



EUMETSAT

ROM SAF

RADIO OCCULTATION METEOROLOGY

ROPP Change Log: v9.0 to v9.1

Version 1.0

30 June 2019


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 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 aids 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 9.1 and the previous release, version 9.0. Principal among these are:

- The introduction of code to process GNOS excess phase data from the FY-3C satellite operated by the Chinese Meteorological Agency;
- The introduction of routines to carry out more accurate transformations between co-ordinate reference frames, as needed to (re-)process EUMETSAT excess phase data;
- Modifications to the single frequency bending angles resulting from the use of finite electron density at the LEO;
- Minor developments to the wave optics propagator, which are important in extreme cases;
- The introduction of routines to process leap seconds correctly.

1. Introduction

1.1 Purpose of the document


This document summarizes the significant differences between the Radio Occultation Processing Package (ROPP) version 9.1 and the previous release, version 9.0. 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 of note to all users 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.

- [AD.1] Proposal for the third Continuous Development and Operations Phase (ROM SAF CDOP-3) March 2017 – February 2022.
Ref: SAF/ROM/DMI/MGT/CDOP3/001
- [AD.2] Co-operation Agreement between EUMETSAT and DMI, Lead Entity for the CDOP-3 of the ROM SAF, signed at the 86th Council meeting on 7th December 2016.
Ref: EUM/C/85/16/DOC/19
- [AD.3] Product Requirements Document (PRD).
Ref: SAF/GRAS/METO/MGT/PRD/001
- [AD.4] System Requirements Document (SRD).
Ref: SAF/ROM/DMI/RQ/SRD/001

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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-9 (v9.1) Release Notes
Ref: SAF/ROM/METO/SRN/ROPP/001 – Version 9.1.

- [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


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

- [RD.4] Summary of science changes in ROPP9.1, S. B. Healy
Ref: SAF/ROM/ECMWF/REP/RSR/031

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) |

1.4 Definitions

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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, Reprocessed, or Offline). The data levels and product types are defined below¹. 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).

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 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)

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.

2. General

- Full build support for a new external dependency package, the Standards Of Fundamental Astronomy library provided by the IAU, has been provided, by means of the usual mini configure scripts.
- Numerous redundant variables, identified by new compilers, have been removed from the code.

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3. ROPP_UTILS

- Three pieces of code associated with leap seconds, and the difference between UTC and GPS time, have been introduced to the DateTimeProgs module:
 - `leapseconds.f90`, which calculates the accumulated leap seconds up to a given UTC;
 - `gpstoutc.f90`, which converts GPS datetimes to UTC datetimes, and vice-versa;
 - `augmentutc.f90`, which returns the UTC that results from adding a given length of time to a given UTC.


In the absence of a ROPP_UTILS User Guide in which these tools can be documented, they are described fully in Appendix A of this Change Log.

- A routine (**eci2eci**) has been provided to transform coordinates between the J2000 ECI reference frame as used by EUMETSAT and the True-of-Date, equinox-based frame used by UCAR. These rotations can be undertaken by means of routines embodied in the Standards Of Fundamental Astronomy (SOFA) libraries, or (by default) by less sophisticated formulas. The ROPP build packages have been extended to accommodate the SOFA library, although its use is not compulsory. The default behaviour of **ecf2eci** and **eci2ecf** has not changed.

In the absence of a ROPP_UTILS User Guide in which these tools can be documented, they are described fully in Appendix B of this Change Log.

