



EUMETSAT

ROM SAF

RADIO OCCULTATION METEOROLOGY

ROPP Change Log: v9.1 to v10.0

Version 1.0

30 September 2020

The ROM SAF Consortium

Danish Meteorological Institute (DMI)

European Centre for Medium-Range Weather Forecasts (ECMWF)

Institut d'Estudis Espacials de Catalunya (IEEC)

Met Office (METO)

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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 radio occultation (RO) data from the Metop and Metop-SG 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>.

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Executive Summary

This document records the significant differences between the Radio Occultation Processing Package (ROPP) version 10.0 and the previous release, version 9.1. Chief among these are:

- The introduction of a two-dimensional wave optics propagation code;
- Updates to the Levenberg-Marquardt solver in the 1dvar module;
- The provision of support for the ECMWF ecCodes software library;
- The ability to read newer format (`format_version` $\geq$ 13.0) EUMETSAT data files.
- Where possible, the other external dependency packages (netCDF, SOFA etc) that are used by ROPP have been updated;
- Numerous corrections and developments throughout the code, as required to reprocess Metop data to acceptable quality.

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1. Introduction

1.1 Purpose of the document

This document summarizes the significant differences between the Radio Occultation Processing Package (ROPP) version 10.0 and the previous release, version 9.1. For guidance on downloading and installing the ROPP software, and the available documentation, please refer to the ROPP Release Notes [RD.1]. All comments on the ROPP software should, in the first instance, be reported via the ROM SAF Helpdesk, which can be found on the ROM SAF home page at <http://www.romsaf.org>. Throughout this report, information for the general user appears in **black**; information mainly for developers appears in **blue**, and items to be noted by all users, usually because they change the previous behaviour of ROPP, appear in **red**.

1.2 Applicable and reference documents

1.2.1. Applicable documents

The following documents explain the context of ROPP within the ROM SAF.

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-10 (v10.0) Release Notes
Ref: SAF/ROM/METO/SRN/ROPP/001 – Version 10.0.

[RD.2] ROPP User Guides
Ref: SAF/ROM/METO/UG/ROPP/001 – Overview
Ref: SAF/ROM/METO/UG/ROPP/002 – ROPP_IO module
Ref: SAF/ROM/METO/UG/ROPP/004 – ROPP_PP module
Ref: SAF/ROM/METO/UG/ROPP/005 – ROPP_APPS module
Ref: SAF/ROM/METO/UG/ROPP/006 – ROPP_FM module
Ref: SAF/ROM/METO/UG/ROPP/007 – ROPP_1DVAR module
Ref: SAF/ROM/METO/UG/ROPP/008 – ROPP_UTILS module

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

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1.3 Acronyms and abbreviations

