WMO FM94 (BUFR) Specification For Radio Occultation Data

Version 2.5

30 June 2019

ROM SAF Consortium
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European Centre for Medium-Range Weather Forecasts (ECMWF)
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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	14/112008	DO	**Version for ROPP-2 (v2.0)**
2.1	19/05/2011	DO	• 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	• Change branding (name & logos) from *GRAS SAF* to *ROM SAF* • 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	• Inserted new ROM SAF document standard text on page 3 & Section 1.5 • 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 **Version for ROPP-7 (v7.0)**

2.4	1/12/2016	DO	• 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 apporved code for GPSOS (was provisional) • Updated Tables 12 & 14 with actual ARHs from EUMETSAT (was provisional) • Minor editorial changes to body text **Version for ROPP-9 (v9.0)**
2.5	30/06/2019	IC	• 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. **Version for ROPP-9 (v9.1)**

ROM SAF

The Radio Occultation Meteorology Satellite Application Facility (ROM SAF) is a decentralised processing centre under EUMETSAT which is responsible for operational processing of GRAS radio occultation (RO) data from the Metop satellites and radio occultation data from other missions. The ROM SAF delivers bending angle, refractivity, temperature, pressure, humidity, and other geophysical variables in near real-time for NWP users, as well as reprocessed Climate Data Records (CDRs) and Interim Climate Data Records (ICDRs) for users requiring a higher degree of homogeneity of the RO data sets. The CDRs and ICDRs are further processed into globally gridded monthly-mean data for use in climate monitoring and climate science applications.

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

The ROM SAF Leading Entity is the Danish Meteorological Institute (DMI), with Cooperating Entities: (i) European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading, United Kingdom; (ii) Institut D'Estudis Espacials de Catalunya (IEEC) in Barcelona, Spain; and (iii) Met Office in Exeter, United Kingdom. To get access to our products or to read more about the ROM SAF please go to: http://www.romsaf.org

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List of Contents

List of Figures

List of Tables

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.

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.

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-3 Proposal: Proposal for the Third Continuous Development and Operations Phase (CDOP-3); Ref: SAF/ROM/DMI/MGT/CDOP3/001 Version 1.2 of 31 March 2016, Ref: EUM/C/85/16/DOC/15, approved by the EUMETSAT Council at its 85th meeting on 28-29 June 2016

[AD.2] CDOP-3 Cooperation Agreement: Agreement between EUMETSAT and DMI on the Third Continuous Development and Operations Phase (CDOP-3) of the Radio Occultation Meteorology Satellite Applications Facility (ROM SAF), Ref. EUM/C/85/16/DOC/19, approved by the EUMETSAT Council and signed at its 86th meeting on 7 December 2016

[AD.3] ROM SAF Product Requirements Document, Ref: SAF/ROM/DMI/MGT/PRD/001

[AD.4] ROM SAF Service Specifications, Ref: SAF/ROM/DMI/RQ/SESP/001

[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 Cod*es. WMO-306, Vol. 1.2, Part B. Copy available via link at: http://www.wmo.int/pages/prog/www/WMOCodes/WMO306_vI2/VolumeI.2.html

[RD.5] WMO. Documentation on recent, current and upcoming operational BUFR tables is available from the WMO web site at: http://www.wmo.int/pages/prog/www/WMOCodes/WMO306_vI2/LatestVERSION/LatestVERSION.html

[RD.6] WMO (2009). *Manual on the Global Telecommunications System*. WMO-386, Vol.1, Part II, Attachment II-5 (Data Designators $T_1T_2A_1A_2$ii in Abbreviated Headings), 2009. WMO, Geneva. ISBN: 978-92-63-10386-4. Latest (2011) version available for purchase via link at: http://www.wmo.int/e-catalog/detail_en.php?PUB_ID=498&SORT=N&q=

[RD.7] ROPP_IO 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 (2013) *BUFR encoding/decoding software*: https://software.ecmwf.int/wiki/display/BUFR

[RD.12] Cygwin website http://www.cygwin.com

[RD.13] ROM SAF website http://www.romsaf.org

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 (Metop)
GRIB	GRIdded Binary (WMO)
GSN	Ground Support Network
GTS	Global Telecommunications System (WMO)
ICDR	Interim Climate Data Record
ISRO	Indian Space Research Organisation
KMA	Korean Meteorological Agency
KOMPSAT-5	GNSS radio occultation receiver (KMA)
Megha-Tropiques	Tropical water cycle (and RO) experiment (India/France)
MetDB	Meteorological Data Base (Met Office)
Metop	METeorological Operational satellite (EUMETSAT)
netCDF	network Common Data Form (Unidata)
NMS	National Meteorological Service
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)
VAR	Variational (NWP data assimilation technique)
WMO	World Meteorological Organisation
WWW	World Weather Watch (WMO Programme)