4. ROPP_IO

- The ROPP reading/writing routines can now handle BUFR files containing FY-3C and FY-3D data from CMA, Megha-Tropiques data from ISRO, KOMPSAT-5 data from KMA (via UCAR), and (in principle) GRACE-FO data from GFZ. New BUFR namelists have been prepared and included in the distribution.
- The `start_time` variable in ROPP netCDF files, which holds the time in seconds between the occultation start time and 0Z 01/01/2000, now takes account of leap seconds. The corresponding change has been made to the routine that reads ROPP netCDF files. This means that if earlier files, which have incorrect `start_times`, are read, they will now, if the '-d' diagnostic flag is invoked and the time difference is less than 30 s, prompt an INFORMATION message that the start time and the UTC date stamp are inconsistent, because they differ by the number of leapseconds that have accrued since 0Z 01/01/2000. In such cases ROPP will use the UTC stamp, which is still correct, so the message may be safely ignored. If the time difference is more than 30 s, a WARNING message is still issued, as leap seconds are unlikely to be the cause of the difference.
- The `time` variable in ROPP netCDF files, which holds the time in seconds between the occultation georeference time and 0Z 01/01/2000, is now correctly calculated as `start_time + time_offset`. (Previously it had been set equal to `start_time`.) This is unlikely to have any effect on users because the `time` variable is read but not used by ROPP.
- Extra diagnostics, activated by use of the '-d' option, have been added to **bufr2ropp**. These allow users to see some of the contents of the BUFR file on stdout, without needing to interrogate the netCDF file (assuming the conversion works) or use an auxiliary program to read the BUFR file (assuming that such a program uses the correct lookup tables).
- **ucar2ropp**
 - This routine's data reading interface has been extended to allow it to read GRAS data provided in UCAR/CDAAC format.
- **eum2ropp**
 - The level 1a satellite positions and velocities, which are provided by EUMETSAT in the J2000 ECI frame, are now rotated to the equinox-based True-of-Date ECI frame. This brings EUMETSAT data closer into line with that produced by UCAR. Typical differences in position components are around 10 km; typical differences in velocity components are around 10 m/s. This does not affect the nominal 'reference' satellite positions and velocities that appear in the BUFR file.
- **ropp2bufr**
 - The bug that sometimes prevented 'reference' POD data from being added to the BUFR file has been fixed.

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5. ROPP_PP

- **ropp_pp_occ_tool** has been amended to allow it to read excess phase data from the GNOS instrument carried by the FY-3C satellite. These changes include the exclusion of occasional occultations with wildly varying satellite positions, and the extrapolation of L2 data below its lowest valid point by means of a fit to L2 – L1 at higher levels. Some QC information has been set accordingly.
- A bug has been fixed in the location of the level above which observed bending angles are fully replaced by climatological bending angles in the statistical optimisation undertaken by **ropp_pp_occ_tool** and **ropp_pp_invert_tool**.
- **ropp_pp_wopt_tool** has been slightly amended in four ways:
 - A change in the damping of the signal below the Earth's surface, from a 1 km width Gaussian centred 1 km above the surface, to a 500 m Gaussian centred at the surface. This allows the bending angle profiles to penetrate deeper in some cases.
 - The inclusion of an extra term in the complex exponential that is integrated over the final 'screen' to give the signal at the LEO. This correction leads to a bending angles that are closer to those produced by high resolution wave optics propagation codes and direct forward modelling of interpolated refractivities.
 - The disregarding of points of low amplitude in the estimation of the Doppler offset in the FSI routine. This allows occasional problematic cases to generate bending angles successfully.
 - A reduction in the default number of points per 'mini-screen' on the final refractivity 'screen' from 100 to 32. (Note the implied three-fold increase in cpu time to propagate the signal from the final refractivity screen to the LEO.)

6. ROPP_FM

- The effects of a finite electron density at the LEO on single frequency bending angles have been included in the single frequency `-direction` option. (Previously, as is usual, $n_e(\text{LEO})$ had been assumed to be zero.) There are two elements to this. One accounts for the incorrect refractive index at the LEO used in the calculation of the impact parameter. This effect is proportional to $n_e(\text{LEO})$. The other arises from the truncation of the Abel transform at $a(\text{LEO})$ rather than infinity. This effect is estimated by a few terms of the 'Zorro series' (see RSR 17), which is rapidly converging at heights above the peak electron density. Each effect can affect the bending angles by around 5% for Metop satellites (at 830 km altitude) and as much as 30% for CHAMP satellites (at 470 km). Both corrections are inversely proportional to the square of the frequency, and therefore their effect on the neutral bending angle is eliminated by the standard ionospheric correction method.
- The ionospheric forward model test script `test_fm_IONO.sh` has been renamed `test_fm_iono2.sh`, because some operating systems cannot distinguish between `test_fm_IONO.sh` and `test_fm_iono.sh`.