1DVAR	1D-Var module of ROPP
AIX	Advanced Interactive eXecutive (IBM)
API	Application Programming Interface
BUFR	Binary Universal Form for the Representation of data (also: FM94) (WMO)
Beidou	Chinese GNSS navigation system. Beidou-2 also known as COMPASS
CDOP	Continuous Development and Operations Phase (EUMETSAT)
CDR	Climate Data Record
CMA	Chinese Meteorological Agency
DMI	Danish Meteorological Institute; ROM SAF Leading Entity
ECMWF	The European Centre for Medium-range Weather Forecasts
EPS	EUMETSAT Polar Satellite System
EUMETSAT	EUropean organisation for the exploitation of METeorological SATellites
FY-3C/D	GNSS radio occultation receivers (CMA)
GCC	GNU Compiler Collection (not to be confused with gcc , the GCC C-compiler)
CHAMP	Challenging Mini-satellite Payload (Germany)
GNOS	GNSS Radio Occultation Sounder (China)
GNU	GNU's Not Unix
GPS	Global Positioning System
GNSS	Global Navigation Satellite System (generic GPS/GLONASS/Galileo/Beidou)
COSMIC	Constellation Observing System for Meteorology Ionosphere and Climate (USA/Taiwan)
GRACE-A/B	Gravity Recovery and Climate Experiment (Germany/USA)
GRACE-FO	GRACE Follow-on experiment (Germany/USA)
GRAS	GNSS Receiver for Atmospheric Sounding (EPS/Metop)
GRIB	GRIdded Binary format (WMO)
HDF5	Hierarchical Data Format version 5
ICDR	Intermediate Climate Data Record
IBM	International Business Machines Corporation
I/Q	In-phase and Quadrature signal components
IEEC	Institut d'Estudis Espacials de Catalunya
ISRO	Indian Space Research Organisation
KMA	Korean Meteorological Agency
KOMPSAT-5	GNSS radio occultation receiver (KMA)
Megha-Tropiques	Tropical water cycle (and RO) experiment (India/France)
Met Office	Meteorological Office of the United Kingdom
MetDB	Meteorological DataBase (Met Office)
Metop	Meteorological Operational Polar satellite (EUMETSAT)
NCO	Numerically Controlled Oscillator
netCDF	Network Common Data Format
NRT	Near Real Time
OS	Operating System
POSIX	Portable Operating System Interface
RHEL	Red Hat Enterprise Linux
RO	Radio Occultation (also: GPS-RO)
ROM SAF	Radio Occultation Meteorology SAF (formerly GRAS SAF)
ROPP	Radio Occultation Processing Package
RS	Raw Sampling
SAF	Satellite Application Facility (EUMETSAT)
SNR	Signal to Noise Ratio
TanDEM-X	German Earth observation satellite carrying an RO sounder
TerraSAR-X	German Earth observation satellite carrying an RO sounder
UCAR	University Center for Atmospheric Research (Boulder, CO, USA)

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1.4 Definitions

RO data products from the Metop and Metop-SG satellites 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 (ROM SAF Level 2 for EPS); (ii) 150 min after measurement (ROM SAF Level 2 for EPS-SG Global Mission); (iii) 125 min after measurement (ROM SAF Level 2 for EPS-SG Regional Mission);

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 software². 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 (ICDR) 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 CDR³.

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

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)

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1.5 Overview of this document

This document is organized as follows:

Chapter 1 contains the introduction;

Chapter 2 lists the changes to ROPP that are common to all modules, such as changes to the build system, and large structural changes;

Chapters 3, 4, 5, 6, 7 and 8 list the changes to the UTILS, IO, PP, FM, 1DVAR and APPS modules respectively;

Chapter 9 directs users to the location of the source code and to the ROM SAF Helpdesk.

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2. General

- It is now possible to build dependency packages outside of the directory from which **buildpack** is called. (This feature was in fact present in ROPP9.1 but was unrecorded in the Change Log.) See *Sec A.4 of the ROPP module user guides for details*.
- Where available as an option, the (highly inadvisable) option to prevent data being range-checked has been consistently changed to `--no-ranchk`. It continues to be deliberately undocumented.

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3. ROPP_UTILS

- The tangent point calculation has been extended to account (optionally) for the bending of the ray. This option is enacted by setting the new configuration variable `tp_bending` to `.TRUE.` in the configuration files of the ropp_pp executables that call them. This option is off by default.
- The tangent point and occultation point latitude and longitude calculation have been corrected, by accounting for the position of the centre of curvature. This will affect results.
- SUBROUTINE `tangent_point` in **`tangent_point.f90`** now needs the centre of curvature as an input argument. If account is taken of the bending angle, as described above, then it will also take the impact parameters as an optional argument.
- SUBROUTINE `occ_point` in **`coordinates/occ_point.f90`** now takes `dtype` as an input argument and returns `time_offset` – the georeferencing time, equal to `dtype` at the nominal occultation point – as output.
- Some memory problems that occurred when using tangent/occultation point routines on large volumes of data have been corrected.
- See Sec 3.7 of the ROPP UTILS user guide for details.

