



EUMETSAT

ROM SAF

RADIO OCCULTATION METEOROLOGY

**WMO FM94 (BUFR) Specification
For Radio Occultation Data**

Version 2.8 DRAFT

31 March 2023

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)
University of Graz, Wegener Center (UG-WEGC)


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DOCUMENT CHANGE RECORD

| Version | Date | By | Description |
|----------------|-------------|-----------|--|
| 1.0 | 10/12/2003 | DO | First release version for general user community comment. |
| 1.1 | 23/01/2004 | DO | Version presented to MetDB Team for submission to WMO |
| 1.2 | 11/05/2004 | DO | Updates after feedback from MetDB Team |
| 1.3 | 26/05/2004 | DO | Version on which formal proposal to WMO/CBS is based (see [RD.10]) |
| 1.4 | 29/07/2004 | DO | Version on which final proposal to 13th Session of WMO/CBS is based. |
| 1.5 | 27/05/2005 | DO | General updates |
| 1.7 | 23/03/2006 | DO | Minor editorial changes |
| 1.8 | 20/02/2007 | DO | Version for ROPP-1 (v1.0) |
| 1.9 | 01/03/2008 | DO | Version for ROPP-1 (v1.1) |
| 2.0 | 14/11/2008 | DO | Version for ROPP-2 (v2.0) |
| 2.1 | 19/05/2011 | DO | <ul style="list-style-type: none"> • Apply updated GRAS SAF document template & logos • Split BUFR Sections & Template into a separate Section 4 with new tables showing BUFR Section 0, 1, 3 & 5 details. • Added new Satellite ID and instrument codes • New geographical area designator code table • General body text updates Version for ROPP-5 (v5.0) |
| 2.2 | 18/02/2013 | DO | <ul style="list-style-type: none"> • Change branding (name & logos) from <i>GRAS SAF</i> to <i>ROM SAF</i> • Note that BUFR Edition 4 is now in use; information on the previous Edition 3 is retained to document settings for older BUFR messages. • Updated WMO URL links • Added to Acronyms list • Included new satellite ID code for Megha-Tropiques in Table 6 • General body text updates Version for ROPP-6 (v6.1) |
| 2.3 | 3/8/2013 | DO | <ul style="list-style-type: none"> • Inserted new ROM SAF document standard text on page 3 & Section 1.5 |

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|---|--|---|
| Ref: SAF/ROM/METO/FMT/BUFR/001 Version: 2.8 DRAFT Date: 31 March 2023 | WMO FM94 (BUFR) Specification for Radio Occultation Data |  |
|---|--|---|

| Version | Date | By | Description |
|---------|------------|-----|--|
| | | | <ul style="list-style-type: none"> • MetO MetDB can now handle messages up to 500,000 bytes, so removed text indicating the old 27,000 byte limit from Section 2.5 • Updated meaning of 'Levels' in Section 3.4 consistent with new Section 1.5 • Split Section 5 into sub-sections • Corrected some typos <p>Version for ROPP-7 (v7.0)</p> |
| 2.4 | 1/12/2016 | DO | <ul style="list-style-type: none"> • Inserted new Table 6 'Satellite Classification' showing GNSS/Tx satellite codes • Updated Table 7 'Satellite Identifier' including new LEO/Rx satellite codes • Updated Table 8 'Satellite Instruments' with approved code for GPSOS (was provisional) • Updated Tables 12 & 14 with actual ARHs from EUMETSAT (was provisional) • Minor editorial changes to body text <p>Version for ROPP-9 (v9.0)</p> |
| 2.5 | 30/06/2019 | IC | <ul style="list-style-type: none"> • Updated Tables 2, 3, 7, 8 and 14 to include new GNSS, LEO and generating centre codes, even if only provisional. • LEO and GNSS POD definitions clarified in Table 5. <p>Version for ROPP-9 (v9.1)</p> |
| 2.6 | 30/09/2020 | IC | <ul style="list-style-type: none"> • Updated Tables 12 and 14 to include ARHs for PAZ data. • Revised definition of NRT product in Sec 1.4. • Specify WGS-84 and EGM-96 as the ellipsoid and geoid references. • Confirmed satellite ID of 104 for Tri-G receiver in Table 8. • Updated Master Table Version Number in Table 3. • Provisional status of bits 8-10 of Quality Flag in Table 9 stressed. <p>Version for ROPP-10 (v10.0)</p> |
| 2.7 | 31/12/2021 | IC | <ul style="list-style-type: none"> • Remove comment about provisional status of bits 8-10 of Quality Flag (Table 9) following their adoption by WMO on 15/11/2021. • Metop-A and COSMIC-1 marked as no longer operational. • Include new LEO satellite and instrument IDs in Tables 7 and 8. • COSMIC-2 polar satellites removed from Table 7. • Sentinel-6 ARHs added to Table 14. • A few small, future-proofing, editorial changes. <p>Version for ROPP-11 (v11.0)</p> |
| 2.8 | 31/03/2023 | SSY | <p>Version updated for internal review to include:</p> <ol style="list-style-type: none"> 1) New descriptor for satellite sub-identifier 2) Alternative code value for time significance 3) Use of sub-centre code for EUMETSAT and DMI <p>Changes:</p> <ul style="list-style-type: none"> • Added text about new descriptor for satellite sub-identifier in the Introduction and Executive Summary. • Updated links in reference documents in Sec 1.2. • Added Spire and PlanetiQ to the list of mission in Sec. 2.1. • Added possible sub-centre code 220 for EUMETSAT and DMI in Sec. 4.2. |

| <i>Version</i> | <i>Date</i> | <i>By</i> | <i>Description</i> |
|----------------|-------------|-----------|---|
| | | | <ul style="list-style-type: none"> • Updated the list of current Originating/Generating centres in Sec. 4.2. • Added NASA, GeoOptics, and PlanetiQ in Table 3, and updated 35 to 39 (version number of master table). • Added text about new descriptor for satellite sub-identifier in Sec. 4.4 and added new Table 5. • Added text about the new descriptor in Sec. 4.5, and added the satellite sub-identifier as an optional first element in Table 6 (modified also Note 7). • Modified time significance (field 6) in Table 6 to allow either 17 = start of phenomenon or 25 = nominal reporting time. Modified accordingly field 29. • Removed specification of (1-32) for GNSS PRN in field 22. • Changed 'GNSS PRN' to 'PRN or similar' in field 22 (because other systems than GPS might not use the PRN as identifier, e.g., for QZSS it is PRN-192 that is commonly used). • Removed sentence in Sec. 5.5 that the date/time in the GTS header should be the start date/time of the observation. • Updated Table 15 to include Spire and PlanetiQ, and removed obsolete last sentence in Sec. 5.6. |

DRAFT

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, iii) Met Office in Exeter, United Kingdom, and iv) Wegener Center, University of Graz, in Graz, Austria. 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 describes the template specification for encoding ROM SAF processed radio occultation (RO) data into the WMO **BUFR** format. This formatting is a requirement for dissemination of near real-time ROM SAF products over the GTS or EUMETCast. The specification is generic to support the encoding of data from other RO missions (COSMIC, CHAMP, GRACE...) and by other RO processing centres (EUMETSAT, UCAR, GFZ...).

The WMO FM94 format (otherwise known as BUFR – Binary Universal Format for data Representation) is a standard for encoding meteorological and other (mainly) observational data for efficient transmission and storage. The data in a BUFR ‘message’ is pure binary (bit-oriented stream). The encoding and decoding process is table-driven, meaning that all data types must be pre-defined, and that these complementary processes must use the same table definitions. Once parameters are defined in this way, and (eventually) accepted and published by WMO, any data within BUFR ‘messages’ is self-defining and can be encoded and decoded by generic routines

The BUFR format (with suitable wrappers for routing of WMO bulletins) may be used for general exchange of any RO data via the Global Telecommunication System (GTS) including the Regional Meteorological Data Communications Network (RMDCN).

Almost all operational meteorological services now transmit and receive observational data in the BUFR format, and most also store (and archive) these data in BUFR, to be retrieved and decoded as needed for assimilation into NWP models etc. Indeed, several NWP centres, including the Met Office, NCEP and ECMWF can handle only BUFR as the interface to their assimilation systems. All new data types must therefore be encoded into BUFR before they can be used in this way. Contact with other countries known to be working with RO data confirmed that no BUFR definition already existed, or had been formally proposed, for this data type. However, a practical – albeit local and informal – implementation had been defined for similar CLIMAP data from the GPS/Met experimental mission.

A proposal for a BUFR specification for RO data was developed in consultation with the RO data producer and user communities and had been demonstrated to work in a practical implementation. The proposal was submitted to the WMO/CBS for approval in 2004, and – after some minor modification – formal ratification was granted at the 13th Session, St. Petersburg, 23 February – 3 March 2005. The RO specification was published in WMO BUFR tables at Version 12, and approved for use on the GTS from November 2005.

In November 2022, a new element descriptor to indicate a satellite sub-identifier (e.g., for commercial data) was approved by WMO, and it was included in WMO BUFR tables at Version 39.

1. Introduction

1.1 Purpose of document

This document describes the template specification for encoding ROM SAF processed radio occultation (RO) data into the WMO FM-94 (BUFR) format [RD.3]. This formatting is a requirement for dissemination of near real-time ROM SAF products ([AD.1]) over the GTS or EUMETCast. The specification is generic, to support the encoding of data from other than the GRAS instrument (COSMIC, CHAMP, GRACE...), and by other RO processing centres (EUMETSAT, UCAR, GFZ...)

BUFR formatting is a requirement for dissemination of near real-time RO data – and most other observational data types – over the WMO Global Telecommunication System (GTS)¹, Regional Meteorological Data Communications Network (RMDCN) [RD.4] or future WMO Information System (WIS) [RD.5] – although we should note that WIS may allow the transmission of certain other formats, such as netCDF [RD.15]. BUFR is also the sole or principal storage/archive and interface format for assimilation into NWP models at many operational centres. Therefore there is a requirement for BUFR, whatever the original format in which the centre may receive the data.

A proposal for a BUFR specification for RO data was developed in consultation with the RO data producer and user communities and had been demonstrated to work in a practical implementation. The proposal ([RD.10]) was submitted to the WMO/CBS for approval in 2004, and – after some minor modification – formal ratification was granted at the 13th Session, St. Petersburg, 23 February – 3 March 2005. The RO specification was published in WMO BUFR tables from Version 12 ([RD.4]), and approved for use on the GTS from November 2005.

In November 2022, a new element descriptor to indicate a satellite sub-identifier (e.g., for commercial data) was approved by WMO, and it was included in Master Table Version 39. The new descriptor is optional in the RO BUFR, and if it is present, it should be inserted in Section 3 of the RO BUFR.

This document is intended for users wishing to encode or decode RO data. Whilst all of the information to do this is available in the published WMO manuals and extracted tables (downloadable from the WMO website), this document provides a convenient ‘one-stop-shop’ to bring all the RO-specific BUFR table details (and more) into one place.

1.2 Applicable and reference documents

1.2.1 Applicable documents

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

- [AD.1] CDOP 4 Proposal: Proposal for the Fourth Continuous Development and Operations Phase (CDOP 4), Ref: SAF/ROM/DMI/MGT/CDOP4/001 (v1.1, 5 April 2021, as approved by the EUMETSAT Council in document reference EUM/C/97/21/DOC/15)
- [AD.2] CDOP 4 Cooperation Agreement between EUMETSAT and DMI on the CDOP 4 of the ROM SAF, Ref: EUM/C/97/21/DOC/21, signed on 31 August and 15 September 2021

¹ In this document, we will refer to the ‘GTS’ meaning the generic WMO-controlled networks used to exchange data between meteorological centres whatever the topology, technology or provider/owner. For our purposes, RMDCN and future WIS and similar network implementations can be considered to be part of ‘The GTS’.

