EIG EUMETNET
GNSS Water Vapour Programme
(E-GVAP-II)

Product Requirements Document

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Prepared by:
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Product Requirements Document

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Document Change Record

Version	Date	By	Change
0.1	2/2/10	DO	**First draft** for E-GVAP Management Team comment. This new E-GVAP-II document is loosely based on the *TOUGH User Requirements Document*, Version 1.0, 15 June 2004 ○ Updated acronyms list ○ Updated body text throughout to reflect current status for E-GVAP-II ○ Section 2 of ref. document moved to Annex ○ Adopt new EUMETSAT concept of *product* rather than *user* requirement and WMO/EUMETSAT 3 levels of performance: 'threshold', 'target' and 'optimal' ○ Used updated (2009) WMO UR tables ○ Re-arranged requirements by product instead of by function ○ Consider wider applications including Local NWP and Research
0.2	3/8/10	DO	**Second daft** for E-GVAP general members comment. ○ Consolidated text throughout ○ Added new items to Abbreviations list ○ Added new items to Reference Documents list ○ Added requirements for Slant Total Delays (STD) ○ Added requirements for Space Weather (TEC) ○ Added product specification tables for Climate and Offline products ○ Added Section 5 (Operational Guidelines)
1.0	21/12/10	DO	**First Release** ○ Updated Section 1 appropriate to document release status ○ Removed highlighted text open for comment in draft version ○ Minor body text & formatting updates

Product Requirements Document

Table of Contents

List of Tables

Product Requirements Document

1. Introduction

EIG EUMETNET is a network grouping 26 European National Meteorological Services [RD.1], providing a framework to organise co-operative programmes between the Members in the various fields of basic meteorological activities such as observing systems, data processing, basic forecasting products, research & development and training. The GNSS Water Vapour Programme – E-GVAP (2005–2009) and E-GVAP-II, 2009–2013) – is set up to provide EUMETNET partners with European GNSS signal delay and water vapour measurements for operational meteorology. This is being done in close collaboration with the geodetic community in Europe.

This Product Requirements Document (PRD) for E-GVAP uses the EU 'TOUGH' User Requirements Document (URD) and EU 'SX5' Requirements Document (RD) as its basis. The layout and some presentation concepts and terminology have been heavily influenced by equivalent EUMETSAT Satellite Applications Facility (SAF) documentation and recent WMO ideas on satellite data requirements. Inputs to this document have been solicited from all E-GVAP-II participants, and results from this exercise have been incorporated. Apart from the Hourly ZTD product, E-GVAP-II has no commitment to generate and deliver products described here; this document merely gathers together in one place requirements for potential future products that users have expressed a wish for. Some of these may not be practical to generate without significant development and/or may never fully meet the requirement (e.g. for climate).

This PRD should be considered to be a 'living document', and will be updated from time to time as the detail of requirements and the maturity of products evolve.

1.1 Purpose of document

This document presents the user and product requirements for the European meteorological (Nowcasting and NWP) and climate user communities with regard to data derived from Global Navigation Satellite System[1] (GNSS) signals received on the ground, which provide information on atmospheric water vapour[2] (hereafter referred to as 'GWV')

A set of User Requirements for GWV was originally gathered under the EU COST Action 716 [RD.2] which was further developed under the EU TOUGH project [RD.3]. Both documents provided a trace-back to fundamental, *technology-free* User Requirements as specified in contemporary WMO documentation. The present document emphasises the *Product* in addition to the *User* Requirements, since we need to acknowledge the practical realities (and limitations) of the GWV technology as a single observing system. We thereby provide requirements which have some chance of being met, rather than being perceived of as an unattainable wish-list. It is then for the end-user of these products to decide if they will meet their own requirements for their specific applications. Current WMO requirements are provided in this document for reference.

The first phase of E-GVAP (2005–2009) laid the foundations for cooperating partners to process and supply data on a more formal (though best-efforts) basis than was the case during COST-716 and TOUGH, thus guaranteeing continued GWV data availability to the E-GVAP partners and the wider user community. The requirements in the TOUGH URD [RD.3] were considered to be appropriate for this phase.

Under E-GVAP-II (2009–2013), the focus is more on bringing the data supply to the status of an operational service, at which point the coordination can be handed over to EUCOS as part of a fully operational phase in parallel with existing projects such as E-AMDAR and E-WINPROF [RD.4]. For this phase, requirements need to be established which reflect what can be provided (a) as a minimum; (b) as a normal operational service; and (c) as a future aspiration (with further developments).

[1] *For E-GVAP-II we have adopted the generic term 'GNSS' to encompass the US GPS, Russian GLONASS and future European Galileo constellations even though today most receivers are only GPS-capable.*

[2] *The principle observable derived from ground-based GNSS receivers of interest to meteorology is the signal delay (expressed as an excess distance over the* in vacuuo *case). As this delay is sensitive to atmospheric water vapour, the term 'GPS (or GNSS) Water Vapour' is in widespread common use for this data type, so we continue to use it here.*

The document is intended for members of the E-GVAP-II project, including cooperating members, who can use it to check requirements against available GWV products and thus make any adjustments to meet them. This document also serves as an interface between the E-GVAP-II user participants and the representatives of the GNSS networking communities. Finally, and most importantly, end-users may refer to this document to provide an expectation of the properties of GWV products that they may wish to use.

The applicability of this document strictly terminates with the end of the E-GVAP-II project, but requirements herein may be taken as the basis for any future operational GNSS network and processing for meteorological applications under EUCOS.

Although this document is prepared by, and for, the E-GVAP-II project, the requirements are generic in the sense that they could apply to similar products for other networks outside of Europe. Ideally, the GWV world-wide supplier and user communities would agree common characteristics of their products so that users could be assured of homogeneous performance, from wherever the data was sourced.

The requirements stated in this document apply to the expected mode of operation of GNSS ground-based networks, including operation of receiver equipment and network connections between receiver stations and regional processing centres (also called Analysis Centres). The expected operational mode of the network is characterised by the following:

- No satellite or ground network anomaly impacts on the on-ground processing;
- The intra-network data flow and data production operate at the planned capacity and efficiency;
- Near-real time data is made available to the NWP community via the GTS[3] in the WMO BUFR format [RD.5];
- BUFR conversion is de-centralised, with processing centres encoding a sub-set of their own products for insertion on to the GTS by their national NMS (or other GTS node);
- An independent centre provides rapid quality control information to users and suppliers;
- Processing centres provide full products in an appropriate format (e.g. netCDF[4]) to a collection hub via public networks for general non-NWP users requiring rapid access;
- Processed data products will be collected for central archiving for off-line users. The archive facilities may be provided by a specialist third party such as the BADC[5] (subject to confirmation by E-GVAP Data Policy);
- Raw data and comprehensive meta-data is archived by the processing centres (and/or collected centrally), and periodic re-processing to current standards will be performed to provide a long-term homogeneous record of GWV data. Central processing using a standard processing scheme may be necessary to achieve this objective.

1.2 Document outline

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Section 2 presents the background generic WMO User Requirements taken from [RD.6] and which may or may not be met for E-GVAP GWV products;
Section 3 provides the Product Requirements in terms of the overall project deliverables;
Section 4 presents the Product Specifications – the performance characteristics of the GWV data products that users can expect in reality from this data type;
Section 5 provides additional guidance on the NRT supply of E-GVAP data to operational NWP centres;
Annex 1 gives a brief description of the GWV processing system as background.

[3] *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'.*
[4] *A proposal for a netCDF file format is in draft This PRD assumes that E-GVAP products will be based on this format and likely content.*
[5] *Discussions are in progress with BADC to host off-line E-GVAP data in the form of consolidated daily netCDF files for access by the general scientific community. The E-GVAP Data Policy places certain restrictions on access and usage.*

1.3 Reference Documents

[RD.1] EUMETNET website: http://www.eumetnet.eu/

[RD.2] Barlag, S. and de Haan, S. (2004). *GPS Meteorology User Requirements*. Version 2.6, April 2004. Ref: COST/716/URD/2.6

[RD.3] Barlag, S., de Haan, S. and Offiler, D. (2004*). User Requirements Document.* TOUGH Project Deliverable Item D15, Version 1.0, 15 June 2004

[RD.4] EUCOS website: http://www.eucos.net

[RD.5] E-GVAP (2009). *WMO FM94 (BUFR) specification for GPS water vapour data*. Ref. E-GVAP/METO/FMT/BUFR/001. Version 1.0, 30 November 2009

[RD.6] WMO (2009). *Database of observational requirements from WMO and other international organizations*. ET-EGOS5-Doc-8_1-1-DB-requirements.apx (Excel spreadsheet) http://www.wmo.int/pages/prog/sat/Databases.html#UserRequirements

[RD.7] WMO (1988). *Technical Regulations Volume I - General meteorological standards and recommended practices*. WMO-Doc.49, 1988, ISBN 92-63-18049-0, WMO, Geneva

[RD.8] Sargent, G.P. (1980). *Computation of vapour pressure, dew-point and relative humidity from dry- and wet-bulb temperatures*. Meterol.Mag. 238–246, **109**.

[RD.9] Jupp, A. and Offiler, D. (2006). *A forward model for the assimilation of ZTD data in 3- or 4DVAR systems*. TOUGH Project Deliverable Item D26, Version 1.0, 24 March 2006.

