The EUMETSAT Network of Satellite Application Facilities

ROM SAF
Radio Occultation Meteorology

ROM SAF CDOP-2

The Radio Occultation Processing Package (ROPP) – An Overview

Version 7.0
(ROPP-7 v7.0)

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Danish Meteorological Institute (DMI)
European Centre for Medium-Range Weather Forecasts (ECMWF)
Institut d'Estudis Espacials de Catalunya (IEEC)

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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)**
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Version 3.0.1	1 Jul 2009	DO	**Release version for ROPP-3 (v3.0)**
Version 4.0	3 Nov 2009	HL/DO	**Release version for ROPP-4 (v4.0)**
Version 4.1	22 Apr 2010	HL	**Release version for ROPP-4 (v4.1)**
Version 5.0	27 Apr 2011	IC DO	Updated text appropriate to ROPP-5. Updated Figure 1 for ROPP-5. **Release version for ROPP-5 DRI**
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Version 6.1	31 Jan 2013	IC	**Release version for ROPP-6 (v6.1)** Apply new template with EUMETSAT ROM SAF logos
Version 7.0	31 Jul 2013	IC DO	Insert new ROM SAF standard text on page 3 & Section 1.5. Include (future) support for ground-based GNSS. Updated body text appropriate to ROPP-7. **Release version for ROPP-7 (v7.0)**

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 data from the Metop satellites and radio occultation (RO) data from other missions. The ROM SAF delivers bending angle, refractivity, temperature, pressure, and humidity profiles in near-real time and off-line for NWP and climate users. The off-line profiles are further processed into climate products consisting of gridded monthly zonal means of bending angle, refractivity, temperature, humidity, and geopotential heights together with error descriptions.

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

The 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

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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 Second Continuous Development and Operational Phase (CDOP-2, March 2012 – February 2017).

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.).

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 version reflects the seventh full release version of ROPP-7 (v7.0).

1. Introduction

1.1 Purpose of 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 Second Continuous Development and Operational Phase (CDOP-2, March 2012 – February 2017) [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 version reflects the seventh full release: ROPP-7 (v7.0).***

1.2 What is ROPP?

Objective: *To provide Users with a comprehensive software package, containing all necessary functionality to pre-process 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 stand-alone 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 1 shows previous releases under CDOP and the intended major functionality over the foreseen releases during CDOP-2. 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 3 notes the file interfaces which ROPP will need to handle and Section 4 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.

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	Pre-processing from bending angles to refractivity; Abel and inverse-Abel transforms. Generic support for writing ROPP formatted text files removed
ROPP-3	Jun 2009	Pre-processing from Doppler to bending angle; additional file conversions and profile thinning options. Code validated with pre-operational GRAS data.
ROPP-4	Dec 2009	2-D 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 planetary boundary layer height diagnostic; non-local operators. Support for ground-based GNSS (text, BUFR, Q/C)
ROPP-9	Dec 2015	Support for more NWP models.
ROPP-10	Dec 2016	Enhancement of ROPP wave optics propagation; support for climate applications.

Table 1. Main functionality of ROPP major releases during CDOP and those planned for CDOP-2.

1.3 Applicable & Reference documents

1.3.1 Applicable documents

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

[AD.1] Proposal for Continuous Development and Operations Phase II (ROM SAF CDOP) as endorsed by Council 29 June 2011

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

1.3.2 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 Guide

Part I	IO	SAF/ROM/METO/UG/ROPP/002
Part II	FM & 1DVar	SAF/ROM/METO/UG/ROPP/003
Part III	PP	SAF/ROM/METO/UG/ROPP/004

[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/

[RD.6] G95 Project website: http://www.g95.org
GFortran website: http://gcc.gnu.org/wiki/GFortran