1.2.2 Reference documents

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

- [RD.1] CLIMAP data format definitions. CLIMAP Technical Report
Ref. TERMA/CLIMAP/TN/3101, October 1999.
- [RD.2] GPS data in WMO FM94 (BUFR) format. CLIMAP Technical report
Ref. METOFFICE/CLIMAP/TN/05, May 2000
- [RD.3] WMO. *Guide to WMO Table-Driven Code Forms*. Copy available via link at:
<http://www.wmo.int/pages/prog/www/WMOCodes.html>
- [RD.4] WMO. *Manual on Codes*. WMO-306, Vol. 1.2, Part B. Copy available via link at:
https://library.wmo.int/?lvl=notice_display&id=10684
- [RD.5] WMO. Documentation on recent, current and upcoming operational BUFR tables is available from the WMO web site at:
<https://community.wmo.int/en/activity-areas/wis/latest-version>
- [RD.6] WMO (2009). *Manual on the Global Telecommunications System*. WMO-386, Vol.1, Part II, Attachment II-5 (Data Designators T₁T₂A₁A₂ii in Abbreviated Headings), 2009. WMO, Geneva. ISBN: 978-92-63-10386-4. Latest (2020) version available at:
https://library.wmo.int/doc_num.php?explnum_id=10469
- [RD.7] ROPP Input/Output Module User Guide.
Ref: SAF/ROM/METO/UG/ROPP/002
- [RD.8] Unidata NetCDF website <http://www.unidata.ucar.edu/packages/netcdf/>
- [RD.9] Kursinski, ER, *et al* (1997). *Observing earth's atmosphere with radio occultation measurements using GPS*. J. Geophys. Res., **102**(D19), pp23429–23465.
- [RD.10] *New BUFR Table D sequence and associated Table B entries for Satellite Radio Occultation data*. Document submitted by Brian Barwell (Met Office) at meetings of WMO/CBS Expert Team on Data Representation and Codes, held in Kuala Lumpur, Malaysia, 21–26 June 2004
- [RD.11] ECMWF (2017) *BUFR encoding/decoding software (ecCodes)*:
<https://www.ecmwf.int/en/elibrary/80526-eccodes>
- [RD.12] Cygwin website: <http://www.cygwin.com>
- [RD.13] ROM SAF website: <http://www.romsaf.org>
- [RD.14] ROPP Overview. Ref: SAF/ROM/METO/UG/ROPP/001

1.3 Acronyms and abbreviations

| | |
|---------------|--|
| ARH | Abbreviated Routing Header (WMO) |
| Beidou | Chinese GNSS navigation system. Beidou-2 also known as COMPASS. |
| BUFR | Binary Universal Format for the Representation of data (WMO) |
| CBS | Committee for Basic Systems (WMO) |
| CDR | Climate Data Record |
| CCT | Common Code Table (WMO) |
| CHAMP | CHallenging Mini-satellite Payload (Germany) |
| CLIMAP | Climate and Environment Monitoring with GPS-based Atmospheric Profiling (EU) |
| CMA | Chinese Meteorological Agency |
| C/NOFS | Communications/Navigation Outage Forecasting System (US) |
| COSMIC | Constellation Observing System for Meteorology Ionosphere and Climate (USA/Taiwan) |
| CREX | Character form for the Representation and EXchange of data (WMO) |

| | |
|------------------------|---|
| ECMWF | European Centre for Medium-range Weather Forecasts |
| ESA | European Space Agency |
| EU | European Union |
| EUMETSAT | EUropean organisation for the exploitation of METeorological SATellites |
| FM94 | WMO Form no. 94 (i.e. BUFR) |
| FY-3C/D | GNSS radio occultation receivers (CMA) |
| Galileo | European GNSS system from 2006 (EU/ESA) |
| RO | Radio Occultation |
| GFZ | GFZ Helmholtz Centre (Potsdam, Germany) |
| GLONASS | Globalnaya Navigatsionnaya Sputnikovaya Sistema (Russia) |
| GNSS | Global Navigation Satellite System (generic GPS/GLONASS/Galileo/Beidou) |
| GPS | Global Positioning System (USA) |
| GRACE | Gravity Recovery And Climate Experiment (Germany/USA) |
| GRACE-FO | GRACE Follow-on experiment (Germany/USA) |
| GRAS | GNSS Receiver for Atmospheric Sounding (on Metop satellite) |
| GRIB | GRIdded Binary (WMO) |
| GSN | Ground Support Network |
| GTS | Global Telecommunications System (WMO) |
| ICDR | Interim Climate Data Record |
| ISRO | Indian Space Research Organisation |
| JPL | Jet Propulsion Laboratory |
| KMA | Korean Meteorological Agency |
| KOMPSAT-5 | GNSS radio occultation receiver (KMA) |
| Megha-Tropiques | Tropical water cycle (and RO) experiment (India/France) |
| MetDB | Meteorological Data Base (Met Office) |
| Metop | METeorological Operational satellite (EUMETSAT) |
| NASA | National Aeronautics and Space Administration |
| netCDF | network Common Data Form (Unidata) |
| NMS | National Meteorological Service |
| NOAA | National Oceanographic and Atmospheric Administration |
| NWP | Numerical Weather Prediction |
| PAZ | Spanish Earth Observation Satellite, carrying a Radio Occultation Sounder |
| PCD | Product Confidence Data |
| POD | Precision Orbit Determination |
| RMDCN | Regional Meteorological Data Communications Network (WMO) |
| ROPP | Radio Occultation Processing Package (ROM SAF software deliverable) |
| ROM | Radio Occultation Meteorology |
| ROSA | Radio Occultation for Sounding of the Atmosphere (Italy/India) |
| SAF | Satellite Application Facility |
| 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 |
| TP | Tangent Point |
| UCAR | University Center for Atmospheric Research (Boulder, CO, USA) |
| UG-WEGC | University of Graz, Wegener Center |
| VAR | Variational (NWP data assimilation technique) |
| WMO | World Meteorological Organisation |
| WWW | World Weather Watch (WMO Programme) |

1.4 Definitions

RO data products from current and upcoming EUMETSAT satellites and other missions are grouped in data levels (Level 0, 1, 2, or 3) and product types (NRT, Offline, NTC, CDR, or ICDR). The data levels and product types are defined below². The lists of variables should not be considered as the complete contents of a given data level, and not all variables may be contained in a given data level in a given file.

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, SNRs, orbit information, I, Q values, NCO (carrier) phases, navigation bits, scintillation parameters, and quality information;

Level 1B: Bending angles and impact parameters, tangent point location, total electron content, 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), electron densities, and 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: Data product delivered less than: (i) 3 hours after measurement (ROM SAF Level 2 products for EPS); (ii) 150 min after measurement (ROM SAF Level 2 products for EPS-SG Global Mission); (iii) 125 min after measurement (ROM SAF Level 2 products for EPS-SG Regional Mission);

Offline, NTC: Data product delivered from about 5 days to up to 6 months after measurement, depending on the applicable 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 software³. 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. The CDR may be referred to as Fundamental (e.g. for Level 1B bending angles) or as Thematic (if related to a specific application area);

ICDR: Interim Climate Data Record which regularly extends in time a CDR using a system having optimum consistency with and lower latency than the system used to generate the CDR⁴.

² Note that the level definitions differ partly from the WMO definitions:
http://www.wmo.int/pages/prog/sat/dataandproducts_en.php

³ (i) GCOS 2016 Implementation Plan; (ii) <http://climatemonitoring.info/home/terminology/>

⁴ <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 contains a general description of BUFR data;

Chapter 3 describes the elements of a radio occultation profile that are encoded in BUFR;

Chapter 4 specifies the BUFR data elements used to encode RO data;

Chapter 5 describes the extra data headers that need to be added to a BUFR file before it can be distributed over the GTS;

Chapter 6 briefly describes the BUFR encoding and decoding tools that are available in the ROM SAF-produced software package ROPP.

DRAFT

2. BUFR – a brief overview

The reader is referred to WMO publications [RD.3] and [RD.4] for more detailed guidance on using BUFR and for the full specification of the BUFR format and tables etc. Documentation on the latest tables is available via the WMO's web pages [RD.5]. See also the User Guide to the ECMWF BUFR library software [RD.11].

2.1 What is BUFR?

The WMO FM94 format (otherwise known as BUFR – Binary Universal Format for data Representation) [RD.3] is a standard for encoding meteorological and other (mainly) observational data for efficient transmission and storage. The data in a BUFR 'message' are encoded into a pure binary (bit-oriented stream). The encoding and decoding process is table-driven, meaning that all data types must be pre-defined, and that these complementary processes must use the same table definitions. Once parameters are defined in this way, and (eventually) accepted and published by WMO (see [RD.5]), any data within BUFR 'messages' is self-defining and can be encoded & decoded by generic routines and (with suitable wrappers for routing of WMO bulletins) be transmitted via GTS links.

Almost all operational meteorological services now transmit and receive observational data in the BUFR format, and most also store (and archive) these data in BUFR, to be retrieved and decoded as needed for assimilation into NWP models etc. Indeed, several NWP centres, including the Met Office, NCEP and ECMWF can handle only BUFR as the interface to their assimilation systems. All new data types must therefore be encoded into BUFR before they can be used in this way. Contact with other countries known to be working with RO data confirmed that no BUFR definition already existed, or had been formally proposed, for this data type. However, a practical – albeit local and informal – implementation had been defined for similar CLIMAP data ([RD.2]) from the GPS/Met experimental mission.

As part of the early GRAS SAF Development Phase activities (1999–2007), the Met Office developed an RO data assimilation capability in order to assess the impact of RO data in its global NWP system. These data first needed to be encoded into BUFR and added to the local on-line meteorological synoptic database, known as the 'MetDB'. This required a prototype BUFR definition for the RO data type, which was implemented for initial assimilation trials.

However, it was always acknowledged that this prototype would not be suitable for more general dissemination to, and use by, other centres. This document describes the final BUFR specification which is better suited to general user needs for RO data. The original prototype description was retained in prior releases of this document (V1.7 and earlier) to highlight the differences, but since it is now obsolete and the WMO-approved version has been in use for several years, this prototype template description has been removed.

The final BUFR specification was derived in close consultation with suppliers of processed RO data (including the ROM SAF and UCAR) and a wide set of potential users in (mostly, but not limited to) the NWP community. This specification has been implemented via Fortran 95 (Met Office) and Perl (UCAR) interfaces to a suite of Met Office generic BUFR kernel encoder and decoder Fortran code, and was demonstrated to work as intended with real CHAMP data processed by GFZ and UCAR. Sample messages were also correctly decoded with the freely-available ECMWF BUFR package ([RD.11]).

At the time of writing, operational data is being exchanged over the GTS in this BUFR template from the Metop-B /C, Sentinel-6, Spire, PlanetiQ, COSMIC-2, TerraSAR-X, TanDEM-X, KOMPSAT-5, GRACE-FO (follow-on), PAZ and FY-3C/D RO missions, and will also be used for data from proposed future missions like Metop-SG. Data from terminated missions Metop-A, COSMIC-1, CHAMP, C/NOFS, GRACE-A/B and SAC-C were also provided in the same BUFR template. See Section 5 for details of the GTS routing headers.

