GRAS Satellite Application Facility

WMO FM94 (BUFR) Specification For GRAS SAF Processed Radio Occultation Data

Version 2.0

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Version 1.1	23 Jan 2004	DO	**Version presented to MetDB Team for submission to WMO**
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Version 1.3	26 May 2004	DO	**Version on which formal proposal to WMO/CBS is based (see [RD.10])**
Version 1.4	29 Sep 2004	DO	**Version on which final proposal to 13th Session of WMO/CBS is based.**
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Version 1.8	20 Feb 2007	DO	Added GRAS SAF URL to Reference Documents list. Replace 'refractivity' with 'humidity' in processing Step 2b (Section3.4) Updated Section 5 (Software Applications) with summary of ROPP support tools Remove obsolete Table 1 (Version 1 prototype template sequence) and associated Table 5 (prototype PCD flag table); shuffle up remaining table numbers and modify body text accordingly. Added MetOp satellites to Table 3. In Table 5, correct ICAO code for Copenhagen from 'EKCH' to 'EKMI' In Table 6, indicate nominal values for some actual products. **Version for ROPP-1 (v1.0)**
Version 1.9	1 Mar 2008	DO	Use new CDOP document template & file naming Updated WMO URLs in Reference Documents Removed Table 2 (new BUFR Table B descriptors) Table 3 -> Table 2 & Table 4 -> Table 3 Added definitions for PCD Bits 9 & 10 in Table 2 Added SAC-C and TerraSAR-X to Table 3 Inserted new Table 4 (Satellite Instrument Codes for RO) Inserted new Table 7 (Summary of ARHs) Noted increased limits for GTS bulletin lengths General body text updates **Version for ROPP-1 (v1.1)**
Version 2.0	14 Nov 2008	DO	Clarify some parameter ranges in Table 1. Update Figure 1 **Version for ROPP-2 (v2.0)**

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Executive Summary

This document describes the template specification for encoding GRAS SAF processed radio occultation (RO) data into the WMO **BUFR** format. This formatting is a requirement for dissemination of near-real time GRAS SAF products. 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 & 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) or, in Europe, the Regional Meteorological Data Communications Network (RMDCN).

Many operational centres 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 has been developed in consultation with the RO data producer and user community and has 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, incorporated into this document – 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 GRAS SAF processed radio occultation (RO) data into the WMO BUFR format [RD.3]. This formatting is a requirement for dissemination of near-real time GRAS SAF products ([AD.1]). 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 is the interface format necessary for assimilation into NWP models at many operational centres. This format may be used for general exchange of any RO data via the Global Telecommunication System (GTS) or, in Europe, the Regional Meteorological Data Communications Network (RMDCN).

A proposal for a BUFR specification for RO data has been developed in consultation with the RO data producer and user community and has 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, incorporated into this document – 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.

1.2 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' is pure binary (bit-oriented stream). The encoding and decoding process is table-driven, meaning that all data types must be predefined, 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/RMDCN links.

Many operational centres 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 GRAS SAF activities, the Met Office has 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 is now in use, this prototype template description has been removed.

The final BUFR specification has been derived in close consultation with suppliers of processed RO data (including the GRAS 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 90 (Met Office) and Perl (UCAR) interfaces to a suite of Met Office generic BUFR kernel encoder & decoder F77 code, and demonstrated to work as intended with real CHAMP data processed by GFZ and UCAR. Sample messages have also been 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 (UCAR), CHAMP, GRACE-A (GFZ) and pre-operationally for Metop (GRAS SAF) RO missions.