1.4 Definitions, levels and types

RO data products from the GRAS instrument onboard Metop and RO data from other missions are grouped in data levels (level 0, 1, 2, or 3) and product types (NRT, Offline, CDR, or ICDR). The data levels and product types are defined below.[2] The lists of variables should not be considered as the complete contents of a given data level, and not all data may be contained in a given data level.

Data levels:

Level 0: Raw sounding, tracking and ancillary data, and other GNSS data before clock correction and reconstruction;

Level 1A: Reconstructed full resolution excess phases, total phases, pseudo ranges, SNR's, orbit information, I, Q values, NCO (carrier) phases, navigation bits, and quality information;

Level 1B: Bending angles and impact parameters, tangent point location, and quality information;

Level 2: Refractivity, geopotential height, "dry" temperature profiles (level 2A), pressure, temperature, specific humidity profiles (level 2B), surface pressure, tropopause height, planetary boundary layer height (level 2C), ECMWF model level coefficients (level 2D); quality information;

Level 3: Gridded or resampled data, that are processed from level 1 or 2 data, and that are provided as, e.g., daily, monthly, or seasonal means on a spatiotemporal grid, including metadata, uncertainties and quality information.

Product types:

NRT product: Data product delivered less than: (i) 3 hours after measurement (SAF Level 2 for EPS); (ii) 80 min after measurement (SAF Level 2 for EPS-SG Global Mission); (iii) 40 min after measurement (SAF Level 2 for EPS-SG Regional Mission).

Offline product: Data product delivered from less than 5 days to up to 6 months after measurement, depending on the requirements. The evolution of this type of product is driven by new scientific developments and subsequent product upgrades.

CDR: Climate Data Record generated from a dedicated reprocessing activity using a fixed set of processing software[3]. The data record covers an extended time period of several years (with a fixed end point) and constitutes a homogeneous data record appropriate for climate usage.

ICDR: An Interim Climate Data Record regularly extends in time a (Fundamental or Thematic) CDR using a system having optimum consistency with and lower latency than the system used to generate the CDR[4].

[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.

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 COSMIC, TerraSAR-X, TanDEM-X, FY-3C/D and Metop-A/B/C RO missions, and will also be used for future data from Megha-Tropiques, KOMPSAT-5, GRACE-FO (follow-on), PAZ, Jason-CS and Metop-SG. Data from terminated missions 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 interpreting[5] 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* ≥ 192) can be defined for temporary or internal use. Since there is no 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.

[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.

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) but a single bulletin of that size would be far too big for the GTS. By international agreement, as specified in [RD.6], single bulletins[7] 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.

[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^{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.

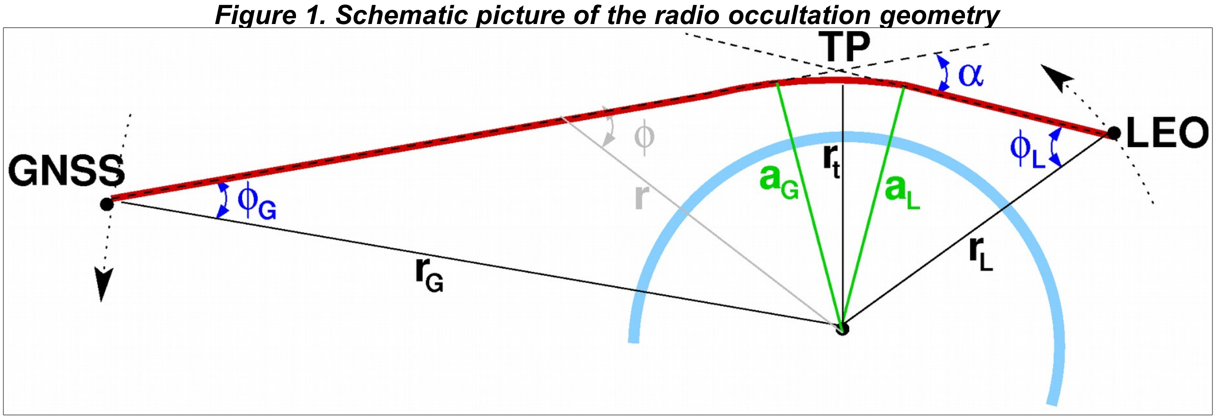
[7] A bulletin is the BUFR (or GRIB, CREX or other WMO format) message with a wrapper or ‘Abbreviated Routing Header’ containing coded information on the message content for GTS routing purposes. The ARH adds some 35 bytes to the BUFR message length – see Section 5.