[RD.10] GRAS SAF (2010*). Radio Occulation Processing Package User Guide: Part II: 1D-Var.* Ref: SAF/GRAS/METO/UG/ROPP/002. Available as part of ROPP distribution from http://www.grassaf.org

[RD.11] IPCC (2007). *IPCC Fourth Assessment Report: Climate Change 2007*. Working Group I: The Physical Science Basis. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html

[RD.12] Van der Linden, P. and Mitchell, J.F.B. (eds.) (2009). *ENSEMBLES: Climate change and its impacts: Summary of research and results from the ENSEMBLES project.* Report to EU Contract no. 505530. Met Office Hadley Centre, FitzRoy Road, Exeter, EX1 3PB, UK. 160pp.

[RD.13] Ringer. M.A. and Healy, S.B. (2008). *Monitoring twenty-first century climate using GPS radio occultation bending angles*. Geoph. Res. Let, **35**, L05708, doi:10.1029/2007GL032462, 2008

[RD.14] CEOS (2008). *Interoperability Handbook*. Issue 1.1, February 2008. http://www.ceos.org/images/WGISS/Documents/Handbook.pdf

[RD.15] WMO. Satellite Data processing – Imagery and Derived Products http://www/wmo.int/pages/prog/sat/Imageryandproducts.html

[RD.16] Bevis, M., S. Businger, T.A. Herring, C. Rocken, R.A. Anthers and R.H. Ware (1992). *GPS meteorology: Remote sensing of atmospheric water vapor using the global positioning system*. J. Geophys. Res., **97**, 15,787-15,801.

[RD.17] Bevis *et al*. (1994). *GPS Meteorology: Mapping Zenith Wet Delays onto Precipitable Water*. Journal of Applied meteorology, **33**, 379-386.

[RD.18] Neill, A.E., (1996). *Global mapping functions for the atmospheric delay at radio wavelengths*. J. Geophys. Res., **101**, 3227-3246.

[RD.19] Saastamoinen, J. (1972). *Atmospheric Correction for the Troposphere and Stratosphere in Radio Ranging of Satellites.* In: The Use of Artificial Satellites for Geodesy, Geophysical Monograph Series, AGU, Washington D.C., **15**, 247- 251.

[RD.20] IGS website: http://igscb.org/

[RD.21] ITRF website: http://itrf.ensg.ign.fr/

[RD.22] EUREF website: http://www.epncb.oma.be/

[RD.23] Zumberge, J.F., M.B. Heflin, D.C. Jefferson, M.M. Watkins and F.H. Webb (1997). *Precise point positioning for the efficient and robust analysis of GPS data from large networks.* J. Geophys. Res., **102**, No.B3, 5005-5017.

1.4 Acronyms, Abbreviations & Initialisms

AC	(GNSS) Analysis Centre
AMDAR	Aircraft Meteorological Data Relay
ATOVS	Advanced Tiros Operational Sounder
ARH	Abbreviated Routing Header
ASI	Agenzia Spaziale Italiana (Matera, IT)
AWS	Automatic Weather Station
BADC	British Atmospheric Data Centre
BKG	Bundesamt für Kartographie und Geodäsie (Frankfurt am Main, DE)
BUFR	Binary Universal Format for the Representation of data (WMO)
CEOS	Committee on Earth Observation Satellites
CLIMAP	Climate and Environment Monitoring with GPS-based Atmospheric Profiling (EU)
CNRS	Centre National de la Recherche Scientifique (Nice, FR)
COST-716	Co-operation in Science and Technology Action 716 (EU)
ECF	Earth Centred Fixed – 3-D orthogonal coordinate system relative to the centre of mass of the Earth
ECMWF	European Centre for Medium-range Weather Forecasts (Reading, GB)
E-GVAP	EUMETNET EIG GPS Water Vapour Programme
EIG	Economic Interest Group
EPN	EUREF Permanent Network
ERP	Earth Rotation Parameters
ESA	European Space Agency
ET-EGOS	Expert Team on Evolution of the Global Observing System (WMO)
EU	European Union
EUMETNET	European Meteorological Services Network
EUMETSAT	European Organisation for Meteorological Satellites
EUREF	European (Terrestrial) reference Frame
FM94	WMO Form no. 94 (i.e. BUFR)
FTP	File Transfer Protocol (under TCP/IP)
Galileo	Future European GNSS system (EU/ESA)
GCOS	Global Climate Observing System
GFZ	GeoForschungsZentrum (Potsdam, DE)
GLONASS	Globalnaya Navigatsionnaya Sputnikovaya Sistema (RU)
GNSS	Global Navigation Satellite System (generic GPS/GLONASS/Galileo)
GOP	Geodetic Observatory Pecny (Pecny, CZ)
GPS	Global Positioning System (US)
GWV	GNSS Water Vapour
GRAS	GNSS Receiver for Atmospheric Sounding (EUMETSAT)
GRIB	Gridded data in Binary format (WMO)
GTS	Global Telecommunications System (WMO)
IEEC	Institut d'Estudis Espacials de Catalunya (Barcelona, ES)
IESSG	Institute for Engineering Satellite Surveying and Geodesy (Nottingham, GB)
IGE	Instituto Geografico Nacional (Madrid, ES)
I/O	Input/Output
IGS	International GNSS Service

ITRF	International Terrestrial Reference Frame
IWV	(vertically) Integrated Water vapour (also: PW or TCWV)
KNMI	Koninklijk Nederlands Meteorologisch Instituut (De Bilt, NL)
LPT	Bundesamt für Landestopographie (Swiss Federal Office of Topography or SwissTopo) (Wabern, CH)
MetDB	Meteorological Data Base (Met Office)
Met Office	NMS of the United Kingdom (Exeter, GB)
netCDF	Network Common Data Form
NGAA	Nordic GPS Atmospheric Analysis centre (Norrköping, SE)
NKG	Nordic Commission of Geodesy (NO, SE)
NMS	National Meteorological Service
NRT	Near-Real Time (typically within 1–3 hours)
NWP	Numerical Weather Prediction
PCD	Product Confidence Data
POD	Precise Orbit Determination
PPP	Precise Point Positioning
PRD	Product Requirements Document
PW	Precipitable Water (also: IWV or TCWV)
QRT	Quasi-Real Time (typically 5 minutes to 1 hour)
RH	Relative Humidity
RD	Requirements Document
RMDCN	Regional Meteorological Data Communications Network (WMO)
RMS	Root-Mean-Square
RO	(GNSS) Radio Occultation
ROB	Royal Observatory Belgium (Bruxelles, BE)
ROPP	Radio Occulation Processing Package (GRAS SAF)
SAF	Satellite Application Facility (EUMETSAT)
SGN	Service de la Géodésie et du Nivellement, Institute Géographique National (IGN) (Saint-Mandé, FR)
SH	Specific Humidity
STD	Slant Total Delay
SYNOP	Standard WMO coded synoptic weather observation disseminated on the GTS
TBC / TBD	To Be Confirmed / Determined (or Defined)
TCSH	Total Column Specific Humidity
TCP/IP	TeleCommunications Protocol / Internet Protocol
TCWV	Total Column Water Vapour (alos: IWV or PW)
TEC	(vertically integrated) Total Electron Content
TEU	TEC Units ($\log_{10}$(TEC) with TEC in m^{-2})
TOUGH	Targeting Optimal Use of GPS Humidity (EU)
VAR	Variational (NWP data assimilation technique)
UR	User Requirement
URD	User Requirements Document
USA	United States of America
WIS	Weather Information System (WMO)
WMO	World Meteorological Organisation
WV	Water Vapour
WVR	Water Vapour Radiometer
VLBI	Very Long Baseline Interferometer
ZHD	Zenith Hydrostatic Delay
ZTD	Zenith Total Delay (sometimes 'Total Zenith Delay')
ZWD	Zenith Wet Delay

2. Observational Requirements for Atmospheric Humidity Data

2.1 Background – WMO Observational Requirements

This section provides a trace-back of the product requirements given in Section 3 – which acknowledges the practicalities of the GWV data – to *technology-free,* generic User Requirements defined by ET-EGOS on behalf of WMO member states. Where applicable, we present user requirements traceable to the WMO Observational Requirements database [RD.6].

Quoting from [RD.6]:

> *"Requirements are expressed for geophysical variables in terms of 5 criteria: horizontal resolution, vertical resolution, observing cycle, timeliness and accuracy. For each of these criteria the table indicates 3 values determined by experts:*
>
> - *the "**threshold**" is the minimum requirement to be met to ensure that data are useful*
> - *the "**goal**" is an ideal requirement above which further improvements are not necessary*
> - *the "**breakthrough**" is an intermediate level between "threshold" and "goal" which, if achieved, would result in a significant improvement for the targeted application. The breakthrough level may be considered as an optimum, from a cost-benefit point of view, when planning or designing observing systems.*
>
> *Since the Breakthrough is expected to be closer to the Goal than to the Threshold, the Breakthrough column has been initially populated in the table by default values calculated as: Goal Power (2/3) X Threshold Power (1/3), pending determination by experts."*

The tables in [RD.6] are presented by application area. For the purposes of GNSS networks for atmospheric applications, we have extracted requirements for the major application classes:

- Global NWP
- Regional NWP
- GCOS (climate)

Climate applications may also be divided into Global and Regional scales, but the WMO tables do not yet reflect that distinction.