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4. ROPP_IO

- The two-dimensional RO profile structure `ROprof2d` has had its `lev2a` substructure made two-dimensional. This means that refractivities, dry temperatures and their geometric and geopotential heights in the `ROprof2d` structure are now 2D slices rather than 1D profiles. This is to allow the ingestion of such data into the new 2D wave optics propagator (see the changes to the `ROPP_PP` module discussed below). No change has been made to the structure of the one-dimensional RO profile structure `ROprof`. See Table 3.4 of the *ROPP IO user guide* for details.
- Support for the ECMWF ecCodes software package has been provided. This supersedes the obsolete `GRIB_API` and `ECBUFR` libraries, and although support for these will continue in `ROPP10.0`, it is likely to be removed at a later release. At `ROPP10.0`, therefore, additional executables have been introduced:
 - `bufr2ropp_eccodes.f90`, which emulates the earlier `bufr2ropp.f90`;
 - `ropp2bufr_eccodes.f90`, which emulates the earlier `ropp2bufr.f90`; and
 - `eum2bufr_eccodes.f90`, which emulates the earlier `eum2bufr.f90`.

Naturally, then, users relying on the tool called (for example) `ropp2bufr` will need to link `ropp2bufr_eccodes` to this file before using the ecCodes version of the tool. See Sec 3.6 of the *ROPP IO user guide* for details.

- ecCodes users wishing to add GTS headers to the BUFR files they produce (i.e. emulating the `-g` or `-gi` options of `ropp2bufr` and `eum2bufr`) will need to do so by means of the `ropp_io/tools/gtsheaders_bufr.pl` script, because ecCodes does not (yet) support this functionality. If users call `ropp2bufr_eccodes` or `eum2bufr_eccodes` with `-g` or `-gi`, the correct options to use in the call to `gtsheaders_bufr.pl` will appear on the standard output. See Sec 3.6 of the *ROPP IO user guide* for details.
- BUFR encoding of RO data with ecCodes requires the environment variable `ECCODES_BUFR_SET_TO_MISSING_IF_OUT_OF_RANGE` set to 1. This is done automatically from within `eum2bufr_eccodes` and `ropp2bufr_eccodes`, but will need to be set manually if RO users wish to use the ecCodes library for other purposes. See Sec 3.6 of the *ROPP IO user guide* for details.
- Note that a small change has been made to the ecCodes tarball supplied with ROPP to suppress the warning message that is produced each time a missing data indicator is set. This change can be made to a user's personal copy of the ecCodes source using the patch at `ropp_io/tools/eccodes_patch`. See App A.3.2 of the *ROPP IO user guide* for details.
- Note that the API for GRIB routines, as used by `grib2bgrasc`, is the same for ecCodes and the old `GRIB_API` package. There is therefore no change to this program. The only difference is the name of the libraries that it uses. (If both are available, ecCodes is used.) See Sec 3.6 of the *ROPP IO user guide* for details.
- A few 'protocol errors', which caused occasional serious problems with netCDF I/O on a Ubuntu system, have been fixed.
- The valid_ranges of some variables have changed.
 - `alt_refrac` now lies between -1.0e3 and 1.5e5 m (cf -1.0e3 and 1.0e5 m before)
 - `geop_refrac` now lies between -1.0e3 and 1.5e5 m (cf -1.0e3 and 1.0e5 m before)
 - `press_sfc_sigma` now lies between 0 and 10 hPa (cf 0 and 5 hPa before)

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- `shum_sigma` now lies between 0 and 50 g/kg (cf 0 and 5 g/kg before)
- `shum` now lies between -20 and 50 g/kg (cf 0 and 50 g/kg before) if the `-nocheck_qmin` option is used in `ropp_ldvar_refrac` or `ropp_ldvar_bangle`.

All these may change results. See Sec 3.3 of the ROPP IO user guide for details.