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 vacuuo* straight line path between the satellites, the total integrated **bending angle** can be calculated.

Figure 1. Schematic picture of the radio occultation geometry



a	Impact parameter	***α***	Bending angle
r_t	Height of ray tangent point	**TP**	Tangent Point
GNSS	GNSS transmitter satellite	**LEO**	Low Earth Orbit receiver

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 11.

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:

- **EUMETSAT**, Darmstadt: 254, sub-centre 0, for GRAS data (Level 1b only);
- **DMI**, Copenhagen: 094, sub-centre 0, for GRAS data;
- **UCAR**, Boulder (via NWS, Washington): 060, sub-centre 0, for COSMIC and KOMPSAT-5;
- **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;
- **ISRO**, New Delhi: 028, sub-centre 0, for Megha-Tropiques data.

[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.*

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 254 = EUMETSAT
7–8	Centre Originating/Generating Sub-Centre (CCT C-12)	173 = GFZ 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]	12
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

[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.

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*). 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)

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 **[10–]**	Descriptor *Repeat 2-octets per descriptor* Total number of descriptors = (Section length - 7) / 2	51738 (**3** x 16384 + **10** x 256 + **26**)
[10]	Pad byte (set to 0) – optional for Edition 4	0 (if Section length = 10)

4.5 BUFR Section 4 (Data Template)

The WMO-approved and published BUFR template sequence definition for RO data is shown in Table 5. This is in the form of the Table D sequence of descriptors and their individual Table B specifications. 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 7, Table 8 and Table 9. 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 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.

[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 4 (Data Template)

Data Field	Element Name	Descrip.	Table B Scale	Table B Ref. Val.	Table B Width	Units	Comments
Radio Occultation header							
1–4	**Satellite data introducer**	**3 10 022**					
1	*Satellite Identifier*	*0 01 007*	0	0	10	Code Table	LEO – **See Table 7**
2	*Satellite instrument*	*0 02 019*	0	0	11	Code Table	e.g. 202 = GRAS – **See Table 8**
3	*Originating centre*	*0 01 033*	0	0	8	Code Table	e.g. 94 = Copenhagen (DMI)
4	*Product type*	*0 02 172*	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 start							
6	**Time significance**	**0 08 021**	0	0	5	Code Table	17 = start of phenomenon
7–9	**Date**	**3 01 011**					
7	*Year*	*0 04 001*	0	0	12	Year	4-digit year
8	*Month*	*0 04 002*	0	0	4	Month	
9	*Day*	*0 04 003*	0	0	6	Day	
10–11	**Time**	**3 01 012**					
10	*Hour*	*0 04 004*	0	0	5	Hour	
11	*Minute*	*0 04 005*	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 9**
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	*Distance from Earth's centre in direction 0° longitude*	*0 27 031*	2	-1073741824	31	Metres	(X)
16	*Distance from Earth's centre in direction 90° east longitude*	*0 28 031*	2	-1073741824	31	Metres	(Y)
17	*Distance from Earth's centre in direction of North Pole*	*0 10 031*	2	-1073741824	31	Metres	(Z)
18–20	**Velocity of Platform** *(see Note 10)*	**3 04 031**					LEO, to 10mm.s^{-1}
18	*Absolute platform velocity – first component.*	*0 01 041*	5	-1073741824	31	Metres per second	(X)
19	*Absolute platform velocity – second component.*	*0 01 042*	5	-1073741824	31	Metres per second	(Y)
20	*Absolute platform velocity – third component.*	*0 01 043*	5	-1073741824	31	Metres per second	(Z)
21	**Satellite Classification**	**0 02 020**	0	0	9	Code Table	GNSS series (e.g. 401=GPS)
22	**Platform Transmitter ID**	**0 01 050**	0	0	17	Numeric	GNSS PRN (1-32)
	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	*Distance from Earth's centre in direction 0° longitude*	*0 27 031*	(1) 2	-1073741824	31	Metres	(X)
24	*Distance from Earth's centre in direction 90° east longitude*	*0 28 031*	(1) 2	-1073741824	31	Metres	(Y)
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)