[RD.7] Cygwin website http://www.cygwin.com

[RD.8] GRAS Level 1 Product Format Specification. EPS/MIS/SPE/97234

[RD.9] Development procedures for software deliverables. NWPSAF-MO-SW-002

[RD.10] ECMWF BUFR software website: http://www.ecmwf.int/products/data/software/bufr.html

[RD.11] ECMWF GRIB_API software website: https://software.ecmwf.int/wiki/display/GRIB/Home

[RD.12] ZLIB website http://www.zlib.net

1.3.3 Release notes

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

1.4 Acronyms, Abbreviations & Initialisms

ADD	Architectural Design Document
API	Application Program Interface
BUFR	Binary Universal Form for the Representation of meteorological data (WMO)
CDOP	Continuous Development and Operational Phase (SAFs)
CGS	Core Ground Segment (EUMETSAT)
CHAMP	CHallenging Mini-satellite Payload (Germany)
CLIMAP	Climate and Environment Monitoring with GPS-based Atmospheric Profiling (EU)
COSMIC	Constellation Observing System for Meteorology Ionosphere and Climate (USA/Taiwan)
C/NOFS	Communications/Navigation Outage Forecasting System (US)
DMI	Danish Meteorological Institute (ROM SAF Leading Entity)
DRI	Delivery Readiness Inspection
ECMWF	European Centre for Medium-range Weather Forecasts
E-GVAP	EUMETNET GNSS water VApour Programme
EPS	Encapsulated PostScript
ESA	European Space Agency
EU	European Union
EUMETcast	EUMETSAT NRT dissemination service via commercial digital video broadcast technology
EUMETNET	EUropean METeorological services NETwork (Brussels, Belgium)
EUMETSAT	EUropean organisation for the exploitation of METeorological SATellites (Darmstadt, Germany)
FM94	WMO Form no. 94 (i.e. BUFR)
Galileo	Future European GNSS system (EU/ESA)
GFZ	GFZ Helmholtz Centre (Potsdam, Germany)
GLONASS	Globalnaya Navigatsionnaya Sputnikovaya Sistema (Russia)
GNSS	Global Navigation Satellite System (generic GPS/GLONASS/Galileo)
GPL	General Public Licence (GNU)
GPS	Global Positioning System (USA)
GRACE	Gravity Recovery and Climate Experiment (Germany/US)
GRAS	GNSS Receiver for Atmospheric Sounding (METOP-A and -B)
GRIB	GRIdded Binary or General Regularly-distributed Information in Binary
GTS	Global Telecommunications System (WMO)
HDF	Hierarchical Data Format
HP-UX	Unix operating system for Hewlett Packard workstations
IDL	Interactive Data Language (ITT Visual Information Solutions)
IEEC	Institut d'Estudis Espacials de Catalunya

LGPL	Lesser GPL (*q.v.*)
MetDB	Meteorological Data Base (Met Office)
MetO	Met Office (of the UK)
METOP	METeorological OPerational satellite (EUMETSAT)
MS-DOS	Microsoft Disk Operating System ('Command Line' application under the Windows O/S)
netCDF	network Common Data Form (Unidata)
NMS	National Meteorological Service
NWP	Numerical Weather Prediction
NRT	Near-Real Time
OS (O/S)	Operating System
PAZ	Spanish Earth Observation Satellite, carrying a Radio Occultation Sounder
PCD	Product Confidence Data
PES	Re-Existing Software
PFS	Product Format Specification (Level 1b data from GCS)
POD	Precision Orbit Determination
RMDCN	Regional Meteorological Data Communications Network (component of the GTS)
PRD	Product Requirement Document
RO	Radio Occultation
ROM SAF	EUMETSAT Satellite Application Facility responsible for operational processing of radio occultation data from the MetOp satellites.
ROPP	Radio Occultation Processing Package
ROSA	Radio Occultation Sounder of Atmosphere (Italy/India)
SAC-C	Satelite de Applicaciones Cientificas – C (Argentina)
SAF	Satellite Application Facility (EUMETSAT)
SG	Steering Group
SNR	Signal to Noise Ratio
TanDEM-X	German Earth Observation Satellite, carrying a Radio Occultation Sounder
TBC	To Be Confirmed
TBD	To Be Determined
TerraSAR-X	German Earth Observation Satellite, carrying a Radio Occultation Sounder
UCAR	University Center for Atmospheric Research (Boulder, CO, USA)
VAR	Variational (NWP data assimilation technique)
WMO	World Meteorological Organisation
WWW	World Weather Watch (WMO Programme)