1.3 Applicable & Reference documents

1.3.1 Applicable documents

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

[AD.1] GRAS SAF User Requirements Document.
Ref: SAF/GRAS/UKMO/RQ/URD/001

1.3.2 Reference documents

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

[RD.1] 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 (2002). *Guide to WMO Table-Driven Code Forms*: (copy available via link at [RD.5])

[RD.4] WMO (2005). *Manual on Cod*es. WMO-306, Vol. 1.2, Part B (copy available via link at [RD.5])

[RD.5] WMO (2005). Documentation on recent, current and upcoming operational BUFR tables is available from the WMO web site at:
http://www.wmo.ch/pages/prog/www/WMOCodes.html

[RD.6] WMO (2003). *Manual on the Global Telecommunications System*. WMO-386, Vol.1, Part II, Attachment II-5 21 March 2003. WMO, Geneva. ISBN: 92-63-12386-1
http://www.wmo.ch/pages/catalogue/New%20HTML/frame/engfil/386.html

[RD.7] ROPP User Guide. Part I: I/O.
Ref: SAF/GRAS/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 (2005) *BUFR encoding/decoding software*: http://www.ecmwf.int/products/data/software/bufr.html

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

[RD.13] GRAS SAF website http://www.grassaf.org

1.4 Acronyms, Abbreviations & Initialisms

ARH	Abbreviated Routing Header (WMO)
BUFR	Binary Universal Format for the Representation of data (WMO)
CBS	Committee for Basic Systems (WMO)
CHAMP	CHallenging Mini-satellite Payload (Germany)
CLIMAP	Climate and Environment Monitoring with GPS-based Atmospheric Profiling (EU)
COSMIC	Constellation Observing System for Meteorology Ionosphere and Climate (USA/Taiwan)
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)
Galileo	European GNSS system from 2006 (EU/ESA)
RO	Radio Occultation
GFZ	GeoForschungsZentrum (Potsdam, Germany)
GLONASS	Globalnaya Navigatsionnaya Sputnikovaya Sistema (Russia)
GNSS	Global Navigation Satellite System (generic GPS/GLONASS/Galileo)
GPS	Global Positioning System (USA)
GRACE	Gravity Recovery And Climate Experiment (Germany/USA)
GRAS	GNSS Receiver for Atmospheric Sounding (Metop)
GSN	Ground Support Network
GTS	Global Telecommunications System (WMO)
HP-UX	Unix operating system for Hewlett Packard workstations
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
PCD	Product Confidence Data
POD	Precision Orbit Determination
RMDCN	Regional Meteorological Data Communications Network (Europe)
ROPP	Radio Occultation Processing Package (GRAS SAF software deliverable)
SNR	Signal to Noise Ratio
TBC	To Be Confirmed
TBD	To Be Determined
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)

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].

2.1 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
§ Section 1 is the identifier section and contains header information, type of data, date etc.
§ 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'

2.2 BUFR Tables

BUFR is driven by a set of tables, known as Tables A, B, C, D and the Code/Flag Tables. The latest ratified tables are published by WMO [RD.3][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 types, such as 'satellite sounding' or 'surface observations' coded in BUFR Section 1. This table is not necessary for the encoding and is only used when interpreting[1] 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 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 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 RO parameters, such as 'Refractivity' and RO-specific code/flag tables did not exist and needed be defined and added to Table B.
- Table C defines the meaning and usage of 'operator descriptors'. This table is not used by encoders or decoders and is not normally implemented explicitly 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 up to the whole 'observation' (e.g. a sounding). An entry in Table D must be defined for each new data type or the sequence can be put into Section 3 of the BUFR message. If the sequence is defined in Table D, then Section 3 contains just the single master sequence descriptor for that data.
- Code/Flag 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.3][RD.4][RD.5] are placed, and 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 quite different parameter.

[1] *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.*

2.3 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 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.

2.4 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 is significant data which is constant (all observations from one station, for instance, where the station details are duplicated for all observations, or a parameter is unvarying – perhaps 'missing'[2]) then compression for that parameter will be maximal, as the value is encoded only once and automatically replicated on decoding. Conversely, a single observation, or multiple observations of different length (for instance profiles with varying numbers of vertical levels) cannot be compressed using this mechanism.

2.5 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 WMO Global Telecommunications System

[2] 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 -999999 depending on the implementation.

(GTS). By international agreement, as specified in [RD.6], single bulletins[3] 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 transmisison 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.