2.2 Sections of a BUFR message

A complete BUFR message consists of six sections:

- Section 0 starts with the characters 'BUFR' and contains the total message length and Edition number
- Section 1 is the identifier section and contains header information, type of data, date etc., the detailed content depending on the Edition.
- Section 2 is optional, and is not used in this application
- Section 3 contains one or more 'descriptors' (see later) which are entries to the look-up tables
- Section 4 contains the encoded (observation) data
- Section 5 is a terminator with the characters '7777'

2.3 BUFR Tables

BUFR is driven by a set of tables, known as Tables A, B, C, D and the Code/Flag Tables. Some code tables are common with other WMO forms (notably CREX) and are published as 'Common Code Tables'. The latest ratified tables are published by WMO [RD.4][RD.5] and computer-compatible versions may be used in the encoding and decoding process.

- **Table A** contains a list of codes for generic data categories, such as 'satellite sounding' or 'surface observations' as coded in BUFR Section 1. Common Code Table C-13 lists data sub-categories associated with Table A entries, also coded in Section 1 (BUFR Edition 4 only). These tables are not necessary for encoding and are only used when interpreting⁵ a decoded message.
- **Table B** defines data elements (parameters) such as 'temperature' by an 'element descriptor' (see below). The descriptor points to meta-data such as the parameter's name, units, a scaling factor, reference offset value and the number of bits needed to represent the valid range of scaled values for that parameter. Some elements refer to a 'code' or 'flag' table; the former is a coded integer value (e.g. satellite identifier) and the latter a related set of flag (binary) bits, such as quality information. Most meteorological variables are already defined, but some parameters, such as 'Bending Angle' and RO-specific code/flag tables did not exist so needed to be defined and added to Table B.
- **Table C** defines the meaning and usage of 'operator descriptors'. This table is not directly used by encoders or decoders and is not normally implemented for computer-compatible use, as the functions defined by Table C are implemented in the core encoding and decoding software.
- **Table D** contains 'sequence descriptors' which define short, commonly used sub-sequences (such as date and time) up to the whole 'observation' (e.g. a sounding). An entry in Table D can be defined for each new data type or the sequence can be put into Section 3 of the BUFR message. If the complete sequence is defined in Table D, then Section 3 contains just the single master sequence descriptor for that data.
- **Code/Flag** tables (and the Common Code Tables) contain the textual meaning of code values and flag bits, e.g. that a satellite classification code of 401 means GPS. As for Table A, the Code/Flag Table is not used for encoding, and is only used for interpreting a decoded message.

Both Table B and Table D are split into two areas: the 'global' set and the 'local' set. The global area is where internationally agreed and published descriptors [RD.4] are placed, and these descriptors should appear in all implementations. Global descriptors have a 'YYY' value (see below) of less than 192. Local descriptors ($YYY \geq 192$) can be defined for temporary or internal use. Since there is no

⁵ The term 'interpreting' in this context means presenting decoded data in human-readable form. Interpretation is usually for diagnostic purposes and is not necessary to the decoding process itself.

central regulation for local descriptors, exchange of BUFR messages containing them could be problematic if the other centre has already defined that descriptor to be a different parameter having incompatible Table B meta-data or implies a different expanded Table D sequence. For this reason, BUFR messages using local descriptors should not be transmitted on the GTS.

2.4 BUFR descriptors

A BUFR descriptor is a three-part integer denoted by **F XX YYY**. The first part, **F**, defines the descriptor type and the interpretation of **XX** and **YYY** depend on **F**:

- F = 0** : an element descriptor (an entry in Table B). **XX** is the element class and **YYY** the entry within the class.
- F = 1** : a repetition descriptor, which specifies how many times (**YYY**) the following **XX** descriptors are to be repeated.
- F = 2** : An operator descriptor for the temporary change of, most commonly, scale, bit width or reference value. **XX** identifies what meta-data to change and **YYY** is the modifying value.
- F = 3** : a sequence descriptor (an entry in Table D). **XX** is the class of descriptor and **YYY** the entry within the class. The expansion of the sequence is a set of descriptors, which may recursively include other sequence descriptors as long as the definition is not circular.

BUFR encoders and decoders internally expand all sequence descriptors (**F = 3**) recursively. The resulting number of element descriptors (**F = 0**) – allowing for repetitions (**F = 1**) and ignoring modifying descriptors (**F = 2**) – must be equal to the total number of data fields to be encoded or decoded.

2.5 BUFR compression

BUFR has a built-in compression mechanism that can give modest reductions in the encoded message volume (typically 2:1). This is achieved by encoding several observations together; the smallest value of each parameter (over all the observations) is first encoded, and then only the increments from this are encoded, thus requiring fewer bits than the full bit width allowed in Table B. This is automatic as far as the user is concerned and does not form part of the BUFR data (descriptor) definition. If there are significant element values which are constant (all observations from one station, for instance, where the station details are duplicated for all observations, or a parameter is unvarying – perhaps 'missing'⁶) then compression for that parameter will be maximal, as the value is encoded only once and automatically replicated on decoding.

2.6 BUFR message length

Compression will be greatest when the range of values for a particular parameter is small over all the observations and smallest when the whole range of possible values is present. In general, it is not possible to predict the message length, as it will depend on the number of observations and the range of each parameter. Uncompressed messages (including single observations, which by definition cannot be compressed), however, are deterministic in their length, since all the parameter bit widths are known from Table B and can be summed together with the fixed and known 'overheads' of Sections 0–3 and Section 5.

There is no theoretical limit to the size of a BUFR message. The largest that can be accommodated in practice by the current (Edition 4) Section 0 header would be almost 17 mega-octets (megabytes)

⁶ Missing or invalid data must still be encoded, as BUFR data is positional. This is accomplished by setting all the bits defined for that parameter to '1'. This implies that the maximum valid range of values of any parameter after scaling and applying the reference offset is zero to $2^{\text{width}}-2$. On decoding, 'all bits set' in the BUFR message is decoded and returned to the user as missing data indicator values, usually -32768, -2147483647 or -9999999, depending on the implementation.

but a single bulletin of that size would be far too big for the GTS. By international agreement, as specified in [RD.6], single bulletins⁷ must be no longer than 500,000 octets (bytes). Prior to 5 November 2007, the GTS limit was 15,000 bytes. Since there are legacy transmission and storage systems not yet able to handle the significantly larger limit, 25,000 bytes is a good safe upper size to use in practice for the time being.

DRAFT

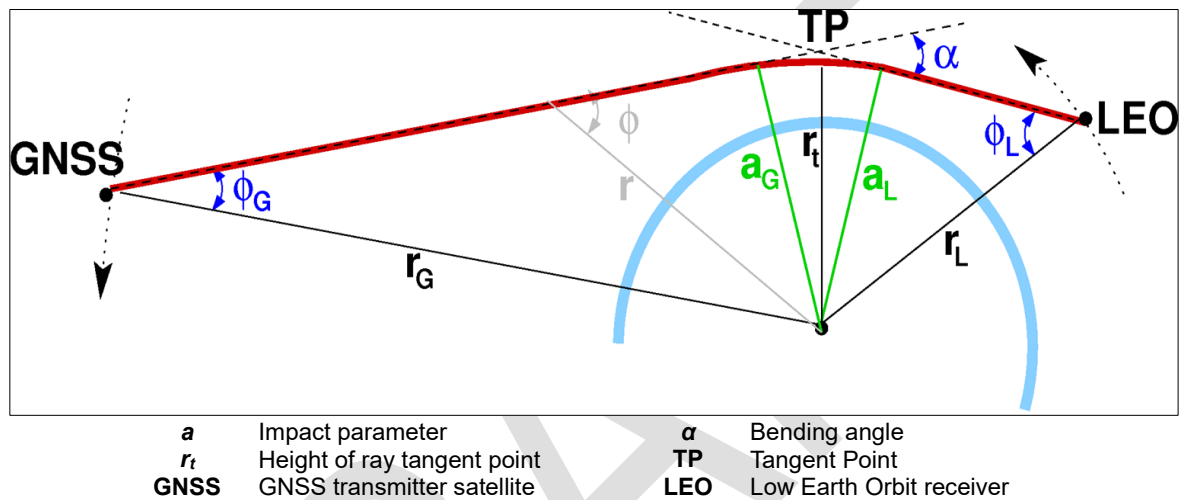
⁷ A bulletin is the BUFR (or GRIB, CREX or other WMO format) message with a wrapper or 'Abbreviated Routing Header' containing coded information on the message content for GTS routing purposes. The ARH adds some 35 bytes to the BUFR message length – see Section 5.

3. Radio occultation data in BUFR

3.1 Key Parameters

The basic geometry for Radio Occultation soundings is indicated in Figure 1. As the two satellites move, the ray – shown in red – ‘scans’ through the atmosphere either downwards (a ‘setting’ occultation) or upwards (a ‘rising’ occultation). The ray is refracted (‘bent’) by density gradients in the atmosphere. By comparing the **phase** (or **Doppler**) of the received radio signal with that expected from the *in vacuo* straight line path between the satellites, the total integrated **bending angle** can be calculated.

Figure 1. Schematic picture of the radio occultation geometry



From the ‘profile’ of **bending angle** as a function of **impact parameter**, a profile of **refractivity** as a function of **geometric height** can be obtained, and thence profiles of **pressure**, **temperature** and **humidity** with **geopotential height**. It is out of the scope of this document to describe the details of these steps, but see for instance [RD.9] for a description of the RO technique and the derivation of geophysical quantities.

3.2 Design Guidelines

The guiding principles, assumptions and objectives for developing the BUFR user requirements – and hence definitions in this document – were:

- the BUFR-encoded version of RO data is intended for dissemination in near real-time via the GTS, and to be used operationally by NWP centres;
- if the BUFR is not suitable for other users/applications, these will be able to use other formats via other dissemination methods;
- the majority of NWP users will apply variational assimilation methods (either full 3- or 4DVAR or 1DVAR pre-processing), using as input Refractivity (N) or sub-sampled Bending Angles (α) in preference to pre-retrieved pressure (P), temperature (T) and humidity (q) profiles or profiles of excess Doppler or phase time-series. While the final retrieved P, T, q values are useful for comparison purposes (and should be included), the ‘raw’ data are unlikely to be useful for NWP users given the (at the time) BUFR limitations on message length and precision (critical for POD), and so will be excluded from the BUFR definition;
- minimise the number new BUFR descriptors and any associated code/flag tables; re-use existing descriptors where possible, using temporary scale/bit-width changes if needed, or extend existing code tables;

- not to include static 'meta-data' parameters and flags into the BUFR, as these are of little practical use to operational NWP, and in any case could be provided off-line e.g. as a look-up table;
- the definition should be as generic as possible, so that RO data from different missions and instruments (e.g. GRAS, CHAMP, COSMIC, etc) and from different processing centres can be accommodated without needing mission-specific descriptors or code/flag tables;
- the definition should be as future-proof as possible i.e. all likely (useful) data is included now, even if initially 'missing', to avoid having to go back to WMO for modifications later;
- the definition should be kept as simple as possible to minimise software development for the BUFR encoding and decoding interfaces and to minimise the complexity of any proposal to WMO and to end-users not familiar with the RO processing details;
- the definition to be based on the content of the (now obsolete) text-based ROPP format [RD.7] (itself modified from an earlier CLIMAP format, [RD.1]) and developed from a prototype BUFR template implemented in the Met Office using local descriptors.