1.5 Definitions

RO data products from the GRAS instrument onboard Metop and RO data from other data providers are grouped in levels and are either NRT or offline products:

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, SNRs, amplitudes, orbit information, I, Q, and NCO values, and navigation bits;

Level 1b: Bending angles and impact parameters, Earth location, metadata and quality information;

Level 2: Refractivity profiles (level 2a), and pressure, temperature, and specific humidity profiles (level 2b and 2c), Earth location, metadata, and quality information;

Level 3: Gridded level 1 and 2 offline profile products in the form of, e.g., monthly and seasonal zonal means, metadata, and quality information;

Product types:

NRT product: data product delivered less than 3 hours after measurement;

Offline product: data product delivered less than 30 days after measurement (the timeliness for some offline level 3 products may be up to 6 months).

2. Overview of ROPP

2.1 Concept and Strategy

- ROPP is ***not*** a “black box” single application, end-to-end processor;
- It is a ***suite of library functions*** and ***example applications*** (Fortran 95 source code) from which users can “pick’n’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 off-line 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.

2.2 Main functionality

- Ingest:
  - 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 off-line 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 GRIB-format
  - E-GVAP ground-based GNSS data in 'COST-format' files
- Support for flexible netCDF I/O of RO data via simple interfaces with a file management/conversion tool
- Staged pre-processing from excess phase up to refractivity
- Forward operators (including adjoints, tangent linear, gradients) for pressure- and height-based and hybrid NWP model vertical grids, and for both refractivity and bending angle simulation, as vertical profiles and 2-D 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 areas/seasons (if found desirable)
- Standalone test harnesses (including test input and example output files)
- BUFR encoder and decoder application tools
- Tool to extract background profiles from GRIB-format gridded datasets
- 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

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 (See Section 2.3), and not all of the above functionality will be available in this current release. The ROPP-7 modules and their main content are listed in Table 2 and their inter-relationships are indicated in Figure 1; the main functions of each module are expanded in Section 4.

Module	*Content*
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; extracting background profiles from GRIB files; profile thinning; file management
ROPP_FM	Forward models (and tangent-linear, adjoints and gradients), 1D and 2D versions
ROPP_1DVAR	1D-Var (user-callable subroutines and stand-alone applications)
ROPP_PP	Pre-processing (from excess phase through to refractivity and dry temperature); TPH diagnostics.
ROPP_UTILS	Utility tools; units conversion, low-level interfaces, etc.
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.
ROPP_BUILD	Scripts and configuration files to aid building and installing ROPP modules and third-party dependency packages consistently, supporting a range of common compilers on several operating systems