While there is no general limit on BUFR message lengths for non-GTS dissemination (for instance via EUMETCast), there may be local operational database storage limits. Met Office's operational MetDB, for instance, has a current limit of 27,000 bytes.

[3] A bulletin is the BUFR (or GRIB or other WMO format) message with a wrapper containing basic coded information on the message content for GTS routing purposes. The wrapper adds some 35 bytes to the BUFR message length – see Section 4

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 (S_0 in Figure 1) the total integrated **bending angle** can be calculated.

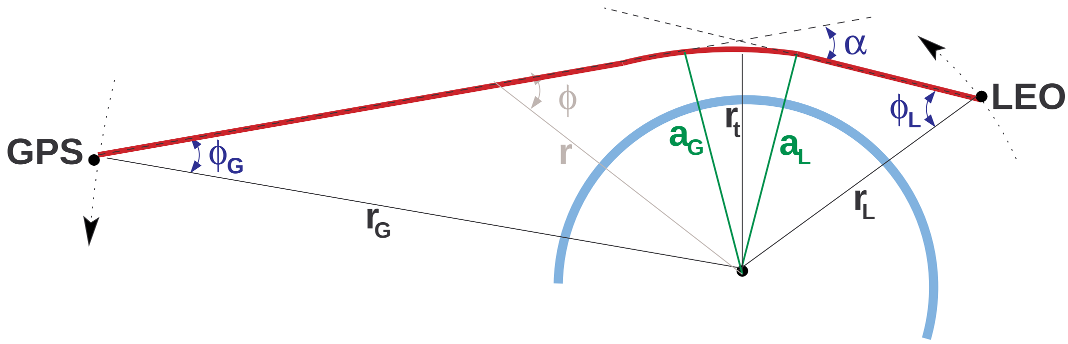

Figure 1. Schematic showing the Radio Occultation geometry

a	Impact parameter	***α***	Bending angle
r_t	Height of ray tangent point	**TP**	Tangent Point
GPS	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 Guidelines

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

- the BUFR-encoded version of RO data is intended specifically for dissemination in near-real time via the GTS/RMDCN, and for assimilation by NWP centres. If the BUFR is not suitable for other users/applications, then other formats via other dissemination methods will be available;
- 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 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 text-based ROPP format [RD.7] (itself modified from an earlier CLIMAP format, [RD.1]) and developed from the 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 has since been 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 are not likely to be required for near-real time, operational NWP use, so not all parameters have been 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 is proposed that only one observation (occultation profile) be encoded per BUFR message. This implies that compression is not used. Tests using sample CHAMP data confirm 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 5.

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.

3.4 Levels & Steps

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

Level	*Generic definition*	*Applied to RO*
Level 0:	Raw source data	Instrument source packets, time-tagged and time-ordered
Level 1a:	Geo-located data in engineering units complete with ancillary data (e.g. calibration information), but not applied to the science data	Time series of excess phase and Doppler GPS & LEO orbit data GSN data for clock corrections & POD
Level 1b:	Science data with calibration applied	Profiles of bending angle as a function of impact parameter Precision orbit data
Level 2:	Calibrated science data 'retrieved' to geophysical units	Profiles of refractivity, pressure, temperature and humidity as functions of height. Surface pressure 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

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.

3.5 BUFR Template Specification

The full BUFR template (sequence) definition for RO data is shown in Table 1, in the form of the Table D sequence of descriptors and their individual meanings. 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. Note that the Code/Flag Tables are not necessary for correct decoding of BUFR messages, but are used only when interpreting the decoded data.

Table 2 defines the Quality Flag bit (sometimes known as Product Confidence Data) definitions for RO data. Table 3 shows the currently defined list of satellites carrying GPS RO instruments and their BUFR code values and Table 4 shows a similar list of RO instruments.

3.6 Quality Flags

The BUFR Quality Flags for RO (descriptor 033039, see Table 2) 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.