3.3 Rationale


Our starting point for generating RO data in BUFR was the 'CLIMAP RO format' [RD.1], which was the form agreed for distribution of GPS/Met RO data within that project for validation and NWP trial assimilation. For widest portability, CLIMAP files contained a simple formatted ASCII representation. This format was later more widely reviewed by potential users and data suppliers, and evolved to the 'ROPP-format' [RD.7]. Similar data from non-CLIMAP format sources (e.g. in netCDF [RD.8]) only require a suitable front-end file interface for a BUFR encoder application.

Some of the parameters specified in the CLIMAP format files were not likely to be required for near real-time, operational NWP use, so not all parameters were included in the BUFR specification. Omitted parameters include static meta-data such as the POD processing method and the 'raw' parameters such as SNR and excess phase and Doppler.

To minimise the number of new elements needing definition in Table B, as many of the existing ones as is practical have been re-used. Some existing BUFR element entries (such as time in seconds) did not have the required precision (scaling) and/or (re-)scaled valid range (bit-width); BUFR sequences can allow for this by defining temporary changes to the Table B definitions. In some cases, an element existed which is a code table entry (e.g. a list of satellite classifiers), so the code value definitions need extending in the relevant table.

In BUFR, as in many other areas, there is often more than one way to do something. For instance for the RO template, we employ a delayed replication count for the profiles. RO systems typically generate raw occultation data at a sample rate of 50Hz; this is far in excess of the requirements for NWP, for which no more than 5Hz or equivalent vertical sampling is sufficient. The lower rate means that up to 500 vertical samples are more than adequate to meet the requirements of NWP [AD.1], while a maximum of only 254 samples could be accommodated within the fixed replication count used for the prototype BUFR. (At the time, 200 samples for bending angles and 150 P, T, q samples were felt to be adequate for current NWP systems, but that is now seen as too inflexible for future use.)

Since the nature of RO data is that profiles are independent and widely separated, and their number per day is small (around 500 per day per receiver) it was proposed that only one observation (occultation profile) be encoded per BUFR message. This implies that compression is not used. Tests using sample CHAMP data confirmed that RO BUFR messages, encoded using the final BUFR sequence are approximately 12Kbytes for a nominal message containing 200 samples (L1+L2+Corrected) for bending angle and 150 samples for refractivity and P, T, q . Since we have also employed delayed replication for the L1+L2+Corrected bending angles, L1+L2 data can be skipped, or indeed data from additional future frequencies included, as desired, giving flexibility and a trade-off between vertical resolution (number of samples) and message length. Indicative message lengths for other combinations of samples are shown in Table 12.

| | | |
|---|--|---|
| Ref: SAF/ROM/METO/FMT/BUFR/001 Version: 2.8 DRAFT Date: 31 March 2023 | WMO FM94 (BUFR) Specification for Radio Occultation Data |  |
|---|--|---|

In summary, we have therefore kept the definition as simple and as generic as possible, consistent with likely operational NWP usage in the future, only defining new elements and sequences where necessary, which were all initially placed in the local areas of the BUFR tables. Wider use of RO data in a proto-operational environment required that these new descriptors be proposed to WMO for inclusion in the global tables for GTS dissemination. With some minor modifications (reflected in this document), the proposal was accepted and is now published in the WMO BUFR Tables [RD.5], for approved use on the GTS as from November 2005 (Version 12).

3.4 Levels and Steps

Following CEOS practice, RO data processing is conventionally split into 'levels':

| Level | Generic definition | Applied to RO |
|------------------|--|---|
| Level 0: | Raw source data | Raw sounding, tracking and ancillary data; other GNSS data before clock correction and reconstruction |
| Level 1a: | Geo-located data in engineering units complete with ancillary data (e.g. calibration information), but not applied to the science data | Reconstructed full-resolution excess phases; SNRs; amplitudes; orbit information; I, Q and NCO values; navigation bits |
| Level 1b: | Science data with calibration applied | Profiles of bending angle as a function of impact parameter; Earth location, metadata and quality information. |
| Level 2: | Calibrated science data 'retrieved' to geophysical units | Profiles of refractivity, pressure, temperature and humidity profiles as functions of height; surface pressure; metadata and quality information. |

However, the nature of RO data processing makes it convenient to further split some of these 'levels'. To avoid confusion with the CEOS definitions, in this document we use the term 'step' with the following definitions (the reader will note the close mapping of 'steps' to CEOS-style 'levels').

| Step | Definition |
|-----------------|---|
| Step 0: | Instrument source packets, time-tagged and time-ordered |
| Step 1a: | Time series of excess phase and Doppler plus satellite orbit information |
| Step 1b: | Profiles of L1, L2 and ionospheric-corrected bending angle as functions of impact parameter |
| Step 2a: | Profiles of refractivity as a function of geometric height |
| Step 2b: | Profiles of pressure, temperature and humidity as functions of geopotential height |
| Step 2c: | Surface pressure and geopotential height |

Depending on context, 'Step n' may refer to the processing which inputs the data from the previous step to the data resulting from that step, or to the output data of that step itself. These steps (and their intermediate outputs) reflect the generic processing stages for current RO algorithms. Specific algorithms may combine or skip some steps, but the above definition serves to split the BUFR products into convenient sub-sets from which users may choose to use for different applications. For reasons outlined above, the BUFR does not contain any Step 0 or Step 1a data apart from basic annotation and nominal orbit parameters.

4. BUFR Template Specification

The WMO Manual on Codes [RD.4] provides the formal Regulations for encoding BUFR messages. The following sub-sections give details of the various parts of a BUFR message as they are implemented for radio occultation data.

4.1 BUFR Section 0 (Indicator)

Section 0 provides meta-data about the message itself; it consists of a data introducer, the total length of the message and the Edition number – see Table 1.

Table 1. BUFR Section 0 (Indicator)

| Octet number | Contents | Value for RO |
|--------------|--|---------------------|
| 1–4 | BUFR (coded in CCITT International Alphabet No. 5) | 'BUFR' |
| 5–7 | Length of whole BUFR message (octets) | Variable |
| 8 | BUFR Edition number | 3 or 4 ⁸ |

4.2 BUFR Section 1 (Identification)

Section 1 includes information on the BUFR data content (in Section 4), and so is data-type specific. Section 1 information is different between Edition 3 (as previously used to encode older RO data) and the newer Edition 4 (as used currently).

Table 2 shows the information in Section 1 for older RO data encoded in Edition 3, and Table 3 likewise for the current Edition 4. The Originating/Generating Centre code is taken from Common Code table C-1 (or C-11 for Edition 4) and the Originating/Generating Sub-Centre code from Common Code Table C-12. The Data Category code is from Table A and the International Data Sub-Category (Edition 4) code from Common Code Table C-13.

Some encoder/decoder implementations – such as the ECMWF library [RD.11] – use Section 1 information to generate run-time BUFR look-up table file names which depend on the local table version and the originating centre and sub-centre codes. The Section 1 header for RO data indicates that only standard operational global table elements are used, so existing files should be loaded for this type of data whatever the centre/sub-centre code values. Recent releases (v19 or later) of the Met Office decoder uses only the table version number from Section 1, but by default will use the current version of the tables.

The 'Originating/Generating Centre' coded into Section 1 would normally be that for the National Meteorological Service (NMS) encoding the data and/or injecting the data onto the GTS. For our purpose, if it is not the RO processing centre doing the encoding, then the code should be that of the NMS of the country disseminating the BUFR via GTS. If the processing centre is also an NMS, the sub-centre is coded as zero. In any case, the Processing Centre identifier is encoded with the observation profile in Section 4.

There are currently six Originating Centres providing RO data on the GTS or EUMETCast:

- **EUMETSAT**, Darmstadt: 254, sub-centre 0 for GRAS and Spire data procured by EUMETSAT (Level 1b only), but sub-centre 220 for Spire and PlanetiQ data procured by NOAA and disseminated over EUMETCast;

⁸ BUFR Edition 3 is deprecated and only Edition 4 messages have been permitted on the GTS since 6th November 2012. RO data is currently encoded in Edition 4, but we include Edition 3 details here to document older BUFR messages that may be archived.

- **DMI**, Copenhagen: 094, sub-centre 0 for GRAS and Spire data procured by EUMETSAT, but sub-centre 220 for Spire and PlanetiQ data procured by NOAA and disseminated over EUMETCast;
- **UCAR**, Boulder (via NWS, Washington): 060, sub-centre 0, for COSMIC, KOMPSAT-5 and Spire and PlanetiQ data procured by NOAA;
- **GFZ**, Potsdam (via DWD, Offenbach): 078, sub-centre 173, for TerraSAR-X and TanDEM-X;
- **CMA**, Beijing: 038, sub-centre 0, for FY-3C/D data;
- **JPL**, NASA: 173, sub-centre 0, for Sentinel-6 data;

Table 2. BUFR Section 1 (Identification) for older Edition 3 messages

| Octet number | Contents | Value for RO |
|--------------|---|---|
| 1–3 | Length of section | 18 |
| 4 | BUFR Master Table | 0 (Meteorology) |
| 5 | Originating/Generating Sub-Centre (CCT C-12) | 173 = GFZ 0 = all others |
| 6 | Originating/Generating Centre (CCT C-1) | 028 = ISRO 038 = CMA 060 = UCAR 078 = DWD (GFZ) 094 = DMI 254 = EUMETSAT |
| 7 | Update Sequence Number | 0 |
| 8 | Optional Section 2 flag | 0 (no Section 2 present) |
| 9 | Data Category (Table A) | 3 (vertical sounding–satellite) |
| 10 | Data Sub-Category (locally defined by Originating Centre) | 14 (GNSS) |
| 11 | Version Number of Master Table ⁹ | 12 |
| 12 | Version Number of Local Table | 0 (local table not used) |
| 13 | Year of Century (2-digit) 'most typical for BUFR message content' | Year of profile |
| 14–17 | Month, Day, Hour & Minute 'most typical for BUFR message content' | Date/Time of profile |
| 18 | Pad to even number of octets | 0 |

Table 3. BUFR Section 1 (Identification) for current Edition 4 messages

| Octet number | Contents | Value for RO |
|--------------|---|---|
| 1–3 | Length of Section 1 | 22 |
| 4 | BUFR Master Table | 0 (Meteorology) |
| 5–6 | Identification of Originating/Generating Centre (CCT C-1 or C-11) | 028 = ISRO 038 = CMA 060 = UCAR 078 = DWD (GFZ) 094 = DMI 173 = NASA 178 = SPIRE 179 = GeoOptics 180 = PlanetiQ 254 = EUMETSAT |
| 7–8 | Centre Originating/Generating Sub-Centre (CCT C-12) | 173 = GFZ (for DWD) 220 = NOAA (for EUM and DMI) |

⁹ The Master Table Version number in which the template was first published. The encoded version number should not be changed to the current Version unless a change to Table B or Table D directly affects this data type.

| Octet number | Contents | Value for RO |
|--------------|---|---------------------------------|
| | | 0 = all others |
| 9 | Update Sequence Number | 0 |
| 10 | Optional Section 2 flag | 0 (no Section 2 present) |
| 11 | Data Category (Table A) | 3 (vertical sounding–satellite) |
| 12 | International Data Sub-Category (CCT C-13) | 50 (RO) |
| 13 | Local Data Sub-Category (locally defined by Originating Centre) | 14 (GNSS) |
| 14 | Version Number of Master Table ⁹ | 39 |
| 15 | Version Number of Local Table | 0 (local table not used) |
| 16-17 | Year (4-digit) 'most typical for BUFR message content' | Year of profile |
| 18-22 | Month, Day, Hour, Minute and Second 'most typical for BUFR message content' | Date/Time of profile |

4.3 BUFR Section 2 (Optional Data)

This section is not used for RO, and is not present in the BUFR messages.