- Some error handling now takes place if there are problems coming out of netCDF define mode for 1D or 2D radio occultation data.
- **ropp2ropp**
 - A `-c` option has been introduced. This allows users to merge two datasets, by filling in absent level types (e.g. level 2a) of data in the input file with those from an auxiliary file.
 - A `-r` option has been introduced. This allows users to remove specified level types of data from the input file.
 - See source code, reference manual or man page for details.
- **eum2ropp and eum2ropp_eccodes**
 - This can now read newer format (`format_version ≥ 13.0`) EUMETSAT data files. See Sec 3.6.7 of the ROPP IO user guide for details.
 - A bug has been fixed in the construction of raw sampling phases from the I and Q components of EUMETSAT level 1a data. This will change results.
 - Sampling times of 0.02 sec (closed loop and open loop) and 0.001 sec (raw sampling) for EUMETSAT level 1a data are now assumed. This allows more open loop data to be processed. This will change results.
 - Open loop SNRs for EUMETSAT level 1a data are now calculated from an average of I and Q, rather than taken from the variable in the datafile, which is currently known to have errors. This will change results. (This change is only applied to data with a `format_version` less than 13.0. In later datasets the bug in the generation of the source data has been fixed.)
 - Remove all open loop data with tracking state = 2 in the beginning of the record from setting occultations, rather than rising ones. This will change results.
 - The time and date of EUM profiles are now taken from level 1a data, because level 1b data are sometimes absent. Level 1b is checked for validity before trying to read it.
 - The `PCD_offline` bit is only set if the netCDF global attribute `environment` is set to `Offline`.
 - A `-c` option has been introduced to read EUMETSAT's open loop/raw sampling navbit-corrected L1 excess phase directly, instead of reconstructing it from the navbit-uncorrected I and Q values.
 - A `-x` option has been introduced to omit the reading of level1b data.
 - See source code, reference manual or man page for details.

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- **ucar2ropp**
 - **atmPrf** files containing `Impact_Height` now account for the undulation when converting this to impact parameter (i.e. $IP = IH + RoC + und$). The earlier calculation (i.e. $IP = IH + RoC$) can be used by calling **ucar2ropp** with the `-x` option.
 - The `PCD_offline` bit is now set when reading **atmPhs** files. This increases `pcd` in the output **ROPP** file by 2.
 - A bug which prevented **ucar2ropp** from reading **sonPrf** files has been fixed.
 - KOMPSAT-5 **atmPhs** files can now be read correctly, by using the differenced open loop phase model variable `xmdlDD` in place of the usual `xmdl` variable. The large values of `xmdlDD` requires the extension of the valid range of the ROPP variable to which it is copied, `open_loop_lcf`, from $(-10^6, 10^6)$ m to $(-10^7, 10^7)$ m.
 - See source code, reference manual or man page for details.
- **eum2bufr and eum2bufr_eccodes**
 - This can now read newer format (`format_version` ≥ 13.0) EUMETSAT data files. See Sec 3.6.7 of the ROPP IO user guide for details.
 - The documentation has been amended to state that L2 extrapolation is off by default.
- **grib2bgrasc**
 - The `PCD_occultation` bit of `PCD` is now set, implying a background profile.
 - Occultation datetimes and satellite IDs are now inherited from those of the auxiliary 'observation file', if provided.
 - The lead time `TLEAD` is now set to `ropp_MDFV`, rather than zero, for time-interpolated background files.
 - The longitudes in the output namelist file now lie in the usual ROPP range $[-180^\circ, 180^\circ]$.