Data Field	Element Name	Descrip.	Table B Scale	Table B Ref. Val.	Table B Width	Units	Comments
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 start)	**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**	**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**	**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, *n1*
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, *n0*
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
N0	*(end delayed replication)*						*N0 = 42+6.n0 elements*
N0+1	**Percent confidence**	**0 33 007**	0	0	7	%	0 = bad, 100 = good
N1	*(end delayed replication)*						*N1 = 38+(5+6.n0).n1 elements*
RO 'Step 2a' data *(see Notes 3–5)*							
	Delayed replication	**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, *n2*
N1+2	**Height**	**0 07 007**	0	-1 000	17	metres	Geometric altitude, -1km to 100km, wrt 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
N2	*(end delayed replication)*						*N2 = N1+1+6.n2 elements*

Data Field	Element Name	Descrip.	Table B Scale	Table B Ref. Val.	Table B Width	Units	Comments
***RO 'Level2b' data** (see Notes 3–5)*							
	Delayed replication	**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, *n3*
N2+2	**Geopotential height**	**0 07 009**	0	-1 000	17	gpm	Geopot. altitude, -1km to 100km, wrt 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
N3	*(end delayed replication)*						*N3 = N2+1+10.n3 elements*
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 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
N							*Total N = N3+7 elements*

Bold (blue) entries indicate new or changed elements.

NOTES:

1) 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)

2) 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 ($n0 \geq 1$), 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.

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) (*n2* 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) (*n3* 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 + *n1*x(5+*n0*x6) + *n2*x6 + *n3*x10. 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 11.

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 6, Table 7 and Table 8 respectively.

Table 6. Satellite Classification (Code Table 002020)

Descriptor	Value	Meaning
0 02 020	**401**	GPS
	402	GLONASS
	403	GALILEO
	404	BEIDOU

Table 7. GNSS RO Satellite Identifier (Common Code Table C–5)

Descriptor	Value	Meaning	Value	Meaning
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**	COSMIC2-E1
	44	PAZ	**751**	COSMIC2-E2
	421	Oceansat-2	**752**	COSMIC2-E3
	440	Megha-Tropiques	**753**	COSMIC2-E4
	522	FY-3C	**754**	COSMIC2-E5
	523	FY-3D	**755**	COSMIC2-E6
	722	GRACE-A	**786**	C/NOFS
	723	GRACE-B	**800**	Sunsat
	724	COSMIC2-P1	**803**	GRACE-C (GRACE-FO)
	725	COSMIC2-P2	**804**	GRACE-D (GRACE-FO)
	726	COSMIC2-P3	**820**	SAC-C
	727	COSMIC2-P4	**825**	KOMPSAT-5
	728	COSMIC2-P5		
	729	COSMIC2-P6		

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

Descriptor	Value	Meaning
0 02 019	**98**	GPS Receiver
	102	GPS TurboRogue Space Receiver (TRSR) (BlackJack)
	103	Integrated GPS and Occultation Receiver (IGOR)
	104	*(NASA) Triple-G (GPS, Galileo, GLONASS) (Tri-G)*[11]
	202	GNSS Receiver for Atmospheric Sounding (GRAS)
	287	Radio Occultation Sounder of the Atmosphere (ROSA)
	351	GPS Demonstration Receiver (GPSDR)
	948	Global Positioning System Occultation Sensor (GPSOS)
	958	Global Navigation Satellite System Occultation Sounder (GNOS)

[11] Entries in italics are provisional.

4.5.2 Quality Flags

The BUFR Quality Flags for RO (descriptor **0 33 039**, see Table 9) 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.

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 9. 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 10. If the message has been encoded correctly, the delimiter occupies the last 4 octets of the total message length indicated in 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 10. 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 5) for any given combination of L1+L2+Lc frequencies and number of samples in the profile per Stage. Some examples are given in Table 11.