Two further classes not included in the WMO tables should be considered as potential users of GWV data:

- Nowcasting (non-NWP)
- Nowcasting (NWP)

The first of these is for qualitative, short-term meteorological application ('human' or 'bench' forecasting) and the second is applied to short-term numerical forecasts, using quasi-continuous assimilation, limited-area NWP models[6], for which quantitative products are required. To avoid confusion, in this document we will use the term 'Local NWP' to mean such fine-scale NWP.

A final category, not considered by WMO, is Research. This category covers any non-operational need for atmospheric water vapour information not covered by other categories above, and therefore will have diverse requirements. We will make the assumption that the requirements for this class of user lie somewhere between those for NWP and Climate in terms of accuracy and timeliness, but are otherwise similar to those for NWP.

It should be stressed that the WMO requirements are generic, and independent of any particular observing system or technology, and take no consideration of absolute or relative monetary cost or affordability in meeting even the minimum requirements.

We should also note that the Terms of Reference for E-GVAP are limited to fulfilling the needs for NWP use of GWV data, so this must be the focus for delivering products under this project. Nevertheless, we should

[6] *Such as the Met Office's 'UKV', a limited-area UK domain with Variable grid-size (at the domain edges). Some 90% of the domain has a grid node spacing of 1.5km. This new operational model is initially being run four times per day, but eventually will be quasi-continuous (every 2-3 hours). Other centres have equivalent models or are developing similar capabilities for operational use within the next few years.*

take account of other classes of users noted above if this data type is to be developed for long-term application.

It is implicit in the WMO requirements that no single observing system is likely to meet all requirements, and that a mix of systems – with different characteristics – is necessary. Individual observation systems (be it surface SYNOP, radiosonde, AMDAR, ATOVS or RO for example) should have standard operational methodologies and procedures, so that reasonably homogeneous data quality can be assured, despite the network being composed of a number of individual instrument types possibly processed by different centres and with different software.

2.2 Humidity parameters of relevance

Atmospheric humidity (water vapour content) can be measured, or expressed, in several different forms: wet-bulb temperature; dew point, vapour pressure; relative humidity; specific humidity or mixing ratio [RD.7]. If the atmospheric temperature and/or pressure are known, in general it is possible to convert between any these forms[7] [RD.8].

In general, *in situ* humidity observations are reported as relative humidity (RH), the ratio of the actual WV pressure to the saturated WV pressure at the same temperature, and expressed as a percentage ([RD.7]). Alternatively, specific humidity, the mass of water vapour per unit mass of moist air, which is equivalent to the ratio of the density of water vapour and the density of moist air, may be reported for some data types.

The GWV humidity product is interpreted as being related to the integral of the water vapour density over the pressure (divided by gravity) vertical profile. This quantity is called Integrated Water Vapour (IWV) and to avoid misinterpretations, IWV is expressed in units of $kg\ m^{-2}$ to distinguish from path delay measurement, which is expressed in units of *mm*, since the quantity IWV – also called precipitable water (PW) or total column water vapour (TCWV) – can also be expressed in mm (1 $kg.m^{-2}$ IWV = 1 mm PW).

WMO Observational Requirements [RD.6] for *accuracy* are given in terms of ‘specific humidity’ for surface or profile levels, in units of percent, which are taken to be a percentage error in SH rather than in RH. Similarly, the term ‘specific humidity’ is also (incorrectly) used for ‘Total Column’ measurements, in units of $kg\ m^{-2}$ which can be taken to be IWV or PW in practice.

The definition of IWV is:

$$IWV = \int \rho_v(z)dz \qquad (1)$$

where:

IWV	Integrated Water Vapour ($kg\ m^{-2}$)
ρ_v	Water vapour density ($kg\ kg^{-1}$)
z	Height (*m*)
TOA	Top of Atmosphere

Since GWV is capable of only providing information on the total vertical column humidity[8], the WMO criterion of ‘vertical resolution’ is not relevant here. We should also note that the WMO tables use the term ‘resolution’; this should be understood to be related to the sampling (observation) separation distance and not the mathematical Nyquist meaning of resolving structure of a certain periodicity. To avoid ambiguity, in this document we use instead the term ‘horizontal sampling’.

[7] *Though not all conversions are linear; some require an iterative approach and some are not exact equations but employ a best-fit polynomial.*
[8] *Slant delays and tomographic techniques have not yet proven to provide useful humidity profile information, and today are subject to ongoing research.*

2.3 Other parameters of interest to operational meteorology

2.3.1 Slant Delays

For assimilation in variational data assimilation systems, users generally prefer the observational data to be in its most raw form, as long as this can be adequately forward-modelled from standard NWP fields. This is why ZTD is preferred over pre-computed IWV, which requires *a priori* external meteorological data and certain assumptions and simplifications which can introduce random and systematic errors [RD.9].

We could go back in the GNSS processing one more step and assimilate direct satellite-to-ground slant delays, which by-pass the need for inexact climatological mapping functions needed to derive ZTD. Slant delays are relatively straightforward to model by using orbit propagation tools to fix the GNSS satellites relative to a ground receiver (or better, their pre-computed ECF coordinates are provided with the slant delay data) and ray-tracing between them through the 3-D NWP model atmosphere. This operator does not depend on mapping functions, and can also take account of bending of the ray at low elevation angles – a phenomenon usually ignored for GWV processing, but absolutely standard for similar 2-D operators used for GNSS Radio Occulation assimilation, where the bending angle is the principle observable [RD.10].

Today, slant delays may be considered a research topic, and this parameter has yet to be demonstrated as useful for NWP, hence here we include it as a requirement under the Research application. With further R&D, slant delays may become a requirement for Global and Regional NWP.

2.3.2 Total Electron Content

GNSS data can be processed to generate non-neutral atmosphere delays – for example ionospheric delay. In turn, this can be converted to the (vertically-integrated) Total Electron Content (TEC) which is analogous to IWV.

There is increasing R&D into ‘Space Weather’ in order to forecast impacts on space-based and long-range terrestrial communications for civil and military applications (for example). TEC is a basic observable that has potential to be assimilated into ionospheric models. There are few (perhaps only one, in the US) such operational models running today, but the UK and other European countries are interested in having such a capability, the only limitation being one of funding and/or a clear commercial market for the Space Weather forecasts. Hence TEC is included in this document as a requirement for Research applications, but which may well be ‘promoted’ to operational NWP in the future.

While TEC is not in the obvious scope of E-GVAP-II, it is a potential output from the same GNSS network hardware and processing used for ZTD, and would very likely be used by the same EUMETNET (and EUCOS) Members supporting E-GVAP, so it would not be unreasonable for this project to consider TEC production at a prototype level by any Analysis Centres willing to generate it. It may be noted that TEC was an expected by-product parameter from the days of COST-716, so there is a slot for TEC values in the COST-format files and the BUFR template for GWV.

The required parameter is a geometry-free (not the quasi-ionosphere free value) TEC, given in TEC Units (TEU) where the TEU value is the base-10 logarithm of the TEC when expressed in electrons per m^2. The typical range is 14–22 TEU.

2.4 Nowcasting

A summary of the requirements for Nowcasting (non-NWP) is shown in Table 1. Note that the figures are not from WMO tables, but are best-estimates based on surface synoptic requirements.

	IWV		
	Threshold	**Breakthrough**	**Goal**
Horizontal Domain	Sub-regional (a few 100km)		
Horizontal Sampling	50 km	10 km	5 km
Observation Cycle	30 mins	10 mins	5 mins
Accuracy	5 kg m^{-2}	2 kg m^{-2}	1 kg m^{-2}
Timeliness	30 mins	10 mins	5 mins

Table 1. Observational requirements for Nowcasting

Notes:

1) Horizontal Sampling in this context means the average horizontal separation distance between nearest-neighbour observations, and requirements depend on the typical application, such as the time- and spatial-scales of the phenomena and grid spacing/resolution for objective analysis (e.g. contouring or full NWP assimilation).
2) Observation Cycle is the effective sampling time interval at the same location.
3) Sampling is assumed to be such that observations are independent; that is, errors between samples are temporally and spatially uncorrelated. Increasing sampling by interpolation does not result in increased information.
4) Accuracy is taken to mean one standard deviation with zero mean (bias-free) or RMS value.
5) Timeliness is the delay from the effective time of the observation to time of receipt by the user. WMO give no explicit requirement, but it is generally understood that in practice, at least 95% of all possible observations are expected to arrive within the required timeliness value for a fully-operational system[9].
6) Nowcasting applications are more concerned with relative values (horizontal gradients, highs and low value areas) than with absolute accuracy, so can tolerate small correlations and biases in the observations, though discontinuities between observing networks should be avoided.

Nowcasting applications will often present observation data graphically on a workstation screen. For IWV this will include 2-D maps – probably contoured – which will involve interpolating the receiver location point values onto a grid prior to display. For this sort of use, where the information is in the geographical patterns and not absolute values, it may be appropriate to simplify the conversion of ZTD to IWV (Equations (A2) and (A3) – see Annex) to:

$$IWV \approx (ZTD - 2.276P_s)/6.5 \quad [\text{kg m}^{-2}] \tag{2}$$

where the coefficients are applicable to mid-latitudes and it is assumed that the local surface pressure, P_s, is appropriate to the GPS antenna location (i.e. the latter are vertically within ~2m of the surface). It should be noted that this simplification will mask synoptic changes due to pressure and topography, and would therefore not be appropriate for other than small-scale mapping, or where the receiving antenna is on a tall building, for instance.