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5. ROPP_PP

- A two-dimensional version of the wave optics propagator, **ropp_pp_wopt_2d_tool**, has been introduced. This extends the functionality of the existing one-dimensional version of the tool by allowing the refractivity to vary in the horizontal. The aim is to allow a better simulation of the propagation of an RO signal through a refractivity field than is possible when spherical symmetry is assumed. *See Sec 6.5 of the ROPP PP user guide for full details.*

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6. ROPP_FM

- The dry temperature is now produced by the 1D forward model (by integrating the implied refractivity from the second highest level, using the hydrostatic equation). See Secs 3.4 and 4.9 of the ROPP FM user guide for details.
- New routines have been introduced to initialize the `Obs1dRefrac` and `Obs1dBangle` structures when `ropp_fm_bg2ro_1d` is called with the `-1` option. This is to avoid the sigma values in these structures being set to the default values ($0.01732 = \sqrt{3e-4}$) produced by `ropp_fm_roprof2obs.f90`. See Sec 4.2.1 of the ROPP FM user guide for details.
- The azimuth, radius of curvature and centre of curvature are now taken from the input 'levels' file when `ropp_fm_bg2ro_1d` is called with the `-1` option. See source code, reference manual or man page for details.
- A `-nocheck_qmin` option to `ropp_fm_bg2ro_1d` and `ropp_fm_bg2ro_2d` has been introduced. This allows negative humidities to appear in the state vector of both ECMWF and Met Office model types. (The default behaviour remains to set a minimum specific humidity of $1.0e-9$ kg/kg.) See Secs 4.1 and 5.3 of the ROPP FM user guide for details.

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7. ROPP_1DVAR

- The Levenberg-Marquardt minimisation scheme has been extensively updated as a result of faults exposed by testing on some Metop-C data. But these corrections have not been systematically tested, which is why the default solver remains minROPP. **LevMarq users will see a difference in their results, however, and they are advised to check them carefully. Any surprising changes should be reported to the ROM SAF Helpdesk at <http://www.romsaf.org/helpdesk.php>. See Secs 4.7.2 and 5.7.2 of the ROPP 1DVAR user guide for details.**
- A bug has been fixed in **ropp_1dvar_add_bgr_error.f90**, the program that merges error covariance data from an auxiliary file into an ROPP-format file. The maximum value of `press_sfc_sigma` in this routine has also been increased from 100 to 1000 Pa. See *Secs 4.2 and 5.2 of the ROPP 1DVAR user guide for details.*
- Two new quality control variables, available in the 1dvar configuration files, have been added:
 - `j_s_limit`, the maximum scaled cost function $2J/m$ (default=5, previously fixed at 5);
 - `n_iter_max`, the maximum number of iterations (default=50, previously set at 25).*See Tables 4.2 and 5.2 of the ROPP 1DVAR user guide for details.*
- The absence of a requested file in **ropp_1dvar/common/ropp_1dvar_covar_bg.f90** is now a fatal error ($\$?=2$) rather than a non-fatal one ($\$?=1$). See *Secs 4.5.2 and 5.5.2 of the ROPP 1DVAR user guide for details.*
- A `-nocheck_qmin` option to **ropp_1dvar_bangle** and **ropp_1dvar_refrac** has been introduced. This allows negative humidities to develop in the 1dvar minimiser. (The default behaviour remains to set a minimum specific humidity of 10^{-9} kg/kg.) See *Secs 4.1 and 5.1 of the ROPP 1DVAR user guide for details.*
- The quality control check on `|ob%time - bg%time|` in **ropp_qc_genqc.f90** has been generalised to handle files whose background times include the forecast lead time, and those that don't. See *Secs 4.1 and 5.1 of the ROPP 1DVAR user guide for details.*

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8. ROPP_APPS

- The way in which the ROprof structure is made ready to include tropopause height diagnostics has been changed. This has the effect of propagating (some) 'extra data' from the input file to the output file, as well as the surface geopotential and pressure.
- A `--no-ranchk` option has been added to **ropp_apps_tph_tool.f90**. See Sec 3 of the *ROPP_APPS user guide* for details.

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9. Conclusions

This document has summarised the significant differences between the Radio Occultation Processing Package (ROPP) version 10.0 and the previous release, version 9.1. Full guidance on downloading and installing the software can be found at the ROM SAF Software download page <http://www.romsaf.org/ropp/index.php>. All enquiries should be made through the ROM SAF Helpdesk at <http://www.romsaf.org/helpdesk.php>.