7. ROPP_1DVAR

- The calculation of the background time in a DMI NRT background file has been amended to account for the forecast length of the ECMWF model run from which it was extracted. This means that ropp_1dvar can now be used with these files, because it no longer rejects them for being too far apart in time. (Users still need to specify a maximum time separation of at least 3 hours to use this data, however.) (Newer CDR files still have the problem. For a workaround, see the Release Notes.)

8. ROPP_APPS

- No changes to report.

9. Conclusions

This document has summarised the significant differences between the Radio Occultation Processing Package (ROPP) version 9.1 and the previous release, version 9.0. 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>.

10. Appendix A: Leap second tools

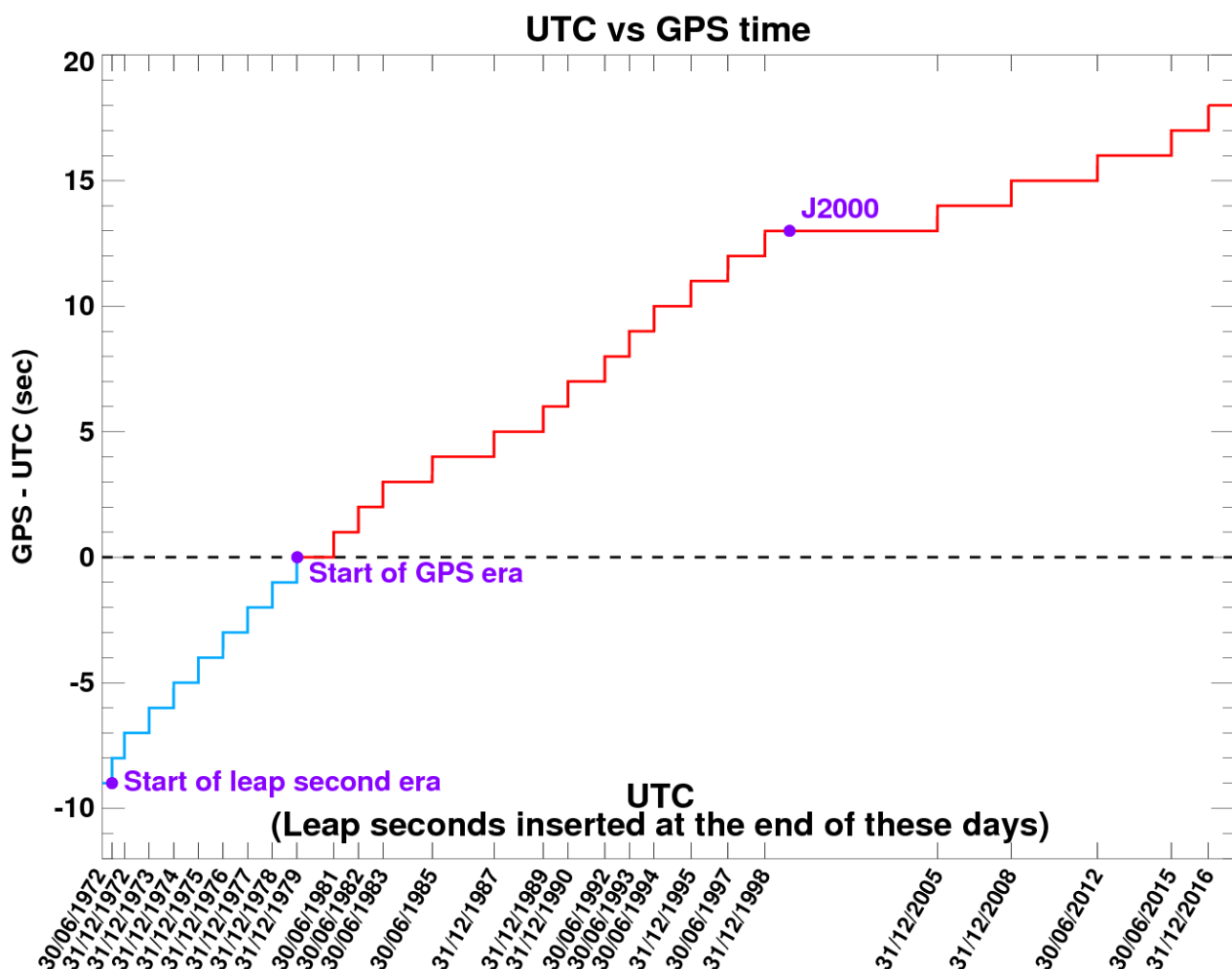
At least three times are of relevance here.