2.5 NWP

A summary of the requirements for Global, Regional and Local NWP is shown in Table 2, Table 3 and Table 4, respectively. Note that figures for Local NWP are not from WMO the tables, but best-estimates based on surface synoptic requirements.

[9] *For COST-716 and TOUGH, the target was a relaxed 75%; for E-GVAP and E-GVAP-II to date the target (or 'breakthrough') is 90%.*

	IWV		
	Threshold	Breakthrough	Goal
Horizontal Domain	Global		
Horizontal Sampling	250 km	50 km	15 km
Observation Cycle	12 h	6 h	1 h
Accuracy	5 $kg.m^{-2}$	2 $kg.m^{-2}$	1 $kg.m^{-2}$
Timeliness	6 h	30 min	5 min

Table 2. Observational requirements for Global NWP

	IWV		
	Threshold	Breakthrough	Goal
Horizontal Domain	Regional (e.g. Europe, N. America)		
Horizontal Sampling	250 km	25 km	3 km
Observation Cycle	12 h	6 h	1 h
Accuracy	5 $kg.m^{-2}$	2 $kg.m^{-2}$	1 $kg.m^{-2}$
Timeliness	6 h	30 min	5 min

Table 3. Observational requirements for Regional NWP

	IWV		
	Threshold	Breakthrough	Goal
Horizontal Domain	Local (100-1000km)		
Horizontal Sampling	100 km	10 km	3 km
Observation Cycle	3 h	1 h	0.5 h
Accuracy	5 $kg.m^{-2}$	2 $kg.m^{-2}$	1 $kg.m^{-2}$
Timeliness	30 mins	10 mins	5 mins

Table 4. Observational requirements for Local NWP

Notes:

1) – 5) see under Nowcasting.

6) For NWP variational analysis (3– and 4D–Var) systems, absolute values are required, and there exists a requirement that observations should (ideally) be bias-free at source and errors should be Gaussian and uncorrelated in space and time. Accurate knowledge of observation error characteristics is essential to use any observation effectively; poor error specification can easily lead to poor analyses and incorrect forecasts.

2.6 Climate

A summary of the requirements for Global and Regional GCOS (Climate) is shown in Table 5 and Table 6, respectively. Note that figures for Regional Climate are from WMO tables for the Tropospheric, not Total Column entry, as proxy for Regional Climate requirements.

	IWV		
	Threshold	Breakthrough	Goal
Horizontal Domain	Global		
Horizontal Sampling	200 km	100 km	50 km
Observation Cycle	6 h	4 h	3 h
Accuracy	3 $kg.m^{-2}$	1.5 $kg.m^{-2}$	1 $kg.m^{-2}$
Timeliness	60 days	14 days	7 days

Table 5. Observational requirements for Global Climate

	IWV		
	Threshold	**Breakthrough**	**Goal**
Horizontal Domain	Regional (e.g. Europe, N. America)		
Horizontal Sampling	200 km	25 km	10 km
Observation Cycle	6 h	4 h	3 h
Accuracy	3 kg.m^{-2}	1.5 kg.m^{-2}	1 kg.m^{-2}
Timeliness	60 days	14 days	7 days

Table 6. Observational requirements for Regional Climate

Notes:
1) – 5) see under Nowcasting
6) For Climate, accuracy in terms of standard deviation can be obtained by averaging individual observations over long periods (e.g. a month). While small biases can be tolerated, it is essential that any systematic temporal change in bias is a small fraction (<10%) of the expected climate change signal. Uncorrectable differential bias changes over time across the observing network are unacceptable.

Climate applications can fall into three general areas:
1. monitoring
2. prediction
3. model validation

For climate monitoring and prediction, trends in the past and future are analysed for which the noteworthy requirement for observations is for long-term system stability. For climate monitoring it is necessary that the data are homogeneous and do not drift because of any deficiency or changes in the instrumentation, the surrounding measurement site, or changes in the processing. According to the climate monitoring principles fostered by GCOS, the quality and homogeneity of data should be regularly assessed as a part of routine operations whereas the details of local conditions, instruments, operating procedures, data processing algorithms and other factors pertinent to interpreting data, i.e. the meta-data, should be documented and treated with the same care as the data themselves.

Climate prediction models and studies performed with re-analysed meteorological data show that trends between 0.1–0.4 kg m^{-2} per decade in the global, yearly averaged atmospheric water vapour content can be expected as global "*increases in temperature lead to increases in the moisture-holding capacity of the atmosphere at a rate of about 7% per ^{o}C*" [RD.11]. For specific (dry) regions these numbers may be even smaller. This is far less than the measurement accuracies of the GWV system at present but is also less than the variations seen in local biases. The significance of any trend detected is therefore extremely sensitive to long-term system stability. A value for the long-term stability near zero is theoretically right and is to be preferred but may be unrealistic in practice. The requirement for stability is therefore expressed as an acceptable drift of the bias on the order of 10–30% of the expected trend within any decade. Except for this requirement, if the requirements for operational meteorology are met, those for climate applications will also be met.

Some data types may not be appropriate for detecting long-term trends, but can still be used indirectly by providing an independent check on the output from climate models in 'hindcast' mode [RD.12]. Climate predictions are only useful if they can first accurately reproduce the present-day climate, and water vapour is a key climate parameter which needs to be correctly represented, being a strong greenhouse gas which is significant for driving radiative forcing and thereby the thermodynamic balance of the atmosphere in addition to the effect of moisture on cloud and precipitation.

Table 7 notes some additional requirements specific to climate applications, not contained in the WMO tables, but coming from the climate community.

	IWV
Horizontal Domain	Regional / Global
Time Domain	>> 10 years
Long Term Stability	0.02 – 0.06 kg m^{-2} per decade

Table 7. Additional Requirements for Climate Monitoring and Prediction

For Climate applications, small systematic biases are not significant as long as they are constant or a small fraction of the expected climate trend. The main issue is the detection of climate trends, which requires the data quality to be homogeneous over long time periods (decades); trends and jumps in the data record due to changes in the network, processing methods, etc, are unacceptable unless well understood and correctable. Ideally, any long time series needs to be (re-)processed using one standard system for the whole horizontal domain. This is less of a constraint for climate model validation, which is comparing short-period averages, and for which a stable, relatively standardised processing for NWP applications may suffice.

2.7 Research

A summary of the requirements for Research is shown in Table 8. The potential use of GWV data is very wide, and could cover preparatory R&D for NWP use, atmospheric dynamics by tracking water vapour features, validation of other sounding observations (radiosondes, WV Radiometers, lidars…), identification of correlations between ZTD and (e.g.) thunderstorm activity, etc. We may surmise that accuracy would need to be generally higher than with NWP requirements, but that timeliness can be more relaxed, with other metrics being similar to those for NWP. In practice, the standard hourly ZTD and IWV product may be adequate.

We have included Total Electron Content (TEC) under Research, but this product is likely to become a requirement for Global or Regional NWP in the not-too-distant future; WMO Expert Teams have been tasked with developing a UR for TEC and appropriate values are expected to be published shortly. Requirements for timeliness would then be the same as those quoted in Table 2 or Table 3.

Note that figures not from WMO tables, but are best-estimates – to be updated when WMO URs for TEC are published.

	IWV		
	Threshold	**Breakthrough**	**Goal**
Horizontal Domain	Global		
Horizontal Sampling	200 km	100 km	50 km
Observation Cycle	6 h	4 h	3 h
Accuracy	3 $kg.m^{-2}$	1.5 $kg.m^{-2}$	1 $kg.m^{-2}$
Timeliness	30 days	7 days	1 day

	TEC		
	Threshold	**Breakthrough**	**Goal**
Horizontal Domain	Global / Regional		
Horizontal Sampling	200 km	100 km	50 km
Observation Cycle	6 h	4 h	3 h
Accuracy	5 TEU	3 TEU	1 TEU
Timeliness	30 days	7 days	1 day

Table 8. Observational requirements for Research

3. Product Requirements

From the above generic WMO requirements for total column humidity data (IWV), it would appear that the primary goal of the GWV networks should be to provide geophysical (Level 2) products which meet the observation requirements in Section 2. However, from several NWP assimilation trials – now in current operational practice at a few NWP centres – and the processing methods highlighted in Annex 1, it is clear that non-geophysical (Level 1b) products are the preferred deliverable for many, if not all, NWP users. Centres applying variational data assimilation methods will certainly prefer to use Zenith Total Delay (or possibly Slant Delay in the future) than Integrated Water Vapour, which requires *a priori* data and various assumptions or simplifications in order to be derived from ZTD. In case an NWP centre needs Integrated Water Vapour (IWV) that quantity can be derived locally from the given ZTD values using the methods indicated in Annex 1.

Traditionally, Climate users would have preferred to use standard meteorological quantities (IWV in this case), but are increasingly realising the benefits of using data in a more 'raw' form which does not contain significant amounts of *a priori* information – be this in the form of background data (observation or model) or simplifying assumptions – in order to derive Level 2 data from Level 1 [RD.13]. The use of reanalysis products (such as those from ECMWF or NCEP) will implicitly have used the NWP assimilation of ZTD. Climate model validation is also optimally done in ZTD-space by using similar forward operators to those in the NWP models to map model parameters to ZTD and comparing with the observed ZTD. Hence we may say that Climate applications will also require ZTD data. Some may require IWV for analysis, but in this case they can be expected to prefer to make the conversion themselves.

