygwin	1.7 or later	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).	[RD.8]

Table 5.1: Third party software packages recommended for use with ROPP-9 (v9.0).

A ROPP and wider ROM SAF documentation

Title	**Reference**	**Description**
ROPP User Licence	SAF/ROM/METO/LIC/ROPP/002	Legal conditions on the use of ROPP software
ROPP Overview	SAF/ROM/METO/UG/ROPP/001	Overview of ROPP and package content and functionality
ROPP_IO User Guide	SAF/ROM/METO/UG/ROPP/002	Description of `ropp_io` module content and functionality
ROPP_PP User Guide.	SAF/ROM/METO/UG/ROPP/004	Description of `ropp_pp` module content and functionality
ROPP_APPS User Guide.	SAF/ROM/METO/UG/ROPP/005	Description of `ropp_apps` module content and functionality
ROPP_FM User Guide.	SAF/ROM/METO/UG/ROPP/006	Description of `ropp_fm` module content and functionality
ROPP_1DVAR User Guide.	SAF/ROM/METO/UG/ROPP/007	Description of `ropp_1dvar` module content and functionality
ROPP UTILS Reference Manual	SAF/ROM/METO/RM/ROPP/001	Reference manual for the `ropp_utils` module
ROPP IO Reference Manual	SAF/ROM/METO/RM/ROPP/002	Reference manual for the `ropp_io` module
ROPP FM Reference Manual	SAF/ROM/METO/RM/ROPP/003	Reference manual for the `ropp_fm` module
ROPP 1D–Var Reference Manual	SAF/ROM/METO/RM/ROPP/004	Reference manual for the `ropp_1dvar` module
ROPP PP Reference Manual	SAF/ROM/METO/RM/ROPP/005	Reference manual for the `ropp_pp` module
ROPP APPS Reference Manual	SAF/ROM/METO/RM/ROPP/006	Reference manual for the `ropp_apps` module
WMO FM94 (BUFR) Specification for Radio Occultation Data	SAF/ROM/METO/FMT/BUFR/001	Description of BUFR template for RO data

Table A.1: ROPP user documentation

Title	Reference	Description
Mono-dimensional thinning for GPS Radio Occultations	SAF/GRAS/METO/REP/GSR/001	Technical report on profile thinning algorithm implemented in ROPP
Geodesy calculations in ROPP	SAF/GRAS/METO/REP/GSR/002	Summary of geodetic calculations to relate geometric and geopotential height scales
ROPP minimiser - minROPP	SAF/GRAS/METO/REP/GSR/003	Description of ROPP-specific minimiser, minROPP
Error function calculation in ROPP	SAF/GRAS/METO/REP/GSR/004	Discussion of impact of approximating erf in ROPP
Refractivity calculations in ROPP	SAF/GRAS/METO/REP/GSR/005	Summary of expressions for calculating refractivity profiles
Levenberg-Marquardt minimisation in ROPP	SAF/GRAS/METO/REP/GSR/006	Comparison of Levenberg-Marquardt and minROPP minimisers
Abel integral calculations in ROPP	SAF/GRAS/METO/REP/GSR/007	Comparison of 'Gorbunov' and 'ROM SAF' Abel transform algorithms
ROPP thinner algorithm	SAF/GRAS/METO/REP/GSR/008	Detailed review of the ROPP thinner algorithm
Refractivity coefficients used in the assimilation of GPS radio occultation measurements	SAF/GRAS/METO/REP/GSR/009	Investigation of sensitivity of ECMWF analyses to empirical refractivity coefficients and non-ideal gas effects
Latitudinal Binning and Area-Weighted Averaging of Irregularly Distributed RO Data	SAF/GRAS/METO/REP/GSR/010	Discussion of alternative spatial averaging method for RO climate data
ROPP 1D–Var validation	SAF/GRAS/METO/REP/GSR/011	Illustration of ROPP 1D–Var functionality and output diagnostics
Assimilation of GPSRO Data in the ECMWF ERA-Interim Re-analysis	SAF/GRAS/METO/REP/GSR/012	Assimilation of GPSRO Data in the ECMWF ERA-Interim Re-analysis
ROPP_PP validation	SAF/GRAS/METO/REP/GSR/013	Illustration of ROPP_PP functionality and output diagnostics