4.4 BUFR Section 3 (Data Description)

This section contains the number of data sets (observations) encoded in Section 4 (*1 for RO*) and flags indicating whether the data is 'observed' (*yes*) and whether they are encoded with compression or not (*no*). For older than Master Table Version 39 (given in BUFR Section 1), this section also contains the single Table D descriptor **3 10 026**, this being the master sequence descriptor for the RO data in BUFR Section 4. This is illustrated in Table 4.

Table 4. BUFR Section 3 (Data Description) for older than Master Table Version 39

| Octet number | Contents | Value for RO |
|--------------|---|--|
| 1–3 | Length of Section 3 (octets) | 9 or 10 ¹⁰ |
| 4 | Reserved | 0 |
| 5–6 | Number of datasets (observations) | 1 |
| 7 | Section 4 Data flags: Bit 1 = 1 for Observed data, 0 for Other data Bit 2 = 1 for Compressed, 0 for Uncompressed Bits 3–8: Reserved (set to 0) | 1 (Observed, Uncompressed) |
| 8–9 | Descriptor | 51738 (3 x 16384 + 10 x 256 + 26) |
| [10–] | Repeat 2-octets per descriptor Total number of descriptors = (Section length - 7) / 2 | |
| [10] | Pad byte (set to 0) – optional for Edition 4 | 0 (if Section length = 10) |

With Master Table Version 39 or higher, Section 3 additionally may contain the descriptor **0 01 016**, this being the Table B element descriptor for the satellite sub-identifier. This descriptor is optional in the RO BUFR because it is not part of the master sequence descriptor. It was approved by WMO in November 2022 to identify a single flight module in larger constellations (e.g., Spire) that otherwise have only one or a few common satellite identifiers in Common Code Table C-5 (see Table 8). If present, this descriptor comes before the master sequence descriptor. Its presence is indicated by the section length. This is illustrated in Table 5.

¹⁰ Depends on the BUFR encoder implementation as to whether an optional Edition 4 even pad byte is inserted or not; e.g. the MetDB encoder inserts this byte and the ECMWF encoder doesn't. Edition 3 required this pad byte.

Table 5. BUFR Section 3 (Data Description) with Master Table Version 39 or higher

| Octet number | Contents | Value for RO |
|--------------|---|-----------------------------------|
| 1–3 | Length of Section 3 (octets) | 11 or 12 ¹⁰ |
| 4 | Reserved | 0 |
| 5–6 | Number of datasets (observations) | 1 |
| 7 | Section 4 Data flags: Bit 1 = 1 for Observed data, 0 for Other data Bit 2 = 1 for Compressed, 0 for Uncompressed Bits 3–8: Reserved (set to 0) | 1 (Observed, Uncompressed) |
| 8–9 | Descriptor | 272 (0 x 16384 + 1 x 256 + 16) |
| 10–11 | Descriptor | 51738 (3 x 16384 + 10 x 256 + 26) |
| [12–] | <i>Repeat 2-octets per descriptor</i> Total number of descriptors = (Section length - 7) / 2 | |
| [12] | Pad byte (set to 0) – optional for Edition 4 | 0 (if Section length = 12) |

4.5 BUFR Section 4 (Data Template)

The WMO-approved and published BUFR template sequence definition for RO data is shown in Table 6. This is in the form of the Table D sequence of descriptors and their individual Table B specifications. If descriptor **0 01 016** is present in Section 3, this sequence is preceded by the satellite sub-identifier, which in Table 6 is the first element while indicating that it is optional. If the satellite sub-identifier is present, it is Data Field number 1, and then 1 should be added to all other data fields in the table. Entries in **bold (blue) text** denote that a new Table B and/or Code/Flag Table entry was required, or that an existing entry in the relevant Code/Flag Table needed to be extended. These are defined in Table 8, Table 9 and Table 10. Note that the Code/Flag Tables are not necessary for correct decoding of BUFR messages, but are used only when interpreting the decoded data.

The complete RO BUFR master sequence of 82 element, sequence and operator descriptors (not including the descriptor **0 01 016**) is assigned to the global section of Table D as descriptor **3 10 026**. This single sequence descriptor is encoded into Section 3 of the BUFR message.

Table 6. BUFR Section 4 (Data Template)

| Data Field | Element Name | Descrip. | Table B Scale | Table B Ref. Val. | Table B Width | Units | Comments |
|---------------------------------------|---|-----------------|---------------|-------------------|---------------|-------------------|---|
| Radio Occultation header | | | | | | | |
| [1] | Satellite sub-identifier | 0 01 016 | 0 | 0 | 16 | Numeric | LEO sub-ID (optional) |
| 1–4 | Satellite data introducer | 3 10 022 | | | | | |
| 1 | <i>Satellite Identifier</i> | <i>0 01 007</i> | 0 | 0 | 10 | Code Table | LEO – See Table 8 |
| 2 | <i>Satellite instrument</i> | <i>0 02 019</i> | 0 | 0 | 11 | Code Table | e.g. 202 = GRAS – See Table 9 |
| 3 | <i>Originating centre</i> | <i>0 01 033</i> | 0 | 0 | 8 | Code Table | e.g. 94 = Copenhagen (DMI) – See Table 3 |
| 4 | <i>Product type</i> | <i>0 02 172</i> | 0 | 0 | 8 | Code Table | 2 = limb sounding |
| 5 | Software ID | 0 25 060 | 0 | 0 | 14 | Numeric | Uniquely defines processing algorithms used by org. centre |
| Time of occultation | | | | | | | |
| 6 | Time significance | 0 08 021 | 0 | 0 | 5 | Code Table | 17 = start of phenomenon 25 = nominal reporting time |
| 7–9 | Date | 3 01 011 | | | | | |
| 7 | <i>Year</i> | <i>0 04 001</i> | 0 | 0 | 12 | Year | 4-digit year |
| 8 | <i>Month</i> | <i>0 04 002</i> | 0 | 0 | 4 | Month | |
| 9 | <i>Day</i> | <i>0 04 003</i> | 0 | 0 | 6 | Day | |
| 10–11 | Time | 3 01 012 | | | | | |
| 10 | <i>Hour</i> | <i>0 04 004</i> | 0 | 0 | 5 | Hour | |
| 11 | <i>Minute</i> | <i>0 04 005</i> | 0 | 0 | 6 | Minute | |
| | Change Table B bit width | 2 01 138 | | | | | Add 10 to bit width |
| | Change Table B scale | 2 02 131 | | | | | Add 3 to scale |
| 12 | Second | 0 04 006 | (3) 0 | 0 | (16) 6 | Second | 0.000 – 59.999s to 1ms |
| | Change scale to Table B | 2 02 000 | | | | | |
| | Change width to Table B | 2 01 000 | | | | | |
| RO summary quality information | | | | | | | |
| 13 | Quality flags for RO Data | 0 33 039 | 0 | 0 | 16 | Flag table | See Table 10 |
| 14 | Percent confidence | 0 33 007 | 0 | 0 | 7 | % | 0 = bad, 100 = good |
| LEO & GNSS POD | | | | | | | |
| 15–17 | Location of Platform (see Note 10) | 3 04 030 | | | | | LEO, to 1cm |
| 15 | <i>Distance from Earth's centre in direction 0° longitude</i> | <i>0 27 031</i> | 2 | -1073741824 | 31 | Metres | (X) |
| 16 | <i>Distance from Earth's centre in direction 90° east longitude</i> | <i>0 28 031</i> | 2 | -1073741824 | 31 | Metres | (Y) |
| 17 | <i>Distance from Earth's centre in direction of North Pole</i> | <i>0 10 031</i> | 2 | -1073741824 | 31 | Metres | (Z) |
| 18–20 | Velocity of Platform (see Note 10) | 3 04 031 | | | | | LEO, to 10mm.s ⁻¹ |
| 18 | <i>Absolute platform velocity – first component.</i> | <i>0 01 041</i> | 5 | -1073741824 | 31 | Metres per second | (X) |
| 19 | <i>Absolute platform velocity – second component.</i> | <i>0 01 042</i> | 5 | -1073741824 | 31 | Metres per second | (Y) |
| 20 | <i>Absolute platform velocity – third component.</i> | <i>0 01 043</i> | 5 | -1073741824 | 31 | Metres per second | (Z) |
| 21 | Satellite Classification | 0 02 020 | 0 | 0 | 9 | Code Table | GNSS series, e.g. 401=GPS – See Table 7 |
| 22 | Platform Transmitter ID | 0 01 050 | 0 | 0 | 17 | Numeric | PRN or similar |
| | Change Table B scale | 2 02 127 | | | | | Subtract 1 from scale |
| 23–25 | Location of Platform (see Note 10) | 3 04 030 | | | | | GNSS, to 10cm |
| 23 | <i>Distance from Earth's centre in direction 0° longitude</i> | <i>0 27 031</i> | (1) 2 | -1073741824 | 31 | Metres | (X) |
| 24 | <i>Distance from Earth's centre in direction 90° east longitude</i> | <i>0 28 031</i> | (1) 2 | -1073741824 | 31 | Metres | (Y) |