UTC = Coordinated Universal Time, a time which, since 0Z 01/07/1972, has been subjected to occasional leap second shifts to ensure that it keeps broadly in step with astronomical time.

TAI = Temps Atomique International, the international atomic time scale based on a continuous counting of the SI second. TAI is currently ahead of UTC by 37 seconds, 27 of which are leap seconds and 10 of which were already in place before leap seconds started to be added in 1972.

GPS = Global Positioning System time, the atomic time scale implemented by the atomic clocks in the GPS ground control stations and the GPS satellites themselves. GPS time matched UTC at 0Z 06/01/1980, at which moment TAI was ahead of UTC by 19 seconds. Since neither GPS time nor TAI time are affected by leap seconds, TAI is always ahead of GPS by 19 seconds. GPS is therefore now ahead of UTC by $37-19=18$ seconds.

This figure records the history of leap second insertions, and their effect on GPS vs UTC.



The following tools have been added to `ropp_utils/datetime` to help users to account for leap seconds correctly.

1) `leapseconds.f90`

This is a function that calculates the total number of leapseconds to have accrued up to a given UTC. Thus, for example,

```
UTC = (/ 2000, 01, 01, 0, 0, 0, 0, 0 /) ! YYYY/MM/DD/Zone/hh/mm/ss/msec  
lpsec = LeapSeconds(UTC)
```

returns

```
lpsec = 22
```

which is the correct number of leapseconds to have accrued by 0Z 01/01/2000, 9 of them before the GPS era began on 0Z 06/01/1980 and 13 of them after.

More examples are given in the header of `ropp_utils/datetime/leapseconds.f90` and (therefore) the ROPP_UTILS reference manual.

2) `gpstoutc.f90`

This is a subroutine that converts between GPS and UTC times. For example,

```
UTC = (/ 2005, 12, 01, 0, 0, 0, 0, 0 /) ! YYYY/MM/DD/Zone/hh/mm/ss/msec  
CALL GPStoUTC (GPS, UTC, -1)
```

returns

```
GPS = (/ 2005, 12, 01, 0, 0, 0, 13, 0 /)
```


showing that the 13 leapseconds that have accrued by 0Z 01/12/2005 since start of the GPS era have been correctly added to the UTC. If we now

```
CALL GPStoUTC (GPS, UTC, 1)
```

we correctly obtain

```
UTC = (/ 2005, 12, 01, 0, 0, 0, 0, 0 /)
```

showing that the transformation between times has been correctly inverted.

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There is a quibble when dealing with datetimes close to the leap second insertion times. For example, a UTC of 23:59:60 31/12/2005 returns a GPS of 00:00:14 01/01/2006, rather than 00:00:13 01/01/2006. (This is because 23:59:60 31/12/2005 is equivalent to 00:00:00 01/01/2006 as far as the ROPP routine CalToJul is concerned, and by that UTC time 14 leapseconds have been added.) Similarly, a GPS time of 00:00:13 01/01/2006 maps to a UTC of 23:59:59 31/12/2005, rather than 23:59:60 31/12/2005 (which would fail range-checking anyway), because the GPS to UTC conversion requires iteration of a non-linear function (because leap second insertion dates are recorded as UTCs). The computational cost of encoding checks and fixes for this behaviour is felt to outweigh the marginal benefit of solving a problem that will be encountered only very rarely - historically, for 27 seconds in 45 years, or about 19 times per billion. This decision could be revisited according to users' wishes (and Steering Group approval).