Table 11. Indicative BUFR message lengths

L1+L2?	No. Step 1b samples	No. Step 2a samples	No. Step 2b samples	Message Length (Kbytes)[12]
Y	247	247	82	13.6[13]
N	300	300	200	11.4[14]
N	247	247	247	10.4[15]
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

[12] 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.
[13] Nominal ROM SAF NRT product (GRAS)
[14] Nominal UCAR NRT product (COSMIC, C/NOFS, SAC-C)
[15] Nominal GFZ NRT product (CHAMP, GRACE-A, 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>nnn<CR><CR><LF>$T_1T_2A_1A_2$ii<SP>cccc<SP>YYGGgg<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 12, 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 **nnn** 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 T_1 is **I** (see Table 12), 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 13 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 **L** inclusive; the other codes are not used.

5.3 Data Identifier

The **ii** field is a 2-character data identifier which should make the $T_1T_2A_1A_2$**ii cccc** part of the ARH unique. For RO, this was chosen to be **14**, denoting GNSS data[16].

[16] ***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****).*

Table 12. 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		
`nnn`	'Message sequence number' generated by the en-coding 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 13)	'`A`' – '`L`' ['`X`' with `EUMC/EUMP/EUMR`]		
`ii`	Product type	'`14`' = (GNSS) ['`01`' with `EUMC/EUMP/EUMR`]		
`cccc`	Source of the message (ICAO Location Indicator)	Possible codes for RO include (but not limited to):		
		'`EDZW`'	Offenbach	DE
		'`EGRR`'	Exeter	UK
		'`EKMI`'	Copenhagen	DK
		'`KWBC`'	Washington[17]	US
		'`EUMC`'	Darmstadt[18]	DE
		'`EUMP`'	Darmstadt[19]	DE
		'`EUMR`'	Darmstadt[20]	DE
		'`KNES`'	Washington[21]	US
		'`BAWX`'	Beijing	CN
		'`DEMS`'	New Delhi	IN
`YYGGgg`	Date/time of observation where:- `YY` = day of month (01-31) `GG` = hour (00-23) `gg` = minute (00-59)	Day & Time of first observation in BUFR message		

Table 13. 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
NH	`A`	`B`	`C`	`D`	
Tropics[22]	`E`	`F`	`G`	`H`	
SH	`I`	`J`	`K`	`L`	
NH	`<------------------ N ------------------>`				
SH	`<------------------ S ------------------>`				
NH					`T`
Global	`<------------------ X ------------------>`				

17 In reality UCAR/CDAAC, Boulder, CO via NOAA/NWS
18 EUMETSAT, Metop-A – BUFR contains only Level 1b (Bending Angle) profiles
19 EUMETSAT, Metop-B – BUFR contains only Level 1b (Bending Angle) profiles
20 EUMETSAT, Metop-C – BUFR contains only Level 1b (Bending Angle) profiles
21 NESDIS
22 For RO bulletins, 'Tropics' is defined as 30°S to 30°N, NH as 30°N to 90°N and SH as 30°S to 90°S

5.4 ICAO Location Indicator

The **cccc** field is the ICAO Location Indicator [RD.12] of the originating centre. Table 12 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. For RO data, **YYGGgg** will be the start date/time of the profile (the same as that encoded into BUFR Section 1) which should normally be less than 3 hours old at the time of encoding.

5.6 Current routing headers

Table 14 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.

Note that (apart from Metop data generated by EUMETSAT) there is no distinction in the ARH of individual satellites, only the source of the bulletin.

Table 14. Summary of ARHs for RO data on the GTS

ARH	Mission	Source
IUT[A-L]14 EKMI	Metop-A/B/C / GRAS	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-L]14 KWBC	COSMIC (1-6) [C/NOFS] [SAC-C]	UCAR Boulder (via GTS node NESDIS, Washington)
IUT[A-L]14 KNES	KOMPSAT-5	UCAR Boulder
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

[Missions in square brackets are no longer active]

6. Software Applications

Software applications for BUFR encoding and decoding for 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) has been validated using GRAS, COSMIC, SAC-C, C/NOFS, CHAMP GRACE-A and TerraSAR-X data. The code has been tested under Red Hat Enterprise Linux 6, OpenSUSE 12 and Microsoft Windows running Cygwin [RD.12] with Intel, Portland Group, NAGware, SUN and GNU Fortran 95 compilers.

The ROPP encoder is being used by the ROM SAF to generate GRAS Level 2 NRT products in BUFR and is also used by GFZ to encode TerraSAR-X and TanDEM-X RO data in NRT. The Met Office kernel encoder library has also been interfaced with a Perl script at UCAR for COSMIC and C/NOFS RO data. 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.