3.7 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

$$PC = 100.\ e^{-(O/E)}$$

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.

Table 1. BUFR template definition for one RO profile.

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 3**
2	*Satellite instrument*	*0 02 019*	0	0	11	Code Table	e.g. 202 = GRAS
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 2**
14	**Percent confidence**	**0 33 007**	0	0	7	%	0 = bad, 100 = good
LEO & GNSS POD							
15–17	**Location of Platform**	**3 04 030**					LEO (ECF coordinate system) to 1cm
15	*Distance from Earth's centre in direction 0^o longitude*	*0 27 031*	2	-1073741824	31	Metres	(X)
16	*Distance from Earth's centre in direction 90^o 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**	**3 04 031**					LEO (ECI coordinate system) 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**	**3 04 030**					GNSS (ECF coordinate system) to 10cm
23	*Distance from Earth's centre in direction 0^o longitude*	*0 27 031*	(1) 2	-1073741824	31	Metres	(X)
24	*Distance from Earth's centre in direction 90^o 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**	**3 04 031**					GNSS (ECI coordinate system) 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 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**					Centre of curvature (ECF coordinate system) to 1cm
32	*Distance from Earth's centre in direction 0^{o} longitude*	*0 27 031*	2	-1073741824	31	Metres	(X)
33	*Distance from Earth's centre in direction 90^{o} 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->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->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 – 10^{-2} 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*
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) The complete GPS RO BUFR sequence of 82 descriptors is assigned to Table D descriptor **3 10 026.**

2) 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 250-1100hPa, but the descriptor can encode any value between 0.0 and 1638.2hPa)

3) 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 60km) (*n1* samples; typically 200–300). There should be a minimum of one set of impact parameter & bending angle 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.

4) 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 60km) (*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.

5) Step 2b data are sampled, interpolated and/or smoothed to a smaller number of profile levels (nominally surface to 50km every 1km) (*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.

6) All profile data should be ordered in increasing altitude, whether the original occultation was ascending or descending.

7) 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 converted to impact parameter, then Step 1b latitudes & longitudes can be interpolated to the Step 2 samples to give slant profiles.

8) 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.

9) 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 5.

10) RO instruments can 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.

Table 2. Quality Flags for RO Data (16-bit Flag Table)

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

See [RD.7] for the interpretation of these bit flags. Bit 1 is a summary flag and shall be set in the event that any other 'non-nominal' bit (i.e. 4,5,6,7, or 14) is/are set and clear otherwise.

Table 3. GPS 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
	722	Grace-A	800	Sunsat
	723	Grace-B	820	SAC-C

Table 4. GPS RO Satellite Instrument Identifier (Common Code Table C–8)

Descriptor	*Value*	*Meaning*
0 02 019	98	GPS Receiver
	102	GPS TurboRogue Space Receiver (TRSR)
	103	Integrated GPS and Occultation Receiver (IGOR)
	202	GNSS Receiver for Atmospheric Sounding (GRAS)
	351	GPS Demonstration Receiver (GPSDR)
	948	Global Positioning System Occultation Sensor (GPSOS)

Table* 5. *Indicative BUFR message lengths

L1+L2?	*No. Step 1b samples*	*No. Step 2a samples*	*No. Step 2b samples*	*Message Length (Kbytes)*[4]
Y	247	247	82	**13.6**[5]
N	300	300	200	**11.4**[6]
N	247	247	247	**10.4**[7]
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**

[4] 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. For NRT NWP applications, bulletins should still be limited to 25,000 bytes

[5] Nominal GRAF SAF NRT product (GRAS)

[6] Nominal UCAR NRT product (COSMIC)

[7] Nominal GFZ NRT product (CHAMP, GRACE-A)

4. WMO Routing Headers

The WMO 'Abbreviated Routing Header' (ARH) [RD.6] allows GTS/RMDCN nodes to route messages (e.g. data in SYNOP, BUFR or GRIB code forms) in a table-driven way to defined destinations without knowing the messages' data contents. Header and trailer sequences form a 'wrapper' around one or more message(s) to form a 'bulletin'.