However, in nowcasting applications there is certainly a need for IWV rather than ZTD, since the former is more familiar to forecasters and (if correctly converted) is independent of the synoptic pressure pattern and orography, though there will still be some correlation with temperature.

For the purposes of E-GVAP-II, we may assume that Research users will mostly require ZTD, but some may prefer IWV products, or access to supporting meteorological observations to convert ZTD to IWV themselves. R&D into Space Weather suggests that TEC products are also required, though the detailed requirements akin to the WMO tables are not yet mature.

It was noted in Section 2 that an observation system type should be capable of producing (reasonably) homogeneous data quality in space and time. This is important for NWP applications, but it is critical for Climate, and has significant implications for the way that the GWV networks are currently organised and processed.

3.1 Product Classes

We identify here a number of classes of product:

- **NRT** : the current near-real time (hourly ZTD) product for Global and Regional NWP applications. Could also include hourly TEC data for Space Weather Research and possibly future NWP.
- **QRT** : a rapid-update, quasi-real time (sub-hourly ZTD) for Nowcasting and Local NWP applications. This is an extension of the standard hourly NRT processing and products rather than a separately-defined product.
- **OFL** : off-line (ZTD) products similar to NRT but which may use (for instance) more accurate GNSS orbit and clock data, or to gather more GNSS stations with a penalty of a longer delivery delay. These products may be more suitable for Research applications
- **CLM** : climate-quality (ZTD and IWV) products. This implies the data is re-processed to a homogeneous quality using an agreed best/standard, and probably central, processing system for individual stations and epochs. Other climate products could potentially be time-averaged gridded (Level 3) products.

In addition, the following supporting items – not considered to be 'products' as such – are necessary for optimum exploitation by users:

VAL : validation products[10] for each of the above data products. This includes the current comparison against NWP model(s), radiosonde and other *in situ* observations of equivalent parameters; centralised quality control including monitoring of supersites; network monitoring (consistency of location solutions, etc).

SFT : software products supporting the use of GWV data for the identified application areas. As a minimum this would include portable code for I/O of GWV data in standard file formats such as netCDF and BUFR, but ideally should also include support for NWP assimilation, such as Forward Model 'observation operators' (plus their Tangent Linear & Adjoint) codes, assimilation-time quality control etc.

USR : user-services in the form of documentation of data products, software and file format specifications, a central Helpdesk, organisation of user workshops and training events, promotion of GWV and other supporting services.

Note that in the context of the E-GVAP-II project only **NRT** and associated **VAL** products, with best-efforts support in the form of some software packages and file documentation are within scope. *Other products are to be considered as being future deliverables and requirements for them noted in this document shall be considered as only a starting point for discussion and not as any commitment of E-GVAP-II to actually provide such products, even at experimental or prototype status.*

3.2 Identification of Requirements

In this document, the term '*shall*' denotes a mandatory requirement; '*should*' denotes a highly desirable option that is expected to be fulfilled where at all possible; and *'may'* denotes an option which is' nice to have' but could be left unfulfilled.

The requirements in this document are uniquely identified as follows:

PRD-m-nn

where *m* represents the requirements group identifier (deliverables) and *nn* is the group requirement number. The following group identifiers are used:

1 General, covering all products and services.
2 Near- and quasi-real time ZTD product
3 Off-line products
4 Climate products
5 Validation
6 Software and other user support services

In the following requirements, '*Product Ref. GWV-<n>*' refers to the ID of the product specification tables in Section 4.

3.3 General

PRD-1-01 The E-GVAP-II project shall develop an operational capability to process GNSS data in near-real time to user products according to the specifications in Product Ref. GWV-01 (as a minimum), plus GWV-02, GWV-03, GWV-04 and GWV-05 as options.

PRD-1-02 The E-GVAP-II project should develop a capability to process GNSS data to ZTD products in quasi-real time, according to the product specifications in Product Ref. GWV-06

PRD-1-03 The E-GVAP-II project should develop the capability to re-process GNSS data to products according to specifications in Product Ref. GWV-07 and GWV-08. This capability should be used to regularly generate off-line products and at certain key points, to re-process the complete dataset up to that point to a common best-practice standard.

[10] *For SAFs, EUMETSAT class validation information as a 'service' rather than a separate product.*

PRD-1-04 The E-GVAP-II project should develop a capability to generate products for climate applications, according to the product specifications in Product Ref. GWV-07 and GWV-08.

PRD-1-05 The E-GVAP-II project shall develop and maintain a software package to support user exploitation of GWV data.

PRD-1-06 E-GVAP-II near-real time, offline and climate products shall conform to appropriate internationally-agreed standards for file formatting.

PRD-1-07 E-GVAP-II products shall be made available to users within the timeliness requirements specified for each Product and via appropriate dissemination methods and file formats.

PRD-1-08 All E-GVAP-II deliverables (products, datasets and software) shall be available freely and on a non-discriminatory basis (but possibly with certain usage restrictions) to users according to EUMETNET data policy.

PRD-1-09 E-GVAP-II products shall be archived for a period of no less than 10 years after the end of the project. A third-party archive centre may be used to provide this service, which shall conform to PRD-1-08

PRD-1-10 Archived products shall be capable of extraction, with no degradation to the original product quality, on user request.

PRD-1-11 Archived products shall be available to users in the same file formats as used for the original archived data.

3.4 Near- and quasi-real time products

PRD-2-01 NRT product files shall contain all required parameters with appropriate annotation including date/time and geodetic location, error estimates and quality control flagging, plus appropriate meta-data. NRT product parameter specifications are as presented in Product Refs. GWV-01 to GWV-05.

PRD-2-02 Of those NRT products available in a raw (e.g. RINEX) format, more than 95% shall be processed to ZTD (as a minimum) and disseminated to users within 1.5 hours of observation time. This availability rate shall be calculated over an appropriate period (e.g. 24 hrs, 7 or 28 days, 1 calendar month).

PRD-2-03 NRT products shall be stored in netCDF format for general exchange and archiving.

PRD-2-04 NRT products for NWP users shall be disseminated via the GTS and shall use the WMO FM94 (BUFR) encoding format.

PRD-2-05 Any NRT product delayed by more than 24 hours from observation time shall not be disseminated via the GTS as an NRT product, but shall be available for off-line access.

PRD-2-06 NRT products shall be archived according to PRD-1-10 and PRD-1-11.

PRD-2-07 The E-GVAP-II project should develop the capability for rapid-update, sub-hourly processing for QRT products with the objective of significantly improving the standard hourly NRT timeliness to meet requirements for Nowcasting and Local NWP applications.

3.5 Off-line products

PRD-3-01 OFL products for general Research applications should be generated to take advantage of

GNSS data not meeting the timeliness requirements for NRT products (delayed access to raw receiver data, improved POD data, synoptic observations, NWP analyses etc) and/or using improved algorithms not appropriate to the NRT requirements. OFL products shall contain all required parameters with appropriate annotation including date/time and geodetic location, error estimates and quality control flagging, plus appropriate meta-data. OFL product parameter specifications are as presented in Product Ref. GWV-09.

PRD-3-02 E-GVAP-II should have the capability to process data from stations other than European networks to generate off-line products to the same specification (within the limits of the available data) as the NRT products but with extended coverage.

PRD-3-03 OFL products shall contain at least the same parameters as the near-real time products, although domain, sampling, accuracy and numbers of samples may be improved to meet non-NWP user requirements; meteorological information and derived parameters should be included.

PRD-3-03 OFL products shall be stored in netCDF format for general exchange and archiving, in a compatible manner with the NRT equivalent products.

PRD-3-04 At least 98% of all available raw data shall be processed to products and shall be available to users within 30 days of observation time. This availability rate shall be calculated over an appropriate period (e.g. 3, 6 or 12 calendar months)

PRD-3-05 Off-line products shall be made available to users via appropriate links, channels or media using standard file formats such as netCDF.

PRD-3-06 Off-line products shall be archived according to PRD-1-10 and PRD-1-11.

3.6 Climate products

PRD-4-01 Climate products should be generated from best-quality off-line products. Climate product parameter specifications are as presented in Product Refs. GWV-07 and GWV-08.

PRD-4-02 As well as individual station data, Climate products should include Level 3 [RD.14], [RD.15] gridded monthly means at various spatial resolutions together with estimates of corresponding errors.

PRD-4-03 Climate products should be made available to users via appropriate links, channels or media using standard file formats such as netCDF, formatted text and images.

PRD-4-04 Climate products shall be archived according to PRD-1-10 and PRD-1-11.

3.7 Validation

PRD-5-01 The E-GVAP-II project shall generate, and make publicly available, validation information supporting all of its products using information obtained from NWP fields and in-situ measurements (radiosondes, WVR, etc)

PRD-5-02 Validation shall include statistics on the consistency (site 3-D location), quality (bias, standard deviation) of key parameters, quantity of products and on the timeliness of NRT product dissemination. Validation information shall be provided by individual GNSS stations and collectively by Analysis or Processing Centre.

PRD-5-03 Validation statistics shall be generated with a time resolution of 1 day and 1 month.

PRD-5-04 Product validation information shall be made publicly available via the project's website.

PRD-5-05 Product validation information shall be archived such that long-term trends in data quality may be monitored.