3) `augmentutc.f90`

This is a subroutine that adds a specified length of time (expressed in days) to a given UTC and returns the resulting UTC, properly taking account of leap seconds. Thus, for example,

```
UTC = (/ 2000, 01, 01, 0, 0, 0, 0, 0 /) ! YYYY/MM/DD/Zone/hh/mm/ss/msec
jday = 242903226.727d0/86400.d0 ! about 7.7 years expressed in days
CALL augmentutc(UTC, jday)
```

returns

```
UTC = (/ 2007, 09, 12, 0, 09, 07, 05, 727 /) = 09:07:05.727 12/09/2007,
```

which matches the result of some independently written Python code (Axel von Engeln, pers. comm.).

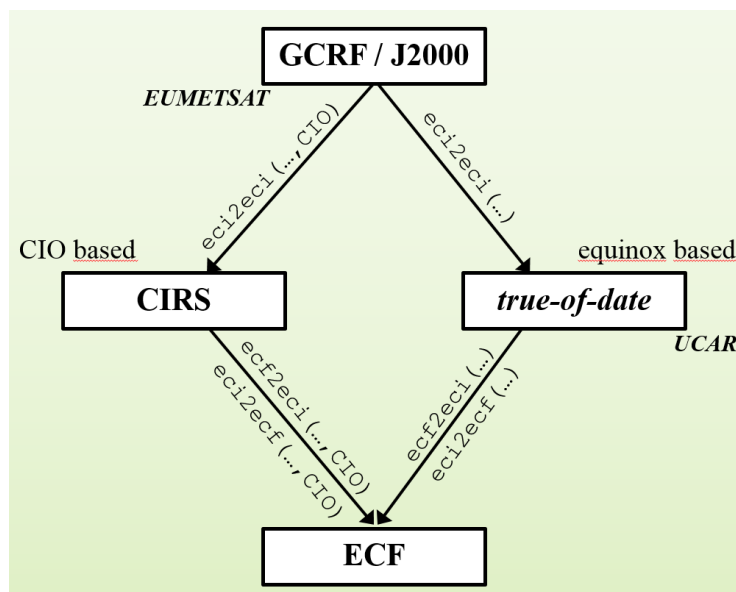
The key impact on ROPP of these changes is that the `start_time` variable in ROPP netCDF files, which holds the time in seconds between the occultation start time (in UTC) and 0Z 01/01/2000, now takes account of leap seconds. The corresponding change has been made to the routine that reads ROPP netCDF files. This means that if earlier files, which have incorrect `start_times`, are read, they will now, if the '-d' diagnostic flag is invoked and the time difference is less than 30 s, prompt an INFORMATION message that the start time and the UTC date stamp are inconsistent, because they differ by the number of leapseconds that have accrued since 0Z 01/01/2000. In such cases ROPP will use the UTC stamp, which is still correct, so the message may be safely ignored. If the time difference is more than 30 s, a WARNING message will still be issued, as leap seconds are unlikely to be the cause of the difference.

11. Appendix B: Extended coordinate transformations

The following text is based on a presentation by H. Gleisner, DMI, to the ROM SAF Project Team in June 2017.

- ROPP_PP assumes that satellite positions are given in an Earth-centered Earth-fixed (ECF) coordinate system. Input satellite velocities are not used by ROPP_PP.
- ROPP reads satellite positions and velocities from Level 1a files:
 - UCAR specifies coordinates in a 'true-of-date' system.
 - EUMETSAT has so far specified coordinates in J2000.
- In general, coordinate transformations are done as a two step procedure:
 1. from an original celestial system (inertial system at a standard epoch, e.g., J2000) to an intermediate system (inertial system at another epoch);
 2. from the intermediate inertial system to a terrestrial system rotating with the Earth.
- The latest IERS Convention (from 2010, described in IERS Technical Note 36) defines a new ('CIO-based') intermediate reference system to replace the old equinox-based system. The new system is used by EUMETSAT.
- Step 1 handles the effects of changes of the pole (Earth's rotation axis) between the two epochs. It is usually described in terms of precession and nutation.
- Step 2 handles the Earth's rotation, and potentially also the polar motion.
- The ROPP subroutines `eci2ecf` and `ecf2eci` implement step 2 (Earth rotation). Before ROPP9.1 it was assumed that the intermediate system was the equinox-based true-of-date system (as used by UCAR).