The header 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 is followed by the BUFR message ('BUFR'…'7777') and finally the end-of-message trailer sequence:

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

The elements of the ARH & trailer are described in Table 6, along with settings being used for RO messages[8]. For more details of the possible values for these elements, see Attachment II-5 to [RD.6].

The ARH, 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 and after the trailer appropriate to particular transmission protocols, such as X.25 or TCP/IP (FTP), the description of which is beyond the scope of this document.

The A_2 element is a letter code identifying the regional location of the data (by hemisphere and quadrant) in the bulletin. For RO data, the appropriate letter is generated from the nominal latitude and longitude of the occultation event in the BUFR message and can be any letter A,B,C…L. This can be used by routing nodes to filter bulletins by broad region without having to decode the BUFR.

For most 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 that of the start of the occultation event.

Table 7 shows a summary of AHRs for radio occultation bulletins currently disseminated in NRT over the GTS/RMDCN. Note that there is no distinction in the ARH of individual satellites, only the source of the bulletin.

[8] *This* $T_1T_2A_1A_2$ii *sequence is unique to all the messages handled by the Met Office telecommunications routers and as far as is known, unique on the GTS so can reliably be used to identify GPS RO bulletins.*

Table 6. WMO Bulletin Routing Header/Trailer elements

Field ID	*Description*	*Value for RO*
<SOH>	‘Start of Header’ character: byte value = 1 decimal (01 hex)	01h
<ETX>	'End of Transmission' character: byte value = 3 decimal (03 hex)	03h
<CR>	‘Carriage Return’ ‘character: byte value = 13 decimal (0D hex),	0Dh
<LF>	‘Line Feed’ character: byte value = 10 decimal (0A hex)	0Ah
<SP>	‘Space’ character: byte value = 32 decimal (20 hex)	20h
nnn	‘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
A_1	Data Sub-type	'T' = Satellite-derived sonde
A_2	Area Code	'A'–'L'
ii	Product type	'14' = GNSS-derived
cccc	Source of the message (ICAO designator)	Possible codes for RO: ‘EDZW’ Offenbach D 'EGRR' Exeter UK ‘EKMI’ Copenhagen DK ‘KWBC’ Washington USA
YYGGgg	Date/time of observation where:- *YY* = Day of month (01-31), *GG* = hour (00-23), *gg* = minute (00-59).	Date & Time of start of RO occultation event (UTC)

Table 7. Summary of AHRs for RO data on the GTS/RMDCN

AHR	*Mission*	*Source*
`IUT[A-L]14 EKMI`	MetOp / GRAS	DMI Copenhagen (GRAS SAF)
`IUT[A-L]14 KWBC`	COSMIC	UCAR (via GTS node NESDIS, Washington)
`IUT[A-L]14 EDZW`	CHAMP, GRACE-A	GFZ (via GTS node DWD, Offenbach)

5. Software Applications

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

The ROPP encoder tool:

- 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 tool has several command-line options to control the process. The tool is implemented in Fortran 95 and uses ROPP libraries and freely-available third-party packages (such as netCDF and udunits from Unidata).

The ROPP decoder tool:

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

The ROPP encoder (and its companion decoder) has been validated using GRAS, COSMIC, CHAMP and GRACE-A data. The code has been tested under HP-UX11, Red Hat Linux 9, Ret Hat Enterprise Linux 4, OpenSUSE 11 and Microsoft Windows running Cygwin [RD.12] with Intel, Portland Group, NAGware and GNU Fortran 95 compilers. The BUFR encoder/decoder is coupled with the ROPP netCDF file format (see [RD.7]). The ROPP encoder is being used by the GRAS SAF in the production of GRAS Level 2 NRT products in BUFR and is also used by GFZ to encode CHAMP and GRACE-A RO data in NRT. The kernel encoder library has also been interfaced with a Perl script at UCAR for COSMIC RO data.

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/RMDCN.

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