| Data Field | Element Name | Descrip. | Table B Scale | Table B Ref. Val. | Table B Width | Units | Comments |
|--|--|-----------------|---------------|-------------------|----------------|-----------------------|--|
| 25 | Distance from Earth's centre in direction of North Pole | 0 10 031 | (1) 2 | -1073741824 | 31 | Metres (Z) | |
| | Change scale to Table B | 2 02 000 | | | | | |
| 26–28 | Velocity of Platform (see Note 10) | 3 04 031 | | | | | GNSS, to 10mm.s ⁻¹ |
| 26 | Absolute platform velocity – first component. | 0 01 041 | 5 | -1073741824 | 31 | Metres per second (X) | |
| 27 | Absolute platform velocity – second component. | 0 01 042 | 5 | -1073741824 | 31 | Metres per second (Y) | |
| 28 | Absolute platform velocity – third component. | 0 01 043 | 5 | -1073741824 | 31 | Metres per second (Z) | |
| Local Earth parameters | | | | | | | |
| | Change Table B bit width | 2 01 133 | | | | | Add 5 to bit width |
| | Change Table B scale | 2 02 131 | | | | | Add 3 to scale |
| 29 | Time increment (since time significance) | 0 04 016 | (3) 0 | -4096 | (18) 13 | Second | 0–240s to 1ms |
| | Change scale to Table B | 2 02 000 | | | | | |
| | Change width to Table B | 2 01 000 | | | | | |
| 30–31 | Location (high accuracy) | 3 01 021 | | | | | |
| 30 | Latitude | 0 05 001 | 5 | -9000000 | 25 | Degrees | to 10 ⁻⁵ deg (~1m) wrt WGS-84 |
| 31 | Longitude | 0 06 001 | 5 | -18000000 | 26 | Degrees | to 10 ⁻⁵ deg (~1m) wrt WGS-84 |
| 32–34 | Location of point | 3 04 030 | | | | | (X, Y, Z) centre of curvature to 1cm |
| 32 | Distance from Earth's centre in direction 0° longitude | 0 27 031 | 2 | -1073741824 | 31 | Metres (X) | |
| 33 | Distance from Earth's centre in direction 90° east longitude | 0 28 031 | 2 | -1073741824 | 31 | Metres (Y) | |
| 34 | Distance from Earth's centre in direction of North pole | 0 10 031 | 2 | -1073741824 | 31 | Metres (Z) | |
| 35 | Earth's local radius of curvature | 0 10 035 | 1 | 62 000 000 | 22 | Metres | RoC of WGS-84 ellipsoid. 6200–6600 km to 10cm |
| 36 | Bearing or azimuth | 0 05 021 | 2 | 0 | 16 | Deg. True | GNSS-to-LEO line of sight |
| 37 | Geoid undulation | 0 10 036 | 2 | -15 000 | 15 | Metres | EGM-96 geoid height above WGS-84 ellipsoid. ±150m to 1cm |
| RO 'Step 1b' data (see Notes 2 & 5) | | | | | | | |
| | Delayed replication | 1 13 000 | | | | | Delayed replication of next 13 descriptors |
| 38 | Replication factor | 0 31 002 | 0 | 0 | 16 | Numeric | Number of Step 1b samples, <i>n1</i> |
| 39–40 | Location (high accuracy) | 3 01 021 | | | | | |
| 39 | Latitude | 0 05 001 | 5 | -9000000 | 25 | Degrees | to 10 ⁻⁵ deg (~1m) wrt WGS-84 |
| 40 | Longitude | 0 06 001 | 5 | -18000000 | 26 | Degrees | to 10 ⁻⁵ deg (~1m) wrt WGS-84 |
| 41 | Bearing or azimuth | 0 05 021 | 2 | 0 | 16 | Deg. True | GNSS-to-LEO line of sight |
| | Delayed Replication | 1 08 000 | | | | | Delayed replication of next 8 descriptors |
| 42 | Replication factor | 0 31 001 | 0 | 0 | 8 | Numeric | Number of frequencies, <i>n0</i> |
| 43 | Mean Frequency | 0 02 121 | -8 | 0 | 7 | Hz | E.g. L1 = 1.5 GHz, L2 = 1.2 GHz, Corrected = 0 |
| 44 | Impact Parameter | 0 07 040 | 1 | 62 000 000 | 22 | Metres | 6200–6600 km to 10cm (distance from centre of curvature) |
| 45 | Bending Angle | 0 15 037 | 8 | -100 000 | 23 | Radians | -10⁻³ – 8x10⁻² rad to 10⁻⁸ rad |
| 46 | First order statistics | 0 08 023 | 0 | 0 | 6 | Code Table | 13 = RMS |
| | Change Table B bit width | 2 01 125 | | | | | Subtract 3 from bit width |
| 47 | (Error in) bending angle | 0 15 037 | 8 | -100 000 | (20) 23 | Radians | 0 – 8x10⁻³ rad to 10⁻⁸ rad |
| | Change width to Table B | 2 01 000 | | | | | |
| 48 | First order statistics | 0 08 023 | 0 | 0 | 6 | Code Table | Missing = off |
| | <i>N0</i> (end delayed replication) | | | | | | <i>N0</i> = 42+6. <i>n0</i> elements |
| <i>N0</i> +1 | Percent confidence | 0 33 007 | 0 | 0 | 7 | % | 0 = bad, 100 = good |
| | <i>N1</i> (end delayed replication) | | | | | | <i>N1</i> = 38+(5+6. <i>n0</i>). <i>n1</i> elements |
| RO 'Step 2a' data (see Notes 3–5) | | | | | | | |

| Data Field | Element Name | Descrip. | Table B Scale | Table B Ref. Val. | Table B Width | Units | Comments |
|--|---|-----------------|---------------|-------------------|----------------|---------------------|---|
| | <i>Delayed replication</i> | 1 08 000 | | | | | Delayed replication of next 8 descriptors |
| N1+1 | Replication factor | 0 31 002 | 0 | 0 | 16 | Numeric | Number of Step 2a samples, <i>n2</i> |
| N1+2 | Height | 0 07 007 | 0 | -1 000 | 17 | metres | Geometric altitude, -1km to 100km, wrt EGM-96 geoid (MSL) |
| N1+3 | Atmospheric refractivity | 0 15 036 | 3 | 0 | 19 | N-units | 0 – 500, to 10⁻³ N-units |
| N1+4 | First order statistics | 0 08 023 | 0 | 0 | 6 | Code Table | 13 = RMS |
| | Change Table B bit width | 2 01 123 | | | | | Subtract 5 from bit width |
| N1+5 | (Error in) refractivity | 0 15 036 | 3 | 0 | (14) 19 | N-units | 0 – 10, to 10⁻³ N-units |
| | Change width to Table B | 2 01 000 | | | | | |
| N1+6 | First order statistics | 0 08 023 | 0 | 0 | 6 | Code Table | Missing = off |
| N1+7 | Percent confidence | 0 33 007 | 0 | 0 | 7 | % | 0 = bad, 100 = good |
| | <i>N2 (end delayed replication)</i> | | | | | | <i>N2 = N1+1+6.n2 elements</i> |
| RO 'Level2b' data (see Notes 3–5) | | | | | | | |
| | <i>Delayed replication</i> | 1 16 000 | | | | | Delayed replication of next 16 descriptors |
| N2+1 | Replication factor | 0 31 002 | 0 | 0 | 16 | Numeric | Number of Step 2b samples, <i>n3</i> |
| N2+2 | Geopotential height | 0 07 009 | 0 | -1 000 | 17 | gpm | Geopot. altitude, -1km to 100km, wrt EGM-96 geoid (MSL) |
| N2+3 | Pressure | 0 10 004 | -1 | 0 | 14 | Pa | 0.1 – 1100 hPa to 0.1 hPa |
| N2+4 | Temperature | 0 12 001 | 1 | 0 | 12 | K | 150 – 350K to 0.1 K |
| N2+5 | Specific humidity | 0 13 001 | 5 | 0 | 14 | kg.kg ⁻¹ | 0 – 50 g.kg ⁻¹ to 0.01 g.kg ⁻¹ |
| N2+6 | First order statistics | 0 08 023 | 0 | 0 | 6 | Code Table | 13 = RMS |
| | Change Table B bit width | 2 01 120 | | | | | Subtract 8 from bit width |
| N2+7 | (Error in) pressure | 0 10 004 | -1 | 0 | (6) 14 | Pa | 0 – 5 hPa to 0.1 hPa |
| | Change width to Table B | 2 01 000 | | | | | |
| | Change Table B bit width | 2 01 122 | | | | | Subtract 6 from bit width |
| N2+8 | (Error in) temperature | 0 12 001 | 1 | 0 | (6) 12 | K | 0 – 5 K to 0.1 K |
| | Change width to Table B | 2 01 000 | | | | | |
| | Change Table B bit width | 2 01 123 | | | | | Subtract 5 from bit width |
| N2+9 | (Error in) specific humidity | 0 13 001 | 5 | 0 | (9) 14 | kg.kg ⁻¹ | 0 – 5 g.kg ⁻¹ to 0.01 g.kg ⁻¹ |
| | Change width to Table B | 2 01 000 | | | | | |
| N2+10 | First order statistics | 0 08 023 | 0 | 0 | 6 | Code Table | Missing = off |
| N2+11 | Percent confidence | 0 33 007 | 0 | 0 | 7 | % | 0 = bad, 100 = good |
| | <i>N3 (end delayed replication)</i> | | | | | | <i>N3 = N2+1+10.n3 elements</i> |
| RO 'Level2c' data | | | | | | | |
| N3+1 | Vertical significance | 0 08 003 | 0 | 0 | 6 | Code Table | 0 = surface |
| N3+2 | Geopotential height (of surface) | 0 07 009 | 0 | -1 000 | 17 | gpm | Geopot. ht of surface, -1km to 10km, wrt EGM-96 geoid (MSL) |
| N3+3 | (Surface) Pressure | 0 10 004 | -1 | 0 | 14 | Pa | 250–1100 hPa to 0.1 hPa |
| N3+4 | First order statistics | 0 08 023 | 0 | 0 | 6 | Code Table | 13 = RMS |
| | Change Table B bit width | 2 01 120 | | | | | Subtract 8 from bit width |
| N3+5 | (Error in) (surface) pressure | 0 10 004 | -1 | 0 | (6) 14 | Pa | 0 – 5 hPa to 0.1 hPa |
| | Change width to Table B | 2 01 000 | | | | | |
| N3+6 | First order statistics | 0 08 023 | 0 | 0 | 6 | Code Table | Missing = off |
| N3+7 | Percent confidence | 0 33 007 | 0 | 0 | 7 | % | 0 = bad, 100 = good |
| | <i>N</i> | | | | | | <i>Total N = N3+7 elements</i> |

Bold (blue) entries indicate new or changed elements.

NOTES:

- Where parameter value ranges are given in the Comments column, these are the nominal User Requirements; the actual values allowed by the descriptor may be different. The quoted range is guaranteed to be encoded correctly. (E.g. surface pressure range is quoted as 250-1100 hPa, but the descriptor can encode any value between 0.0 and 1638.2 hPa)
- For GTS dissemination, Step 1b data would be sampled, interpolated and/or smoothed to a smaller number of profile levels (for GRAS, 247 fixed levels from near surface to 60 km) (*n1* samples; typically 200–300). There should be a minimum of one pair of impact parameter and bending angles per sample (*n0* ≥ 1), representing ionosphere-corrected values (when mean frequency is set to zero); sets for GPS L1 and L2 signals may also be present, and the delayed replication mechanism could in principle be used to include sets derived from additional (future) frequencies.

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- 3) For GTS dissemination, Step 2a data would be sampled, interpolated and/or smoothed to a smaller number of profile levels (for GRAS, 247 fixed levels from near surface to 60 km) (n_2 samples; typically 100–300). Depending on the processing algorithms, Step 2a profiles may or may not be on the same height grid as Step 1b.
- 4) Step 2b data are sampled, interpolated and/or smoothed to a smaller number of profile levels (nominally surface to 60 km with an average spacing of 1 km) (n_3 samples; typically 50–150). For 1D-VAR retrievals, the levels would usually be those of the *a priori* background, but could be on the same height grid as the Step 2a profile.
- 5) All profile data should be ordered in increasing altitude, whether the original occultation was ascending or descending.
- 6) A Step 2 profile can be assumed to be vertical and at the nominal time and surface location of the given local radius of curvature co-ordinates. Alternatively, the height information can be converted to impact parameter, then Step 1b latitudes & longitudes can be interpolated to the Step 2 samples to give slant profiles.
- 7) The total number of data elements is $47 + n_1 \times (5 + n_0 \times 6) + n_2 \times 6 + n_3 \times 10$, not counting the optional satellite sub-identifier. For a nominal message containing 200 Step 1b (L1+L2+Corrected) and 150 Step 2a and 100 Step 2b profile samples, this would total 6547 elements.
- 8) A single BUFR message contains one (uncompressed) occultation; each message is 11,338 bytes long for a nominal message containing 200 Step 1b (L1+L2+Corrected), 150 Step 2a and 100 Step 2b profile samples. Indicative message lengths for other combinations of samples are shown in Table 12.
- 9) RO instruments can typically produce up to about 500 occultations (BUFR messages) per day per satellite; hence the maximum RO data volume in BUFR would be of the order of 7 Mbytes per day per receiver.
- 10) The components of satellite location and absolute satellite velocity are defined in an Earth-centered inertial frame at the nominal time with the following orientation:
 - (X) First component: along the line from the Earth's centre to 0° longitude at the Equator.
 - (Y) Second component: along the line from the Earth's centre to 90° east longitude at the Equator.
 - (Z) Third component: along the line from the Earth's centre to the North Pole.
 See also the WMO FM 94 BUFR Table B document, class 01, footnote (6), and BUFR descriptors 0 27 031, 0 28 031 and 0 10 031.