Table 2. ROPP-7 modules and their main content

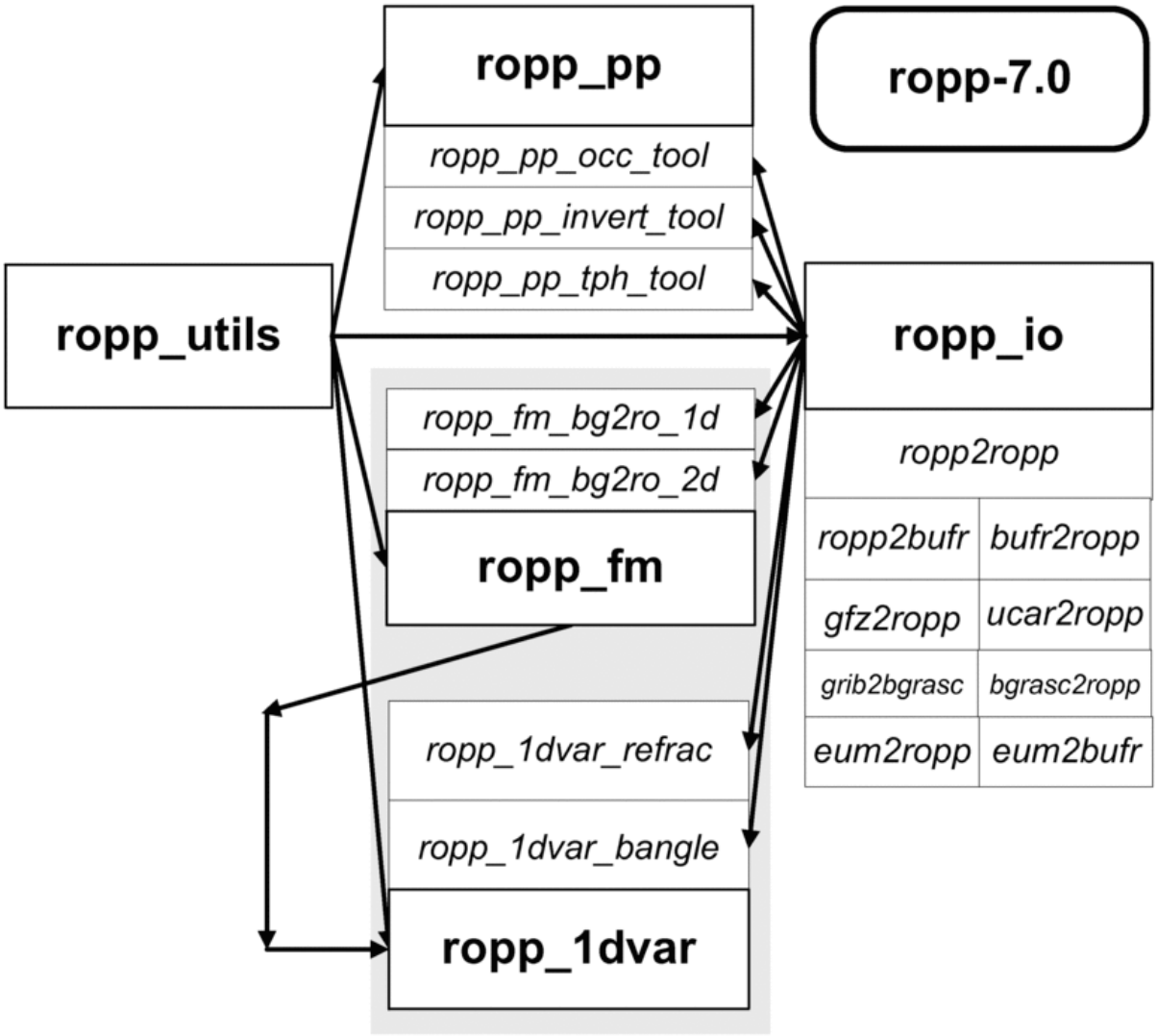

Figure 1. ROPP-7 (v7.0) modules and their relationships. Stand-alone applications provided with each module are shown in italics. Connecting lines indicate module dependencies, with arrow heads pointing to the modules or stand-alone tools which require that module.