We therefore have the following net of transformations (again, courtesy H. Gleisner):



- A new subroutine `eci2eci` has therefore been written to accommodate the transformations between the inertial coordinate systems (at different epochs).
- The IERS standard software package SOFA has been incorporated in ROPP-9.1. SOFA is provided by the IAU as a collection of Fortran 77 routines. Full build support for this optional package has been provided, via the usual 'mini-configure' scripts.
- The alternative to SOFA is a set of simple textbook formulas (Hoffman-Wellenhof et. al., 2008) for precession and daily rotation. These do not include the effect of the Earth's nutation, unlike the SOFA routines.
- The transformation subroutines `eci2eci`, `eci2ecf`, and `ecf2eci` take optional logical arguments `SOFA` and `CIO`. Without these optional arguments, or if the SOFA package has not been installed, all three use the textbook formulas instead, which is what `eci2ecf`, and `ecf2eci` did before ROPP-9.1 anyway. (If SOFA routines are requested but unavailable a WARNING message is issued.)

- Thus, for example,

```
r_eci_to = eci2eci(year, month, day, hour, minute, sec, dsec, r_eci_from,
                  SOFA=.TRUE.)
```

will return, in `r_eci_to`, the (x, y, z) coordinates that result from mapping the (x, y, z) ECI coordinates from the standard epoch J2000.0 held in `r_eci_from` to the equinox-based true-of-date frame at the time defined by (year, month, day, hour, minute, sec, dsec)⁴. The accurate, nutation-including SOFA routines are used (if available). It does not transform the ECI coordinates to the CIO frame because the optional logical argument `CIO` is by default `.FALSE.`

- Similarly,

```
r_eci = ecf2eci(year, month, day, hour, minute, sec, dsec, r_ecf,
                SOFA=.TRUE., CIO=.TRUE.)
```

will return, in `r_eci`, the (x, y, z) coordinates that result from mapping the (x, y, z) ECEF coordinates held in `r_ecf` to the CIO-based ECI frame at the time defined by (year, month, day, hour, minute, sec, dsec)⁵. The accurate, nutation-including SOFA routines are used, if available. If they are unavailable, or if the optional logical argument `SOFA` is `.FALSE.`, either deliberately or by default, then the ECEF coordinates will be transformed to the equinox-based ECI frame, using the Hoffman-Wellenhof et. al. formulas. Only the SOFA routines can transform to or from the CIO-based ECI frame.