4.5.1 New Satellite and Instrument Codes

New GNSS- and RO-specific satellite and instrument codes have been defined and are included in the BUFR Code/Flag tables – see Table 7, Table 8 and Table 9 respectively.

Table 7. Satellite Classification (Code Table 002020)

| Descriptor | Value | Meaning |
|------------|-------|--|
| 0 02 020 | 401 | GPS |
| | 402 | GLONASS |
| | 403 | GALILEO |
| | 404 | BDS (BeiDou navigation satellite system) |

Table 8. GNSS RO Satellite Identifier (Common Code Table C–5)

| Descriptor | Value | Name | Value | Name |
|-----------------|-------|------------------------|-------|--------------------|
| 0 01 007 | 3 | Metop-1 (Metop-B) | 740 | COSMIC-1 |
| | 4 | Metop-2 (Metop-A) | 741 | COSMIC-2 |
| | 5 | Metop-3 (Metop-C) | 742 | COSMIC-3 |
| | 40 | Ørsted (or Oersted) | 743 | COSMIC-4 |
| | 41 | CHAMP | 744 | COSMIC-5 |
| | 42 | TerraSAR-X | 745 | COSMIC-6 |
| | 43 | TanDEM-X | 750 | COSMIC-2 E1 |
| | 44 | PAZ | 751 | COSMIC-2 E2 |
| | 66 | Sentinel-6A | 752 | COSMIC-2 E3 |
| | 67 | Sentinel-6B | 753 | COSMIC-2 E4 |
| | 265 | GeoOptics CICERO OP1 | 754 | COSMIC-2 E5 |
| | 266 | GeoOptics CICERO OP2 | 755 | COSMIC-2 E6 |
| | 267 | PlanetIQ GNOMES-A | 786 | C/NOFS |
| | 268 | PlanetIQ GNOMES-B | 800 | SUNSAT |
| | 269 | Spire Lemur 3U CubeSat | 803 | GRACE C (GRACE-FO) |
| | 421 | Oceansat-2 | 804 | GRACE D (GRACE-FO) |
| | 440 | Megha-Tropiques | 820 | SAC-C |
| | 522 | FY-3C | 825 | KOMPSAT-5 |
| | 523 | FY-3D | | |
| | 722 | GRACE A | | |
| | 723 | GRACE B | | |


Table 9. GNSS RO Satellite Instrument Identifier (Common Code Table C–8)

| Descriptor | Value | Type/longname (shortname) |
|-----------------|-------|--|
| 0 02 019 | 98 | Atmospheric temperature and humidity sounder (GPS receiver) |
| | 102 | GPS turborogue space receiver (TRSR) (CHAMP GPS sounder) |
| | 103 | Integrated GPS and Occultation Receiver (IGOR) |
| | 104 | Triple-G (GPS, Galileo, GLONASS) (Tri-G) |
| | 202 | GNSS receiver for atmospheric sounding (GRAS) |
| | 287 | Radio Occultation Sounder of the Atmosphere (ROSA) |
| | 351 | GPS demonstration receiver (GPSDR) |
| | 526 | GeoOptics Cion GNSS occultation receiver A (Cion-A) |
| | 527 | GeoOptics Cion GNSS occultation receiver B (Cion-B) |
| | 528 | GeoOptics Cion GNSS occultation receiver C (Cion-C) |
| | 529 | GeoOptics Cion GNSS occultation receiver D (Cion-D) |
| | 530 | Spire global navigation satellite system occultation sounder A (SGNOS-A) |
| | 531 | Spire global navigation satellite system occultation sounder B (SGNOS-B) |
| | 532 | Spire global navigation satellite system occultation sounder C (SGNOS-C) |
| | 533 | Spire global navigation satellite system occultation sounder D (SGNOS-D) |
| | 534 | PlanetIQ Pyxis GNSS occultation receiver A (Pyxis-A) |
| | 535 | PlanetIQ Pyxis GNSS occultation receiver B (Pyxis-B) |
| | 948 | Global positioning system occultation sensor (GPSOS) |
| | 958 | Global navigation satellite system occultation sounder (GNOS) |

4.5.2 Quality Flags

The BUFR Quality Flags for RO (descriptor **0 33 039**, see Table 10) are defined as generically as possible so as to be mission and processing algorithm independent. The general philosophy is that if a bit is clear (unset or zero) this is 'normal', and if set (unity) then 'not normal'; note that the latter condition does not necessarily imply poor data. We retain some spare 'reserved' bits for future quality information. Note that BUFR defines the order of bit flags as 'left to right' (i.e. the order that bits are transmitted). *This convention is the opposite of that used for most computer definitions, where bit 1 (or bit 0) is 'rightmost' or least significant bit.*

Note that bit 1 is a summary bit and should be set if one or more certain other bits are set, and clear if all of those other bits are clear.

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Ultimately, the exact reason for the setting of these flag bits is algorithm-dependent, and therefore need to be defined and published by the processing centre in association with the unique combination of Originating (processing) Centre and Software ID parameters. It is for the user to take action (or not) on these flags in the light of experience.

Table 10. Quality Flags for RO Data (16-bit Flag Table)

| Descriptor | Bit | Meaning when clear | Meaning when set |
|-----------------|--------|-----------------------------------|---------------------------------------|
| 0 33 039 | 1 | Nominal quality | Non-nominal quality |
| | 2 | NRT product | Offline product |
| | 3 | Descending occultation | Ascending occultation |
| | 4 | Excess Phase processing nominal | Excess Phase processing non-nominal |
| | 5 | Bending Angle processing nominal | Bending Angle processing non-nominal |
| | 6 | Refractivity processing nominal | Refractivity processing non-nominal |
| | 7 | Meteorological processing nominal | Meteorological processing non-nominal |
| | 8 | Closed loop data only used | Open loop data included |
| | 9 | No surface reflections detected | Surface reflections detected |
| | 10 | L2P GNSS signals used | L2C GNSS signals used |
| | 11–13 | Reserved | Reserved |
| | 14 | Background profile nominal | Background profile non-nominal |
| | 15 | Retrieved profile | Background profile |
| | All 16 | As above | Missing |

4.5.3 Quality parameter

We have included in the RO BUFR the parameter ‘Percentage Confidence’. The meaning of this parameter depends on the context and to a large degree on the specific processing algorithms used (and hence its derivation has to be defined by the data processing centre), but we may give some guidance as to the intent.

At a user-level, ‘Percentage Confidence’ (PC) can be used as a first indicator of whether a particular datum point is likely to be useful. In NWP, the concept of ‘probability of gross error’ is often used for quality control in variational assimilation systems. The objective is to reject observations with extreme errors, particularly if they do not lie within the normal (assumed) Gaussian error distribution.

In the simplest case, PC could be derived from the estimated error(s) in the associated ‘observed’ parameter. Assuming an estimated observed error variance O and an *a priori* variance E , then

$$PC = 100 \exp(-O/E)$$

would be a suitable value. Errors for several observables may be combined to form an overall scaled probability value.

Other PC values might be derived from other Q/C information – for instance the PC for bending angles might be nominally derived as above, but assigned a lower value (even zero) if loss-of-lock (freewheeling) condition is detected. In this case, the observables may have apparently sensible values but there is little or no confidence in them. The end-user can then make the decision on whether to use such data or not. If no useful PC value is available, it should be just set to 100. Conversely, if the data it applies to is known to be unusable, but not actually set to ‘missing’, then PC should be set to zero.

4.6 BUFR Section 5 (End of Message)

This section flags the end-of-message, with the delimiter shown in Table 11. If the message has been encoded correctly, the delimiter occupies the last 4 octets of the total message length indicated in

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Section 0. Further, the total message length should also be equal to the sum of the lengths of the individual sections (as given in Sections 1–4, plus 8 octets for Section 0 and 4 octets for Section 5).

Table 11. BUFR Section 5 (End of Message)

| Octet number | Contents | Value for RO |
|--------------|--|--------------|
| 1–4 | 7777 (coded in CCITT International Alphabet No. 5) | '7777' |

4.7 Indicative BUFR Message Lengths

As noted previously, the length of BUFR-compressed observations cannot be pre-determined, but since RO data is encoded as a single profile per BUFR message, and therefore compression cannot be applied, it is possible to sum up the Table B bit-widths (see Table 6) for any given combination of L1+L2+Lc frequencies and number of samples in the profile per Stage. Some examples are given in Table 12.

Table 12. Indicative BUFR message lengths

| L1+L2? | No. Step 1b samples | No. Step 2a samples | No. Step 2b samples | Message Length (Kbytes) ¹¹ |
|--------|---------------------|---------------------|---------------------|---------------------------------------|
| Y | 247 | 247 | 82 | 13.6 ¹² |
| N | 300 | 300 | 200 | 11.4 ¹³ |
| N | 247 | 247 | 247 | 10.4 ¹⁴ |
| Y | 300 | 300 | 300 | 19.4 |
| Y | 300 | 200 | 100 | 16.1 |
| Y | 200 | 200 | 200 | 13.0 |
| Y | 200 | 150 | 100 | 11.3 |
| Y | 300 | 0 | 0 | 13.0 |
| N | 0 | 300 | 300 | 6.6 |

¹¹ Maximum bulletin length on GTS up to 4 November 2007 was 15,000 bytes. It is now 500,000 bytes so in principle, higher resolution profiles can be transmitted.

¹² Nominal ROM SAF NRT product (e.g. Metop-B)

¹³ Nominal UCAR NRT product (e.g. COSMIC-2)

¹⁴ Nominal GFZ NRT product (e.g. TerraSAR-X, TanDEM-X)

5. GTS dissemination

A 'naked' BUFR message alone cannot be transmitted on the GTS; some standard headers need to be added so that messages can be routed as required.

The WMO 'Abbreviated Routing Header' (ARH) [RD.6] allows GTS nodes to route messages (e.g. data in SYNOP, BUFR or GRIB code forms) – or to accept messages for broadcast topologies – in a table-driven way without knowing the messages' data contents. The ARH is a set of characters from the International Alphabet No. 5 (CCITT-IA5 - equivalent to ASCII) and takes the form:

`<SOH><CR><CR><LF>n n n<CR><CR><LF>T1T2A1A2i i<SP>c c c c<SP>Y Y G G g g<CR><CR><LF>`

This sequence is followed by the BUFR message ('BUFR'...'7777') and finally the end-of-message trailer sequence:

`<CR><CR><LF><ETX>`

The header, message and trailer are collectively known as a bulletin. A bulletin may contain more than one message, but typically contains only one, which will be the case for RO data. There may be additional characters before the routing header appropriate to particular GTS transmission protocols, such as TCP/IP (FTP), the description of which is beyond the scope of this document. In any case, these 'wrapper' characters are not part of the GTS transmission and are not seen by end-users.

The elements of the WMO header & trailer are described in Table 13, along with reserved settings for RO messages. For more details of the possible values for these elements, see [RD.6].