Table A.2: GRAS SAF Reports

Title	Reference	Description
A review of the geodesy calculations in ROPP	SAF/ROM/METO/REP/RSR/014	Comparison of various potential geodesy calculations
Improvements to the ROPP refractivity and bending angle operators	SAF/ROM/METO/REP/RSR/015	Improved interpolation in ROPP forward models
Simplifying EGM96 undulation calculations in ROPP	SAF/ROM/METO/REP/RSR/016	Simplifying ROPP undulation calculations
Simulation of L1 and L2 bending angles with a model ionosphere	SAF/ROM/METO/REP/RSR/017	Simulating L1 and L2 bending angles in ROPP
Single Frequency Radio Occultation Retrievals: Impact on Numerical Weather Prediction	SAF/ROM/METO/REP/RSR/018	Potential impact of loss of L2 bending angle on NWP
Implementation of the ROPP two-dimensional bending angle observation operator in an NWP system	SAF/ROM/METO/REP/RSR/019	Implementation of ROPP 2D forward model at ECMWF
Interpolation artefact in ECMWF monthly standard deviation plots	SAF/ROM/METO/REP/RSR/020	Investigation into plot anomaly
5th ROM SAF User Workshop on Applications of GPS radio occultation measurements	SAF/ROM/METO/REP/RSR/021	Report on 5th ROM SAF User Workshop
The use of the GPS radio occultation reflection flag for NWP applications	SAF/ROM/METO/REP/RSR/022	Impact of reflected occultations at ECMWF
Assessment of a potential reflection flag product	SAF/ROM/METO/REP/RSR/023	Assessment of flagged COSMIC occultations
The calculation of planetary boundary layer heights in ROPP	SAF/ROM/METO/REP/RSR/024	Description of ROPP PBLH diagnostics
Survey on user requirements for potential ionospheric products from EPS-SG radio occultation measurements	SAF/ROM/METO/REP/RSR/025	Results of a ROM SAF survey of the interest in possible EPS-SG ionospheric products
Estimates of GNSS radio occultation bending angle and refractivity error statistics	SAF/ROM/METO/REP/RSR/026	RO error statistics as derived by forward modelling ECMWF model errors
Recent forecast impact experiments with GPS radio occultation measurements	SAF/ROM/METO/REP/RSR/027	Impacts in NWP of 2014–2015 RO data
Testing reprocessed GPS radio occultation datasets in a reanalysis system	SAF/ROM/METO/REP/RSR/029	Impact of reprocessed RO data on reanalyses

Table A.3: ROM SAF Reports

Title	Reference	Description
A first look at the feasibility of assimilating single and dual frequency bending angles	SAF/ROM/METO/REP/RSR/030	Single and dual frequency assimilation
An initial assessment of the quality of RO data from KOMPSAT-5	SAF/ROM/METO/REP/RSR/032	KOMPSAT-5 quality assessment
Some science changes in ROPP-9.1	SAF/ROM/METO/REP/RSR/033	ROPP-9.1 science

Table A.4: ROM SAF Reports (continued)

Title	Reference	Description
CDOP-3 Proposal	SAF/ROM/DMI/MGT/CDOP3/001	Proposal for the Third Continuous Development and Operations Phase (CDOP-3) March 2017 – February 2022
Co-operation Agreement	EUM/C/85/16/DOC/19	C/A between EUMETSAT and DMI, Lead Entity for the CDOP-3 of the ROM SAF, signed at the 86th Council meeting on 7th December 2016
Product Requirements Document (PRD)	SAF/ROM/DMI/MGT/PRD/001	Detailed specification of the products of the ROM SAF
System Requirements Document (SRD)	SAF/ROM/DMI/RQ/SRD/001	Detailed specification of the system and software requirements of the ROM SAF

Table A.5: Applicable documents

B Authors

Many people, inside and outside the ROM SAF, have contributed to the development of ROPP. The principal authors are listed in Table B.1. The ROM SAF extends its sincere appreciation for their efforts.

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 1D–VAR extensions. PP module.
Dave Offiler	Met Office	ROPP Project Manager, IO application code and IO extensions, BUFR format/template.
Sean Healy	ECMWF	Original 1D FM code, 2D FM operator code, introduction of compressibility factors, improved FM vertical interpolation scheme, forward modelling of L1 and L2 bending angles, wave optics propagator.
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 and planetary boundary layer height diagnostics, forward modelling of L1 and L2 bending angles.
Chris Burrows	Met Office	2nd ROPP Test Manager. Test folder developments, improved FM vertical interpolation scheme.
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, ec{i/f}2ec{i/f} code.
Carlo Buontempo	Met Office	Savitzky-Golay thinner code.
Torsten Schmidt	GFZ	Guidance on tropopause height diagnostics.
Feiqin Xie	Texas A & M	Suggested boundary layer height diagnostic algorithms.
Barbara Scherllin-Pirscher	Wegener Center	BAROCLIM (3) dataset for statistical optimisation.
Helge Jønch-Sørensen	DMI	BAROCLIM code.
Kent Bærkgaard Lauritsen	DMI	Code reviews; liaison with EUMETSAT (licences, beta tester contracts).

Table B.1: Contributors to ROPP

C Copyrights

The majority of ROPP code is

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> This software was developed within the context of the EUMETSAT Satellite Application Facility on Radio Occultation Meteorology (ROM SAF), under the Cooperation Agreement dated 29 June 2011, between EUMETSAT and the Danish Meteorological Institute (DMI), Denmark, by one or more partners within the ROM SAF. The partners in the ROM SAF are DMI, Met Office, UK, the Institut d'Estudis Espacials de Catalunya (IEEC), Spain and the European Centre for Medium-Range Weather Forecasts (ECMWF), UK

Some parts of the source code within this distribution were developed within the Met Office outside the context of the ROM SAF and represents pre-existing software (PES); this portion is

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This ROPP package also contains open source code libraries available through its author, Christian Marquardt. This is also PES, and is

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This ROPP package may also contain a dataset available through its author, Barbara Scherllin-Pirscher, and is