3.8 Software and other User Support Services

E-GVAP-II should include information services such as user documentation, education and Helpdesk and other web-based resources for its products, plus supporting users through holding workshops. In this context, the term 'user' is any person or institute not directly participating in, or contributing to, the E-GVAP project, whether in a signed-up EUMETSAT Member State or not. E-GVAP-II participating members are assumed to have full access to all data, software etc, without the need for formal requirements specified here.

PRD-6-01 E-GVAP-II shall make available software supporting I/O for the file formats employed for dissemination and archiving. It should extend this package to software supporting NWP assimilation of GWV data in variational data systems. This package shall include key user documentation describing the software, and shall include: Release Notes, User Guide and Reference Manual(s), and shall include appropriate build/installation tools and instructions for their use.

PRD-6-02 Software shall be coded in ISO-standard high-level languages (principally Fortran-95) with supporting scripts (e.g. Bash/Perl/Python) and shall follow programming standards guidelines. The code shall be designed to be portable so as to be capable of being built, installed and run on a variety of different POSIX-compliant platforms and compilers. The source code shall be maintained under a version control system.

PRD-6-03 Access to E-GVAP-II software deliverables shall require the user to agree to a User Licence and register as a user (so they can be notified of updates), but the software shall be available at no charge and on a non-discriminatory basis. The Software Licence may have certain restrictions, according to EUMETNET Data Policy.

PRD-6-04 E-GVAP-II shall make the software and associated supporting documentation and datasets available or download from the project website and/or FTP server. An automated User Licence and Registration system meeting PRD-6-03 should be implemented.

PRD-6-05 E-GVAP-II shall establish and maintain a project website as an on-going service to users. This user service shall include (but not be limited to) news and announcements about, and information and documentation on, E-GVAP-II products, validation, software and data sets; technical and scientific reports; announcements of seminars and workshops; information on how to contact the E-GVAP-II project members; and how to apply for access to data products and software.

PRD-6-06 E-GVAP-II shall implement a user interface function (Helpdesk) for users to report problems, request help or give other feedback. The Helpdesk facility shall track user interactions, and shall acknowledge receipt of a new contact. Helpdesk shall answer at least 90% of requests within 3 working days. Resolution of an issue depends on its complexity, and is thus not guaranteed.

PRD-6-07 Except for NWP users obtaining NRT products via the GTS, access to E-GVAP-II products (data, software) shall require the user to first register their details. GTS users shall be encouraged to also register.

PRD-6-08 User Services shall include a User Notification service as an option for registered users to be notified by email of changes to operational or off-line products, software or data sets or on their availability via the GTS, website, FTP server or external archive centre, or other news, as appropriate to the user's registered group(s).

4. Product Specifications

The following tables summarize the specifications for each E-GVAP product. These specifications are partly driven by the generic user requirements (URs) but acknowledge the practical limitations of this data type, and these may or may not meet the URs in full or even in part. The limitations may in some cases be overcome by continued development; in others they may be out of the control of the E-GVAP-II project (like network density) and yet others may be fundamental to the observation type.

What these *product* specifications are intended to indicate, however, is the performance that users can expect from this particular data type as (a) the minimum, (b) mostly achievable today, and (c) the best likely (with further development). Note that (c) does not need to (and should not) exceed the UR; on the other hand, even the best possible performance might still fall short of the UR.

Note that 'threshold', 'target' and 'optimal' need not be met simultaneously for all performance criteria for the data to be useful.

Definitions:

Threshold	The minimum performance limit which is needed so that the product is considered as being useful
Target	The product performance that is targeted in the development and the validated reference performance before (pre-)operational product generation and dissemination.
Optimal	The performance that can be reached under optimum conditions
Horizontal Sampling	Network mean nearest-neighbour separation distance[11]
Timeliness	Maximum time difference from observation to user for fastest 95% of observations processed (i.e. up to 5% of observations may arrive later than this time)

[11] *In the case of E-GVAP, only within the bounds of the land-based receiver network(s), so discounting large gaps, e.g. across large bodies of water.*

4.1 NRT – Global and Regional NWP

Ref: GWV-01	**Name: Hourly ZTD Product**		**Abbrev: HZTD**
Type	NRT Zenith Total Delay Product – standard hourly data		
Applications and users	Global and Regional NWP		
Characteristics and Methods	Standard GNSS processing		
Comments	Primary product for E-GVAP-II		
Generation frequency	Hourly		
Input data	Raw GNSS receiver data, external orbit/clock data		
Verification method	NWP, Radiosonde, WVR, WV Lidar		
Performance			
	Threshold	Target	Optimal
Accuracy	15 mm	10 mm	5 mm
Timeliness	2 h	1.5 h	1 h
Spatial coverage	Europe	Europe + N.America	Global
Horizontal Sampling	200 km	100 km	30 km
Dissemination			
Format	Means	Type	
BUFR, netCDF	GTS, FTP	NRT	

Ref: GWV-02	Name: Hourly ZWD Product		Abbrev: HZWD
Type	NRT Zenith Wet Delay Product – standard hourly data		
Applications and users	Global and Regional NWP		
Characteristics and Methods	ZTD minus estimated ZHD using surface pressure data		
Comments	Depends on availability and accuracy of external data		
Generation frequency	Hourly		
Input data	GNSS ZTD (HZTD product), external AWS/SYNOP/NWP		
Verification method	NWP, Radiosonde, WVR, WV Lidar		
Performance			
	Threshold	Target	Optimal
Accuracy	5 mm	2 mm	1 mm
Timeliness	2 h	1.5 h	1 h
Spatial coverage	Europe	Europe + N.America	Global
Horizontal Sampling	200 km	100 km	30 km
Dissemination			
Format	Means	Type	
BUFR, netCDF	GTS, FTP	NRT	

Ref: GWV-03	Name: Hourly IWV Product		Abbrev: HIWV
Type	NRT Integrated Water Vapour Product – standard hourly data		
Applications and users	Global and Regional NWP		
Characteristics and Methods	Derived from HZTD or HZWD product using surface temperature data		
Comments	Depends on availability and accuracy of external data		
Generation frequency	Hourly		
Input data	GNSS ZTD/ZWD (HZTD or HZWD products), external AWS/SYNOP/NWP		
Verification method	NWP, Radiosonde, WVR, WV Lidar		
Performance			
	Threshold	Target	Optimal
Accuracy	5 kg m^{-2}	2 kg m^{-2}	1 kg m^{-2}
Timeliness	2 h	1.5 h	1 h
Spatial coverage	Europe	Europe + N.America	Global
Horizontal Sampling	200 km	100 km	30 km
Dissemination			
Format	Means	Type	
BUFR, netCDF	GTS, FTP	NRT	

Ref: GWV-04	Name: Hourly Slant Total Delay Product		Abbrev: HSTD
Type	NRT Slant Total Delay Product – standard hourly data		
Applications and users	Research, with potential for use by Global and Regional NWP		
Characteristics and Methods	Standard GNSS processing		
Comments	Direct individual satellite-to-ground slant delays, *not* derived from ZTD by mapping functions. Assumed to be provided at the same nominal observation times as for HZTD product values.		
Generation frequency	Hourly		
Input data	Raw GNSS receiver data, external orbit/clock data		
Verification method	Ray-trace through 3-D NWP-modelled refractivity fields		
Performance			
	Threshold	Target	Optimal
Accuracy	20 mm	15 mm	10 mm
Timeliness	2 h	1.5 h	1 h
Spatial coverage	Europe	Europe + N.America	Global
Horizontal Sampling	200 km	100 km	30 km
Dissemination			
Format	Means	Type	
BUFR, netCDF	GTS, FTP	NRT	

Ref: GWV-05	Name: Hourly TEC Product		Abbrev: HTEC
Type	NRT Total Electron Content Product – standard hourly data		
Applications and users	Research, with potential for use by Global and Regional NWP		
Characteristics and Methods	Derived from ionospheric delay (geometry-free solution)		
Comments	May require separate processing to ZTD (depends on software package in use)		
Generation frequency	Hourly		
Input data	GNSS		
Verification method	GPS RO TEC, Ionospheric models		
Performance			
	Threshold	Target	Optimal
Accuracy	5 TEU	2 TEU	1 TEU
Timeliness	2 h	1.5 h	1 h
Spatial coverage	Europe	Europe + N.America	Global
Horizontal Sampling	200 km	100 km	30 km
Dissemination			
Format	Means	Type	
BUFR, netCDF	GTS, FTP	NRT	

4.2 QRT - Nowcasting & Local NWP

Ref: GWV-06	**Name: Sub-Hourly ZTD Product**		**Abbrev: SZTD**
Type	QRT Zenith Total Delay Product		
Applications and users	Nowcasting and Local NWP		
Characteristics and Methods	Sub-hourly, rapid-update processing, minimal delivery delays		
Comments	Temporal sampling should not result in significant error correlation between individual ZTD samples. Minimal timeliness is the driver for these applications, not temporal resolution.		
Generation frequency	Sub-hourly		
Input data	GNSS, external orbit/clock data		
Verification method	NWP, Radiosonde, WVR		
Performance			
	Threshold	Target	Optimal
Accuracy	15 mm	10 mm	5 mm
Timeliness	1 h	30 min	15 min
Spatial coverage	Europe	Europe to National	Regional to National
Horizontal Sampling	100 km	50 km	20 km
Dissemination			
Format	Means	Type	
BUFR, netCDF	GTS, FTP	NRT	

If a sub-hourly ZTD product were to be developed to address the requirements for Nowcasting & Local NWP, while continuing to meet the needs for Global and Regional NWP, then a future SZTD product could in principle replace, or be merged with, the HZTD product.