2.3 Development

- ROPP is developed incrementally from scientifically validated prototype code, with a phased release programme until the required functionality is achieved. Current functionality will be validated for ROPP-7 and all subsequent releases using operational GRAS 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.9].
- 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. 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 re-coding certain functions.
- A second release package (ROPP-2) with extended and improved functionality was released in December 2008. The main change in ROPP-2 was the inclusion of a new ROPP_PP (pre-processor)

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) 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) contained extended 2-dimensional forward models for NWP systems that can employ this feature. Use of 2-D 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, 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, February 2012) focused on reconciling the pre-processing package (ROPP_PP) with its original source code, 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-6.1, February 2013) provided a tool to extract background profiles from gridded fields in GRIB format, and the tools to read “grouped” RO data in netCDF-4 files. The dry temperature was also retrieved and output by default (as a Level 2a quantity).
- A seventh full release (ROPP-7, September 2013) included various diagnoses of the Tropopause height, derived from bending angle, refractivity, dry temperature or temperature.
- Minor releases will be made as required (bug fixes, extending portability, improving functionality to existing modules, etc.) in-between major releases.
- Support, maintenance and further scientific and technical development – such as detection of boundary layer top heights, support for netCDF-4 [RD.4] and HDF5 [RD.5] and support for ground-based GNSS – can be expected as part of the Continuous Development and Operations Phase II (CDOP-2 [2012–2017]) of the ROM SAF.

2.4 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 Section 5.5.5.
Specifically:

a) ROPP is developed, tested, and fully supported on Linux (currently Red Hat Enterprise Release 6.3 – RHEL6) with Intel (‘ifort’ v11, v12 & v13), NAG ('nagfor' v5.2), Portland Group (‘pgf95’ v6 & v7), SUN ('sunf95' v8) and GNU ('gfortran' v4.4.6, 'g95' v0.93) Fortran 95 compilers. Third-party dependency packages employing C-language code is compiled with GNU C (‘gcc’ v4.4.6) compilers.

b) 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 Met Office 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.

c) 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.

d) ROPP-5 and ROPP-6 have been successfully tested on IBM Power-6 HPC system with AIX Fortran Compiler ('xlf95' v12.1), and ROPP6.1 and ROPP-7 on IBM Power-7 HPC with 'xlf95' (v12.1).

e) ROPP is built, and has undergone user-level testing, under Cygwin on Microsoft Windows with GNU G95 ('g95') and GFortran ('gfortran') (and GNU C ('gcc')). Support for building the package will *only* be under the Cygwin [RD.7] environment, which provides Linux-like shell and build tools under Windows. Some recent dependency packages cannot be built with g95 so we recommend using gfortran on Cygwin. 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.

f) ROPP will be tested on other (non-SAF) POSIX-compliant platforms & 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.

g) Building & installation is not supported for OpenVMS platforms, 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. Though not supported and untested by the ROPP Development Team, users have reported successfully building ROPP on OS/X.

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:

√ supplied facilities to build and install the package components (e.g. configure scripts to generate and run 'make' files) and example stand-alone applications and reference test data and results;

√ correcting bugs or other deficiencies (in software or documentation) noted by users;

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

√ continuous development of the code in response to user feedback in terms of improved science, functionality and efficiency;

√ 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, v4.1 and 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 Second Continuous Development and Operational Phase (CDOP-2) of the ROM SAF ([AD.2], March 2012 to February 2017) and beyond that, assuming formal extension agreements are put in place.

Required:

√ 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.

√ 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 Section 5.

√ 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.

3. 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.

3.1 netCDF

Files produced by the ROM SAF at Level 2 and disseminated via EUMETCast or via an FTP server. These files also contain a sub-set 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 stand-alone tools in other modules.

3.2 BUFR

Files produced by EUMETSAT containing a sub-set (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 sub-set 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-A and TerraSAR-X (and previously CHAMP) 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.

3.3 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.11] for specification of the GRIB file format, and for information on how to download the libraries.

3.4 Other

Non-GRAS data from other missions (COSMIC, CHAMP, GRACE-A, 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.

The EUMETNET E-GVAP project employs a text-based file format – the so-called 'COST-format' – for exchanging delay and integrated water vapour data (plus supporting meta-data). The ROPP_GBG module will provide I/O interfaces to these files, with similar netCDF support should the project adopt this file format in the future.