5.1 Channel Sequence Number

The `n n n` element is a sequential three-digit number in the range 001 to 999, normally generated by the encoder or routing node. Its purpose is two-fold:

1. it allows possibly missing bulletins to be identified and re-requested; and
2. it allows bulletins to be re-ordered if data has to be split between bulletins and needs to be merged back (GTS does not guarantee reception in any particular order of sending).

5.2 Geographic Area Designator

When `T1` is `I` (see Table 13), the `A2` element is a Geographical Area Designator (letter code) identifying the regional location of the data in the bulletin. These location codes (from Table C3 in [RD.6]) are shown in Table 14 and can be used by routing nodes to filter bulletins by broad region without having to decode the BUFR.

For RO data, the appropriate letter is generated from the values of latitude and longitude at the nominal tangent point of the profile. For global coverage radio occultation data, this code letter may take any valid codes from `A` to `I` inclusive; the other codes are not used.

5.3 Data Identifier

The *ii* field is a 2-character data identifier which should make the $T_1T_2A_1A_2ii\ cccc$ part of the ARH unique. For RO, this was chosen to be **14**, denoting GNSS data¹⁵.

Table 13. WMO Bulletin Routing Header/Trailer elements

| Field ID | Description | Value for RO | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---------------|--|--|--------|-----------|----|--------|--------|----|--------|------------|----|--------|--------------------------|----|--------|-------------------------|----|--------|-------------------------|----|--------|-------------------------|----|--------|--------------------------|----|--------|---------|----|--------|-----------|----|--------|--------------------------|----|
| <SOH> | 'Start of Header' character: byte value = 1 decimal (01 hex) | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| <ETX> | 'End of Transmission' character: byte value = 3 decimal (03 hex) | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| <CR> | 'Carriage Return' character: byte value = 13 decimal (0D hex), | 13 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| <LF> | 'Line Feed' character: byte value = 10 decimal (0A hex) | 10 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| <SP> | 'Space' character: byte value = 32 decimal (20 hex) | space | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| <i>nnn</i> | 'Message sequence number' generated by the encoding or routing centre | '001'-'999' | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T_1 | Data Exchange format | 'I' = Observations in binary code | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| T_2 | Data Type | 'U' = Upper Air ['E' with EUMC/EUMP/EUMR] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A_1 | Data Sub-type | 'T' = Satellite-derived sonde ['G' with EUMC/EUMP/EUMR] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A_2 | Area Code (see Table 14) | 'A' – 'L' ['X' with EUMC/EUMP/EUMR] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| <i>ii</i> | Product type | '14' = (GNSS) ['01' with EUMC/EUMP/EUMR] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| <i>cccc</i> | Source of the message (ICAO Location Indicator) | Possible codes for RO include (but not limited to): <table border="1" data-bbox="813 1120 1378 1512"> <tbody> <tr> <td>'EDZW'</td> <td>Offenbach</td> <td>DE</td> </tr> <tr> <td>'EGRR'</td> <td>Exeter</td> <td>UK</td> </tr> <tr> <td>'EKMI'</td> <td>Copenhagen</td> <td>DK</td> </tr> <tr> <td>'KWBC'</td> <td>Washington¹⁶</td> <td>US</td> </tr> <tr> <td>'EUMC'</td> <td>Darmstadt¹⁷</td> <td>DE</td> </tr> <tr> <td>'EUMP'</td> <td>Darmstadt¹⁸</td> <td>DE</td> </tr> <tr> <td>'EUMR'</td> <td>Darmstadt¹⁹</td> <td>DE</td> </tr> <tr> <td>'KNES'</td> <td>Washington²⁰</td> <td>US</td> </tr> <tr> <td>'BAWX'</td> <td>Beijing</td> <td>CN</td> </tr> <tr> <td>'DEMS'</td> <td>New Delhi</td> <td>IN</td> </tr> <tr> <td>'KWNO'</td> <td>Washington²⁰</td> <td>US</td> </tr> </tbody> </table> | 'EDZW' | Offenbach | DE | 'EGRR' | Exeter | UK | 'EKMI' | Copenhagen | DK | 'KWBC' | Washington ¹⁶ | US | 'EUMC' | Darmstadt ¹⁷ | DE | 'EUMP' | Darmstadt ¹⁸ | DE | 'EUMR' | Darmstadt ¹⁹ | DE | 'KNES' | Washington ²⁰ | US | 'BAWX' | Beijing | CN | 'DEMS' | New Delhi | IN | 'KWNO' | Washington ²⁰ | US |
| 'EDZW' | Offenbach | DE | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 'EGRR' | Exeter | UK | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 'EKMI' | Copenhagen | DK | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 'KWBC' | Washington ¹⁶ | US | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 'EUMC' | Darmstadt ¹⁷ | DE | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 'EUMP' | Darmstadt ¹⁸ | DE | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 'EUMR' | Darmstadt ¹⁹ | DE | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 'KNES' | Washington ²⁰ | US | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 'BAWX' | Beijing | CN | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 'DEMS' | New Delhi | IN | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 'KWNO' | Washington ²⁰ | US | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| <i>YYGGgg</i> | Date/time of observation where:- <i>YY</i> = day of month (01-31) <i>GG</i> = hour (00-23) <i>gg</i> = minute (00-59) | Day & Time of first observation in BUFR message | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

¹⁵ *ii=14* is also used for ground-based GNSS bulletins, but with $T_1T_2A_1=ISX$. However, this value is not reserved for, or unique to, GNSS (The origins of this value derive from the EU COST Action 716: $7+1+6=14$).

¹⁶ In reality UCAR/CDAAC, Boulder, CO via NOAA/NWS

¹⁷ EUMETSAT, Metop-A – BUFR contains only Level 1b (Bending Angle) profiles

¹⁸ EUMETSAT, Metop-B – BUFR contains only Level 1b (Bending Angle) profiles

¹⁹ EUMETSAT, Metop-C – BUFR contains only Level 1b (Bending Angle) profiles

²⁰ NESDIS

Table 14. Geographical Area Designator (A2) codes

| | 0°W – 90°W | 90°W – 180°W | 180°E – 90°E | 90°E – 0°E | 45°W – 180°W |
|------------------------------|------------|--------------|--------------|------------|--------------|
| <i>NH</i> ²¹ | A | B | C | D | |
| <i>Tropics</i> ²¹ | E | F | G | H | |
| <i>SH</i> ²¹ | I | J | K | L | |
| <i>NH</i> ²² | <-----> | | N | -----> | |
| <i>SH</i> ²² | <-----> | | S | -----> | |
| <i>NH</i> ²² | | | | | T |
| <i>Global</i> ²² | <-----> | | X | -----> | |

5.4 ICAO Location Indicator

The cccc field is the ICAO Location Indicator [RD.12] of the originating centre. Table 13 shows the ICAO codes associated with some centres which may put RO bulletins onto the GTS.

5.5 Date and Time

For most GTS routing nodes, the date/time indicated by YYGGgg must be current or the data may be blocked or rejected. 'Current' is typically defined as not more than 24 hours old and not in the future by more than 10 minutes.

5.6 Current routing headers

Table 15 shows the fixed part of the ARHs for those headers in current use for RO bulletins. GTS nodes wanting to collect these headers should contact the appropriate source centre if these headers are not already being routed to them.

²¹ Here, NH means north of 30°N, SH means south of 30°S and Tropics means everywhere else.

²² Here, NH means north of the equator, SH means south of the equator and Global means unspecified latitude.

Table 15. Summary of ARHs for RO data on the GTS

| ARH | Mission | Source |
|------------------------|--|--|
| IUT [A-L] 14 EKMI | Metop-[A]/B/C / GRAS Spire PlanetiQ | DMI Copenhagen (ROM SAF) |
| IEGX01 EUMC | [Metop-A / GRAS] | EUMETSAT HQ (Darmstadt) |
| IEGX01 EUMP | Metop-B / GRAS | EUMETSAT HQ (Darmstadt) |
| IEGX01 EUMR | Metop-C / GRAS | EUMETSAT HQ (Darmstadt) |
| IUT [A-LNS] 14 EUMS | Spire PlanetiQ | EUMETSAT HQ (Darmstadt) |
| IUT [A-L] 14 KWBC | [COSMIC (1-6)] COSMIC-2 (E1-E6) [C/NOFS] [SAC-C] | UCAR Boulder (via GTS node NESDIS, Washington) |
| IUT [A-L] 14 KNES | KOMPSAT-5 | UCAR Boulder (via GTS node NESDIS, Washington) |
| IUT [A-L] 14 KWSS | Spire | UCAR Boulder (via GTS node NESDIS, Washington) |
| IUT [A-L] 14 KWSP | PlanetiQ | UCAR Boulder (via GTS node NESDIS, Washington) |
| IUT [A-L] 14 EDZW | [CHAMP] [GRACE-A/B] GRACE-C/D (GRACE-FO) TerraSAR-X TanDEM-X | GFZ Potsdam (via GTS node DWD, Offenbach) |
| IUT [A-L] 14 BAWX | FY-3C/D / GNOS | CMA Beijing |
| IUT [A-L] 14 DEMS | [Megha-Tropiques / ROSA] | ISRO New Delhi |
| IUT [A-L] 14 KWNO | PAZ / ROHPP | UCAR Boulder (via GTS node NESDIS, Washington) |
| IPX [A-B] 0 [1-2] KWBC | Sentinel-6A/B from primary (1) or backup (2) processor | NASA/JPL (via NOAA) |

[Missions in square brackets are no longer active]

6. Software Applications

Software applications for BUFR encoding and decoding of this data type have been developed in the Met Office as part of the ROM SAF software deliverable 'Radio Occultation Processing Package' (ROPP) (see for instance [RD.7]).

The ROPP encoder tool `ropp2bufr`:

- reads one or more ROPP netCDF files each containing one or more profiles,
- pre-processes the occultation data to BUFR standards,
- calls a generic kernel encoder library
- outputs the resulting BUFR bit string(s), with optional ARH, to a file

The ROPP decoder tool `bufr2ropp`:

- reads a BUFR data file containing any number of arbitrary messages or complete bulletins,
- rejects non-RO messages
- calls a generic kernel decoder library
- post-processes the occultation data to ROPP standards,
- outputs the resulting ROPP data to one or more netCDF files

These tools have several command-line options to control the process. They are implemented in Fortran 95 and use ROPP libraries and third-party packages (such as netCDF from Unidata and BUFR from the Met Office or ECMWF).

The ROPP encoder and its companion decoder have been validated on a range of compilers and platforms, using a variety of operational RO data streams. For more details see [RD.7] and [RD.14].

The ROPP encoder is being used by the ROM SAF to generate Level 2 NRT products in BUFR and is also used by GFZ to encode TerraSAR-X and TanDEM-X RO data in NRT. We note that NRT RO data from the CHAMP (processed by GFZ) and SAC-C (processed by UCAR) missions – now both terminated – were also encoded using this software.

RO data processing centres are encouraged to implement the ROPP encoder, in order to encode the BUFR locally and then disseminate both their own format (e.g. as netCDF [RD8] or text-based files) and BUFR files in parallel (to different users and possibly by different methods, depending on user requirements). BUFR is the only approved format for the dissemination of RO data via the GTS.

The ROPP software may be obtained via the ROM SAF website [RD.13]. The package is cost-free and fully supported, but users are required to register and agree to a simple license under EUMETSAT Data Policy for SAF deliverables.