4.3 OFL - Research

Ref: GWV-09	Name: Offline ZTD Product		Abbrev: OZTD
Type	Offline Zenith Total Delay Product		
Applications and users	General research applications		
Characteristics and Methods	Best-quality off-line processing		
Comments	Delayed product to maximise station coverage and optimal ancillary data. Timeliness may be limited by availability of IGS Final orbits (currently 12-18 days in arrears)		
Generation frequency	Daily (in arrears)		
Input data	Individual stations or combined solution GNSS, post-processed external orbit/clock data		
Verification method	NWP, Radiosonde, WVR, WV Lidar		
Performance			
	Threshold	Target	Optimal
Accuracy	10 mm	7 mm	4 mm
Timeliness	2 months	1 month	2 weeks
Spatial coverage	Global	Europe to National	Regional
Horizontal Sampling	300 km	100 km	50 km
Dissemination			
Format	Means	Type	
netCDF	FTP, DVD	OFL	

Ref: GWV-10	Name: Offline IWV Product		Abbrev: OIWV
Type	Offline Integrated Water Vapour Product		
Applications and users	General research applications		
Characteristics and Methods	Best-quality off-line processing. Derived from OZWD product using surface temperature data or NWP		
Comments	Delayed product to maximise station coverage and optimal ancillary data		
Generation frequency	Daily (in arrears)		
Input data	GNSS ZTD/ZWD (OZTD product), external AWS/SYNOP/NWP		
Verification method	NWP, Radiosonde, WVR, WV Lidar		
Performance			
	Threshold	Target	Optimal
Accuracy	5 kg m^{-2}	2 kg m^{-2}	1 kg m^{-2}
Timeliness	2 months	1 month	2 weeks
Spatial coverage	Global	Europe to National	Regional
Horizontal Sampling	300 km	100 km	50 km
Dissemination			
Format	Means	Type	
netCDF	FTP, DVD	OFL	

See also requirements for NRT Slant Delays (GWV-03/HSTD) and Total Electron Content (GWV-04/HTEC) which might be initially prototyped under similar Offline (Research) application products.

4.4 CLM - Climate applications

Note that the accuracy requirement is for individual Level 1b (ZTD) or Level 2 (IWV) observations. Climate applications can reduce the RMS errors significantly by temporal averaging over (for instance) calendar months to generate Level 3 products according to application.

Ref: GWV-07	**Name: Climate ZTD Product**		**Abbrev: CZTD**
Type	Climate Zenith Total Delay Product		
Applications and users	Global and Regional Climate		
Characteristics and Methods	Best-quality off-line processing		
Comments	Optimal long-time series, homogeneous, data quality. This will require occasional back-processing of all archived data using current best-practice processing and ancillary data		
Generation frequency	Daily (in arrears) or Monthly		
Input data	Raw GNSS receiver data, external post-processed orbit/clock data, combined solutions		
Verification method	NWP, Radiosonde, WVR, WV Lidar		
Performance			
	Threshold	Target	Optimal
Accuracy	10 mm	7 mm	4 mm
Timeliness	3 months	2 months	1 month
Spatial coverage	Global	Europe to National	Regional
Horizontal Sampling	300 km	100 km	50 km
Dissemination			
Format	Means	Type	
netCDF	FTP, DVD	OFL	

Ref: GWV-08	**Name: Climate IWV Product**		**Abbrev: CIWV**
Type	Climate Integrated Water Vapour Product		
Applications and users	Global and Regional Climate		
Characteristics and Methods	Best-quality off-line processing. Derived from CZWD product using surface temperature data or NWP		
Comments	Depends on availability and accuracy of external data		
Generation frequency	Hourly		
Input data	GNSS ZTD/ZWD (HZTD or HZWD products), external AWS/SYNOP/NWP		
Verification method	NWP, Radiosonde, WVR, WV Lidar		
Performance			
	Threshold	Target	Optimal
Accuracy	5 kg m^{-2}	2 kg m^{-2}	1 kg m^{-2}
Timeliness	3 months	2 months	1 month
Spatial coverage	Global	Europe to National	Regional
Horizontal Sampling	300 km	100 km	50 km
Dissemination			
Format	Means	Type	
netCDF	FTP, DVD	OFL	

Climate products may also potentially be required at Level 3 [RD.14], [RD.15] – e.g. as averaged monthly time-series or 2-D gridded monthly mean fields of ZTD (or IWV) – but this is beyond the scope of the current E-GVAP-II project.

5. Operational Guidelines

This section gives some points of guidance to Analysis Centres (AC) supplying NRT data for operational NWP directly or via the GTS, that have been requested from the end-users.

It must be understood that while good quality observational data can assist in production of accurate NWP forecasts, relatively small amounts of poor-quality data can cause serious degradation to a forecast. It is implicit in the formulation of modern variational analysis techniques that the data to be assimilated has normally-distributed (Gaussian) errors with zero-mean systematic error. Bad data can usually be detected and removed, but data having errors just within the tolerance of *a priori* expected error bounds may still pass this quality control step. These guidelines should be followed to minimise the possibility of erroneous data getting into operational assimilation systems.

1. Whenever an AC is about to make a significant change to their network or processing software etc, they are asked to give advance notice (ideally at least a week), so that end users – especially those operationally assimilating the data – can be warned. Users can then keep a closer eye on things when the change occurs, just in case of problems. Some users may prefer to stop assimilation temporarily and only re-introduce the data after a period of monitoring to confirm the data quality. Small changes, like adding or removing one or two sites, or re-adjusting station coordinates (if within a few metres), does not need any action.

2. When an AC is planning on replacing an operational stream with another (for instance implementing a significantly updated or new processing system), a period of overlap (of at least 4 weeks) is requested. The test-operational data can be provided to GTS users via a different stream for separate monitoring, and when end-users agree, the test-data may be swapped over to become the operational stream, replacing the old one. This may require coordination with the central E-GVAP server host/BUFR conversion centre (currently the Met Office).

3. Planned changes should be made only during normal working hours, preferably not late in the afternoon, and never on a Friday afternoon. Tuesdays mornings are traditional 'change days' in many NWP centres (leaving Mondays to fix any weekend issues, and the rest of the week to check that the change did what was expected), though other days are of course acceptable for external changes.

4. Unplanned changes because of unexpected circumstances to correct a problem should of course be made at the earliest opportunity, though users should be informed as soon as possible what the problem was. Users may not be able to retrospectively do anything about it, but operational centres generally keep logs of such issues which might potentially correlate with NWP forecast anomalies (in the worst case).

5. Known (planned or otherwise) loss of data being uploaded to the E-GVAP server or via the GTS should also be notified, with an estimate of when the data flow might be restored.

6. No new sites should be included in the NRT (or BUFR) files until the station details (notably the 3-D location solutions) are verified by the AC to be valid and stable. This may mean processing the new site(s) but just not writing it to the NRT file for (say) the first month after initial acquisition.

These guidelines are not only for the users' benefit, but also for the AC, as they will get more rapid feedback on any issues which should be easier to correlate with the change they made. There have been many cases – for almost all data types – where a “transparent change not affecting the users” has turned out to be anything but transparent.

Although tailored for E-GVAP data, the above guidance is fairly generic (except item 6, but there are parallels for other data types), and is standard user-expectation for all suppliers of (semi-)operational data; it applies equally to entities such as EUCOS, EUMETSAT, ESA, NOAA, NASA and other satellite, radar and aircraft data providers.

ANNEX 1. Ground-based GNSS data processing

A1.1 GNSS signal processing to delay parameters

Global Navigation Satellite System (GNSS) signals are delayed due to 'neutral' molecules in the atmosphere[12]. In high precision geodetic applications this delay is estimated along with the geodetic parameters by introducing so-called Zenith Total Delay (ZTD) parameter [RD.16]. The ZTD can be separated into a hydrostatic delay, due to the dry components of the atmosphere (also known as the Zenith Hydrostatic Delay, ZHD), and a Zenith Wet Delay (ZWD) due to the dipole moment of the water vapour in the atmosphere [RD.17]. The interest of meteorology lies in the estimation of this wet delay as a measure of the amount of water vapour in the atmospheric column overlying a receiver.

In the process of estimating the ZWD for a particular receiver location from the signals of the available GNSS satellites, the Slant Total Delays (STD) from these transmitters are modelled with the help of an *a priori* estimate of the Zenith Hydrostatic Delay (ZHD) and *a priori* functions mapping the hydrostatic and wet delays to the slant direction. The most commonly used mapping functions are those derived by Neill [RD.18] by ray-tracing several years of radiosonde profiles. The Neill mapping functions are functions of elevation, latitude, altitude and day of year, with separate functions for mapping the dry and wet components:

$$STD = mf_{hyd} \times ZHD + mf_{wet} \times ZWD \qquad \text{(A1)}$$

ZHD can be approximated using an estimate (or better, a local measurement) of the atmospheric pressure P_a at the receiver antenna height H_a (from Saastamoinen, [RD.19]):

$$ZHD = \frac{k_1 R_d P_a}{9.784(1 - 0.0026\cos(2lat) - 2.8.10^{-7} H_a)} 10^{-3} \quad \text{[mm]} \qquad \text{(A2)}$$

where k_1 is 77.6 K hPa^{-1}, R_d is the specific gas constant for dry air (287.0586 J kg K^{-1}) and lat is the latitude in degrees.