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

4. 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 stand-alone applications for RO data processing.

In this section we list the main software sub-components of ROPP. This list is limited to the higher-level, user-callable routines and stand-alone 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 sub-list 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. Upper case names refer to user callable (API) routines; lower case names are stand-alone (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.

4.1 Input/Output (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 or 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 "grouped" RO data	netCDF-4 file	netCDF file	6.1	S
eum2bufr	Read "grouped" RO data	netCDF-4 file	BUFR file	6.1	S

4.2 Forward Models (ROPP_FM)

The FM modules provides forward models (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. gpht profile	Refractivity vertical profile as fn of geopotential height or pressure	1.0	S
ROPP_FM_BANGLE_1D	Map model 1-D state vector to bending angle	Model P,T,q vs gpht profile	Bending angle vertical profile as fn of impact parameter or pressure	1.0	S
ROPP_FM_BANGLE_2D	Map model 2-D state vector to bending angle	Model P,T,q vs gpht 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 to above forward models			1.0	S
ropp_bg2ro_1d	Stand-alone tool to map 1-D model profiles into refractivity profile	ROPP file containing model background P,T,q vs. gpht profile(s)	ROPP file containing model-equivalent bending angle and refractivity profile(s)	1.0	S
ropp_bg2ro_2d	Stand-alone tool to map 2-D model profiles into bending angle profile	ROPP file containing model background P,T,q vs. gpht profiles	ROPP file containing model-equivalent bending angle profiles	4.0	S

4.3 1D-VAR (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 together with observation and background covariance matrices. Also performs data quality control checks.

Name	Purpose	Input	Output	RV	P/S
ROPP_1DVAR	Interface definitions	n/a	n/a	1.0	S
ROPP_1DVAR_REFRAC	1D-Var optimal estimation for refractivity (model-independent)	Model pressure levels, background T,q profiles, observed refractivity profile, b/g & ob error covariance matrices	Solution vector, simulated refractivity profiles (b/g & solution), penalty function, K matrix	1.0	S
ROPP_1DVAR_BANGLE	1DVAR optimal estimation for bending angle (model-independent)	Model pressure levels, background T,q profiles, observed bending angle profile (on impact parameter levels), b/g & ob error covariance matrices, RoC	Solution vector, simulated bending angle profiles (b/g & solution), penalty function, K matrix, PGE	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 bending angle or refractivity, model background, b/g & ob error covariance matrices	Retrieved profiles of T,q, gpht 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 or refractivity, model background, b/g & ob error covariance matrices	Retrieved profiles of T,q, gpht on pressure levels	1.2	S

4.4 Preprocessing (ROPP_PP)

The PP module provides functions to compute channel L1 and L2 bending angles from measured Excess Phase by geometrical optics and wave optic methods. Processing to apply ionospheric correction to L1 and L2 bending angles to derive corrected bending angle 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*).

Name	Purpose	Input	Output	RV	P/S
ROPP_PP	Interface definitions	n/a	n/a	2.0	S
ROPP_PP_ICORR	Ionospheric corrections to L1 & L2 signal	Uncorrected L1 and L2 bending angle profiles	Corrected bending angle profile	2.0	S
ROPP_PP_INVERT	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
SMOOTH_BAPROF	Optimal smoothing & thinning of bending angle profile	Full-resolution bending angle profile (user-set controls)	Smoothed/thinned profiles	2.0	S
PHASETODOPPLER	Convert Excess Phase to Excess Doppler	Excess Phase time series	Excess Doppler time series	3.0	S
ROPP_PP_BA_GO	Calculate bending angle profile (Geometrical Optics method)	Excess Doppler time series	Bending angle as function of impact parameter	3.0.	S
ROPP_PP_BA_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
REFRAC_LATLON	*Interpolate bending angle lat/lons to corresponding refractivity altitudes.*	*Bending angle 3-D locations*	*Refractivity profile lat/lons*	*8.0*	*S*
ROPP_PP_TPH_TOOL	Calculate tropopause heights	Bending angle, refractivity, dry temperature or temperature	Impact param, geom. height, geom. height or geopotential of tropopause, resp.; processing flags.	7.0	S