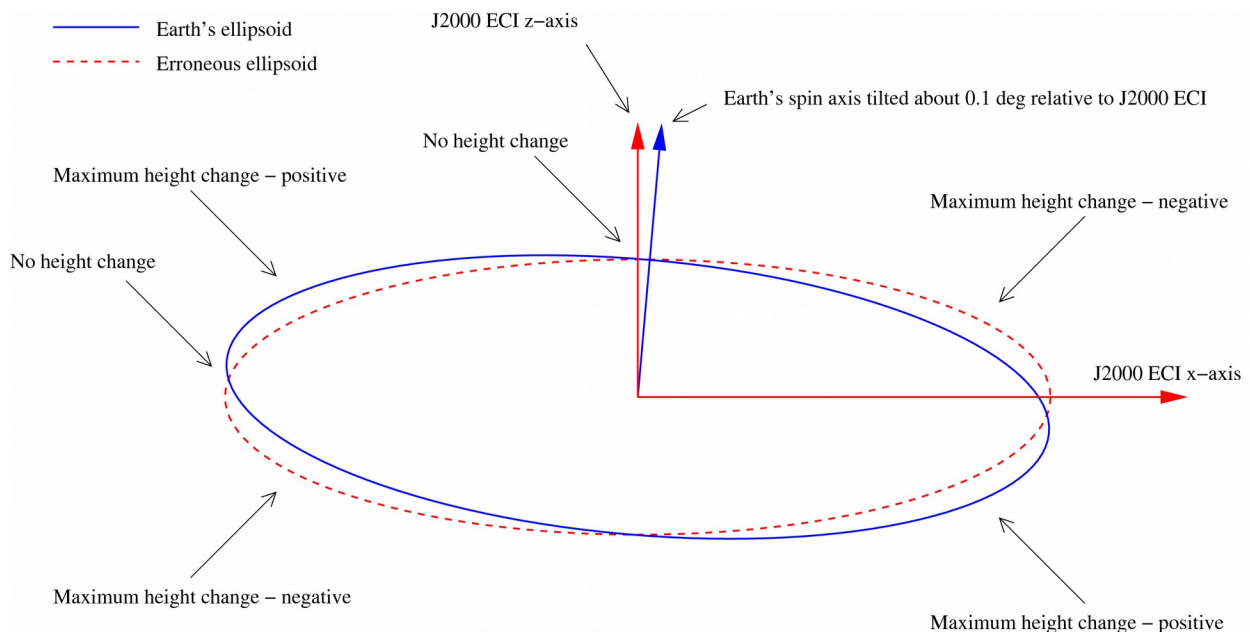
- Further particulars on these coordinate transformation routines can be found in the ROPP_UTILS reference manual.

⁴ In fact, because `eci2eci` is a slowly varying transformation between inertial frames, only (year, month, day) are used.

⁵ In this case, because `ecf2eci` is a rapidly varying transformation between an inertial and a non-inertial frame, (year, month, day, hour, minute, sec, dsec) are all used.

Results

The effect of the Earth's precession up to 2017 can be understood from the following sketch, courtesy S. Syndergaard, DMI. It basically shows the difference between the J2000 frame and the classical equinox-based frame. It explains the complicated 'quadrupole' distribution of RMS errors that appears when the effect is not corrected.



Back-of-the-envelope estimates:

Earth's Radii varies by 21 km from equator to pole
 At mid-latitudes it varies about 350 m pr deg, i.e., 35 m pr 0.1 deg
 35 m error in the vertical corresponds to about 0.5% error in refractivity – scale height = 7 km

Earth's spin axis tilt is very slowly varying – changed from 0 to 0.1 deg in 16.5 years (precession with a period of 26000 years)
 Metop orbit plane in ECI rotates 90 deg in 3 months – tilt angle can be considered constant
 Largest effect is when Metop orbit plane is in the plane of the drawing
 Smallest effect is when Metop orbit plane is perpendicular to the drawing 3 months later
 Explains the observed change in standard deviation from early March to early May

Further results are presented in the following figure, which shows the changes in the (x, y, z) positions and (u, v, w) velocities that result from mapping some Metop-A level 1a POD data from J2000 ECI coordinates to: the equinox-based ECI frame using the Hoffman-Wellenhof et. al. textbook formulas ('ERS_H-W'); the equinox-based ECI frame using the SOFA library routines, which include nutation ('SOFA_eqx'); and the CIO_based ECI frame using (as required) the SOFA library routines ('SOFA_CIO'). Results are shown for the LEO receiver and the GNSS transmitter.

Differences in position between J2000 and equinox-based frame are ~10 km, which is comparable with the shift in the location of the LEO during 12 years of the Earth's precession. 'ERS_H-W' and 'SOFA_eqx' are generally very close, with the ~100 m differences probably accounted for by nutation. 'SOFA_CIO' is an entirely different ECI frame, which is displaced in the x-y frame by ~10 km from 'SOFA_eqx' (H Gleisner, pers. com.), in agreement with the results. In all cases $|\mathbf{r}|$ and $|\mathbf{v}|$ are closely conserved, as would be expected from rotational transformations.

(Data: GRAS_1B_M02_20120909000057Z_N_T_20141111112929Z_G15_NN.nc) Different ECI co-ordinates