However, during the GNSS data processing stage, accurate surface pressure measurements are not usually available to compute the ZHD, and thus an approximate value for ZHD is computed using a standard atmosphere. GNSS processing centres generally have different ways to estimate ZHD and sometimes use different mapping functions. Therefore, ZTD and not the derived ZWD, is the preferred quantity to be exchanged. The ZTD value can be assimilated into a numerical weather prediction model, or the ZWD can be extracted from the ZTD by subtraction of a more accurately computed ZHD using NWP model estimates or measurements of surface pressure from nearby synoptic reports. A surface pressure accuracy of about 1 hPa is sufficient for this purpose.

Also the way in which the ZWD is modelled, and therefore ZTD, can be different for different GNSS processing centres. The ZWD is modelled in some of the GNSS analysis software as a random walk process, assuming a known *a priori* power spectral density. In these cases the ZWD is estimated every epoch, but the model is further strengthened by assuming that the difference between two epochs has zero mean with a standard deviation related to the assumed power spectral density and interval. In other software packages the ZWD is modelled as a step function, e.g. estimating one ZWD parameter every 20 to 60 minutes, depending on the analysis centre. Also when the ZWD is modelled as a step function, relative constraints are sometimes applied between consecutive estimates of ZWD. The actual interval used for the ZWD, and therefore the interval for ZTD, may differ depending on the processing centre. The raw GNSS data is usually provided at 30–second intervals using hourly files. However, some of the processing centres choose to sub-sample the GNSS data into intervals of e.g. 5 minutes.

[12] *Signals are also delayed by the active electron layers of the ionosphere; in this case, the delay is dispersive (frequency-dependent) and the effect can be removed to first order by a linear combination of the L1 and L2 (or other) signals. This document hereafter assumes that ionospheric correction has been pre-applied, and we are only concerned with the influence of the neutral atmosphere. Total Electron Content (TEC) can be related to the ionospheric delay correction.*

A1.2 Characteristics of GNSS network systems

Zenith Total Delay (ZTD) is estimated along with several other geodetic parameters. The parameters that are estimated depend to a large extent on the domain of the receiver network. The network of the International GNSS Service (IGS) [RD.20] is a world-wide network of 200–300 receivers and is mainly used to estimate precise orbits and clock parameters for the GNSS satellites. Other parameters that are estimated are the daily station coordinates, receiver clock errors, ZTD and phase ambiguities, as well as Earth rotation parameters (ERP). Delays due to the ionosphere are estimated by using a linear combination of phase measurements on two frequencies, thereby eliminating the first order ionosphere delay. Other short periodic effects, such as solid earth tides, ocean tide loading, phase wind-up, antenna elevation dependent delays, etc., are taken care of by using *a priori* models. There are three main types of IGS products:

- Ultra-rapid orbits (available twice daily) which include a prediction for up to one day
- Rapid orbits, satellite clocks and ERP (available after two days)
- Final orbits, satellite clocks and ERP (available after two weeks)

The main objective of the IGS network is to define a global and long-term stable reference frame, based on ITRF [RD.21], below the centimetre level accuracy level for the ground based stations and at the centimetre level for the satellite orbits.

The IGS products can be used in other ground-based networks for both geodetic and meteorological purposes. The final IGS satellite orbits and ERP are used for instance in the EUREF Permanent Network (EPN) [RD.22], a regional densification of the IGS network in Europe of about 200 receivers. The EPN provides daily coordinate time-series, and plays a crucial role in the maintenance of the European part of the terrestrial reference frame. The EPN network is a very robust network that is well monitored, and every station is processed by at least three (of a total of 14) EPN analysis centres. The EPN also provides time-series of hourly estimates of ZTD, which is also a combined product of the individual analysis centres and is available with a delay of 2–3 weeks.

A1.3 GPS network processing strategies

Two different strategies can be used for the processing of local and regional networks:

Network approach using zero or double difference

In the network approach only IGS orbits and ERP parameters are used. The IGS satellite clock parameters are not used as the satellite clock parameters are estimated in the network along with the other parameters such as station coordinates, receiver clocks, ZTD and phase ambiguities. Within the network approach broadly two different methods exist: double and zero difference processing.

In the double differencing method, the satellite and receiver clock parameters are eliminated on an epoch-by-epoch basis by forming differences of the observations. First, observations of two different receivers to the same satellite are subtracted, eliminating the satellite clock parameters, giving the so-called single difference. Next, two single differences are subtracted to eliminate the receiver clock parameter, giving the double difference. This greatly reduces the amount of parameters to be estimated in the batch least squares adjustment, leaving only station coordinates, phase ambiguities and ZTD to be estimated. In the zero-difference approach the satellite and receiver clock parameters are estimated along with the other parameters, usually using a Kalman-filter type of approach. However, this differencing can amplify random errors, and works best with high-accuracy ultra-stable oscillator receiver clocks.

The zero difference and double difference methods in theory give identical results, although the implementation in software may result in small differences. The main advantage of the double difference approach is that it results in normal equations, which later on can be combined to constrain the solution or combine different estimates. The main advantage of the zero difference approach is that it is slightly more flexible with respect to changes in the tracking configuration. The other advantage is that it usually uses a Kalman filter (although a Kalman filter is sometimes also used in single or double difference processing), and is therefore is a little more flexible in modelling the temporal changes of parameters such as ZTD.

The domain of the receiver network is important. In a local network only coordinate and ZTD differences between two stations can be estimated; this is because the satellite clock parameters have to be estimated as well. Absolute ZTDs can be estimated only when the network covers a reasonably large region, because then the same satellite is seen from different elevation angles at different stations, allowing the estimation of both satellite clock parameters as well as absolute ZTD.

Precise Point Positioning (PPP) approach

In the Precise Point Positioning (PPP) approach, both previously estimated satellite orbits and ERP are used, as well as satellite clock parameters [RD.23]. Therefore, for each receiver, only station coordinates, epoch-wise receiver clock parameters, ZTD and phase ambiguities have to be estimated. One of the advantages of the PPP approach is that stations can be processed station by station, and that it is not necessary to process a regional network.

The disadvantage of the PPP approach that it is much more difficult to estimate integer phase ambiguities, as is often done in the network approach. In the PPP approach this is only possible when several stations are processed together. It is essential in the PPP approach that orbits, ERP and satellite clock parameters come from the same source as in general these parameters are highly correlated. This is a problem in particular for near-real time applications, because the IGS ultra-rapid products cannot provide an accurate clock prediction. Therefore, for near-real time applications analysis centres that use a PPP approach either precede their PPP processing by a global network adjustment in order to get good orbits and satellite clocks, or use one of the few near-real time orbit and satellite clock products that are available at present. It is expected that in future the number and quality of the near-real time orbit and clock products will continue to improve.

A1.4 Other issues of relevance for meteorological applications

The estimated ZTD are spatially correlated, and this is the case both for the network and PPP approach. In the network approach errors in the satellite orbits and the satellite clock parameters that are estimated introduce correlations between the ZTD, which depend on the network size. In the PPP approach correlations between the ZTD are introduced because of common mode errors in the satellite orbits and clocks. Furthermore, in the near-real time processing many of the GNSS processing centres fix (i.e. do not estimate) the station coordinates onto weekly and monthly averages in order to get a more stable ZTD time-series. Although this reduces the noise, it may cause small time varying biases. Also, the ZTD estimation is very sensitive to elevation dependent effects. Errors in the calibration of satellite and receiver elevation-dependent phase delays, or errors in the mapping functions, may result in small systematic effects of a few millimetres in the estimated ZTD. However, using the wrong antenna type in the processing, or fixing the coordinates to the wrong values (e.g. after an earthquake), may result in gross-errors of occasionally up to 1–2 cm in ZTD. In general, the error in the ZTD, and thus ZWD, is below the 10 mm level.

A1.5 Estimation of column water vapour

The total water vapour content (IWV or PW) along the zenith path, equal to the integrated water vapour density in the column, can be derived from the wet delay (ZWD) by using the mean atmospheric temperature, T_m which may be modelled from the surface (screen-level) temperature, T_s:

$$IWV = ZWD / k \quad \text{[kg m-2]} \qquad \text{(A3)}$$

where:

$$ZWD = ZTD - ZHD$$
$$k = R_v (k_3 / T_m + k_2 - k_1 R_d / R_v)$$
$$T_m = 83.0 + 0.673 T_s$$

and k_2 is 70.4 K Pa^{-1}, k_3 is 373900 K^2 hPa^{-1} and R_v is the specific gas constant for water vapour (461.525 J Kg K^{-1}). ZHD may be calculated from Equation A2. Used in this way, co-incident measurements of surface pressure and temperature yield values of column water vapour with accuracy of the order of 1–2 kg m^{-2} on a total content of order 10–40 kg m^{-2} for temperate regions. For a crude estimate, k can be taken to be 6.5.

Because of the additional assumptions (and hence errors) that can be introduced in converting from ZTD to IWV, NWP centres running variational assimilation schemes generally prefer to directly assimilate ZTD values. Here, the model quantities (P,T,q) in the vertical profile above the GPS station coordinates are forward modelled (via 'observation operators') into ZTD-space and the model parameters adjusted to minimize model and observed ZTD within the *a priori* errors of both. [RD.9] gives an example of a ZTD forward operator used within the Met Office's Unified Model.