4.5 Ground-based GNSS (ROPP_GBG)

The GBG module provides a stand-alone package of library routines and application tools supporting 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). This module is based on the E-GVAP 'GWV' export package, with some of the library utility routines being common with those in UTILS. Depending on user requirements, the GBG module may be enhanced with GBG-equivalent FM routines to support NWP assimilation.

Name	Purpose	Input	Output	RV	P/S
ROPP_GBG_COST	*COST-format I/O, Q/C & utility library*	*E-GVAP COST file*	*E-GVAP COST file*	*8.0*	*S*
ROPP_GBG_NETCDF	*NetCDF I/O library*	*E-GVAP netCDF file*	*E-GVAP netCDF file*	*9.0*	*S*
cost2cost	*File converter/checker*	*E-GVAP COST file*	*E-GVAP COST file*	*8.0*	*S*
cost2netcdf	*File converter*	*E-GVAP COST file*	*E-GVAP netCDF file*		
cost2bufr	*BUFR encoder*	*E-GVAP COST (or netCDF) file*	*BUFR file*	*8.0 (9.0)*	*S*
bufr2cost	*BUFR decoder*	*BUFR file*	*E-GVAP COST or netCDF) file*	*9.0*	*S*

4.6 Utility routines (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 sub-set of the routines in this module.

Name	Purpose	Input	Output	RV	P/S
GEOPOT_HEIGHT	Geopotential height conversion	Geometric heights (wrt ellipsoid)	Geopotential heights (wrt geoid)	1.0	S
GEOMET_HEIGHT	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 & 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	3-D location of point in system #1 (lat/lon/ht or X,Y,Z)	3-D location of point in system #2 (lat/lon/ht or X,Y,Z)	3.0	P

4.7 Testing (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 stand-alone test harness	RO observation files (sub-set supplied with ROPP) and randomly-generated RO data	RO data Validated against input data	–	S
	FM stand-alone test harness (also implicitly tests IO and UTILS modules)	NWP background files (sub-set supplied with ROPP)	Refractivity and bending angle profile	–	S
	1D-Var stand-alone test harness (also implicitly tests FM, IO and UTILS modules)	RO observation files NWP background files (sub-set supplied with ROPP)	Derived T,q,P vs. h (or T,q,h vs. P) profile files	–	S
	PP stand-alone test harness (also implicitly tests UTILS and IO modules)	RO Level 1a/b observation files	Derived Refractivity profiles	–	S

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.

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, 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 3rd 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 distributions, 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 re-testing 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-7 v7.0) are shown in Table 3.

Name	Version	Purpose	Original Source[1]
For all supported platforms:			
netCDF	4.1.3	I/O interface library to a platform-independent, self-documenting binary file data format. Only required by the ROPP_IO module.	See [RD.4]
MOBUFR	19.3	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.	See [RD.10]
GRIB_API	1.9.9	A WMO-standard format for gridded data. Only needed if background profiles are to be extracted from such datasets, using the ROPP_IO module.	See [RD.11]
HDF5	1.8.8	Software suite which underpins netCDF-4. Only needed if "grouped" RO data are to be read. Not required for the classic netCDF model used for the standard ROPP data format.	See [RD.5]
ZLIB	1.2.7	Compression library used by HDF5.	See [RD.12]
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).*	See [RD.7]

Table 3. Third party software packages used with ROPP-7 (v7.0)

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.

[1] *Note that the SAF provides the package versions listed in Table 3 alongside the ROPP distribution on the ROPP download webpage via http://www.romsaf.org*

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.