TOUGH

Targeting Optimal Use of GPS Humidity data in meteorology

USER REQUIREMENTS DOCUMENT

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TOUGH User Requirements Document

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TOUGH User Requirements Document

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Acronyms, Abbreviations and Initialisms

AC	Analysis Centre (of ground-based GPS data – e.g. ASI, GFZ, etc)
ACRI	ACRI–Sciences de la Terre (ACRI-ST, Sophia Antipolis, FR)
ASI	Agenzia Spaziale Italiana (Matera, IT)
BKG	Bundesamt für Kartographie und Geodäsie (Frankfurt am Main, D)
BUFR	Binary Universal Format for the Representation of data (WMO)
CBS	Commission for Basis Systems (WMO)
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)
EC	European Community
ECMWF	European Centre for Medium-range Weather Forecasts (Reading, UK)
ERP	Earth Rotation parameters
EPN	EUREF Permanent GPS network
ESA	European Space Agency
EU	European Union
EUREF	European Reference Frame
FM94	WMO Form no. 94 (i.e. BUFR)
FTP	File Transfer Protocol (under TCP/IP)
Galileo	European GNSS system from 2006 (EU/ESA)
GB-GPS	Ground-Based GPS (in this context for the observation of atmospheric water vapour)
GCM	General Circulation Model
GCOS	Global Climate Observing System
GFZ	GeoForschungsZentrum (Potsdam, D)
GLONASS	Globalnaya Navigatsionnaya Sputnikovaya Sistema (Russia)
GNSS	Global Navigation Satellite System (generic GPS/GLONASS/Galileo)
GOP	Geodetic Observatory Pecny (Pecny, CZ)
GPS	Global Positioning System (USA)
GRIB	Gridded data in Binary format (WMO)
GTS	Global Telecommunications System (WMO)
HIRLAM	High Resolution Limited Area Model
HPUX	Unix operating system for Hewlett Packard workstations
IEEC	Institut d'Estudis Espacials de Catalunya (Barcelona, ESP)
IGS	International GPS Service
ITRF	International Terrestrial Reference Frame
IWV	Integrated Water Vapour
KNMI	Koninklijk Nederlands Meteorologisch Insitut (De Bilt, NL)
LPT or L+T	Bundesamt für Landestopographie (Swiss Federal Office of Topography) (Wabern, CH)
MetDB	Meteorological Data Base (Met Office)
Met Office	NMS of the United Kingdom (Exeter, UK). Also **METO**
NASA	National Aeronautics and Space Administration (USA)
NKG	Nordic Commission of Geodesy
NMS	National Meteorological Service
NWP	Numerical Weather Prediction
PCD	Product Confidence Data
POD	Precise Orbit Determination
PWV	Precipitable Water Vapour
RMDCN	Regional Meteorological Data Communications Network (Europe)
SGN	Service de Geodesie et Nivellement (Toulouse, F)
TBC	To Be Confirmed
TBD	To Be Determined
TCP/IP	TeleCommunications Protocol / Internet Protocol

TOUGH	Targeting Optimal Use of GPS Humidity (EU)
VAR	Variational (NWP data assimilation technique)
USA	United States of America
UTC	Universal Time Co-ordinated (in practice same as Greenwich Mean Time)
WMO	World Meteorological Organisation
WWW	World Weather Watch (WMO)
W3	World Wide Web, component of the Internet data access system
ZHD	Zenith Hydrostatic Delay (component of ZTD due to neutral dry atmosphere)
ZPD	Zenith Path Delay (same as ZTD)
ZTD	Zenith Total Delay (sometimes 'Total Zenith Delay' also ZPD)
ZWD	Zenith Wet Delay (component of ZTD due to water vapour)

1 Introduction

1.1 Purpose of the Document

This document summarises the user requirements of the European meteorological (Nowcasting and NWP) and climate user communities with regard to meteorological data derived from the Global Positioning System (GPS) signals received on the ground. These user requirements were originally gathered under the COST-716 Action by Working Group 3 (Meteorological and Climate Applications) and commented on by Working Group 2 (Demonstration Networks) together with feedback from the Final COST-716 Workshop in De Bilt.

This document forms the TOUGH deliverable item D15 for Work Package WP2000.

The document is intended for members of the TOUGH Project Team, who can use it to check available GPS network products against the evolving User Requirements and thus make any adjustments to meet them. This document also serves as an interface between the TOUGH participants and the representatives of the GPS networking communities. The applicability of this document terminates with the end of the TOUGH project, but requirements herein may be taken as the minimum basis for any future operational GPS network and processing for meteorological applications.

The requirements stated in this document apply to the expected mode of operation of GPS ground based networks, including operation of receiver equipment and network connections between receiver stations and regional processing centres (also called Analysis Centres). The expected operation 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,
- During the demonstration phases the data are expected to be sent from the processing centres to user centres via public networks.
- A sub-set of data, according to the TOUGH Data Policy, may be made available to the NWP community via the GTS in the WMO BUFR format.

1.2 Applicable and Reference Documents

1.2.1 Applicable Documents

The following list contains documents with a direct bearing on the contents of this document.

[AD.1] TOUGH Proposal. EVG2-2-001-00058, 22 July 2002.

[AD.2] COST-716: GPS User Requirements.. COST716/URD/2.6, Version 2.6, April 2004.

1.2.2 Reference Documents

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

[RD.1] WMO (1996). *CBS Working Group on Satellites*. Second Session, 15–19 April 1996, Final Report.

[RD.2] WMO (2002). SAT-26 *Statement of Guidance How Well Satellite Capabilities Meet WMO User Requirements in Several Application Areas*. Technical Document, WMO/TD No. 1052

[RD.3] Higgins, M. (2000). *Simulated 1D-variational assimilation of ground based GPS measurements of total zenith delay*. Met Office Forecasting Research, Technical Report No. 285

[RD.4] de Haan, S (2002). *Derivation routines COST-716*. KNMI, Version 1.2, 8 November 2002

[RD.5] 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.6] Bevis *et al*. (1994). *GPS Meteorology: Mapping Zenith Wet Delays onto Precipitable Water*. Journal of Applied meteorology, **33**, 379-386.

[RD.7] Neill, A.E., (1996). *Global mapping functions for the atmospheric delay at radio wavelengths*. J. Geophys. Res., **101**, 3227-3246.

[RD.8] 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.9] 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*, Journal of Geophysical Research, **102**, No.B3, 5005-5017.

[RD.10] WMO (1988). *Technical Regulations,* Vol.1, Doc.No.49, 1988. ISBN 92-63-18049-0, WMO, Geneva.

[RD.11] WMO (2003). *Affiliate and CEOS Member Requirements*. Mission and Instrument Database (CD-ROM). Version 2.5, February 2003.

[RD.12] COST-716 (2003). *Format specification for COST-716 processed GPS data*. Version 2.0a, 23 September 2003

1.3 Identification of Requirements

The requirements in this document are uniquely identified as follows:

XXX-nnnn

where *XXX* represents the requirements group identifier (products) and *nnn* is the requirement number. The following group identifiers are used:

TOP	Top level generic, covering all products and services.
GMP	GPS Meteorology product
RTV	Near-Real Time Validation product
OLV	Off-Line Validation product

1.4 General Description

The approach to define the User Requirements for ground-based GPS meteorological products is reflected in the the following sections. In Section 2 we give an overview of the capability of GPS receiver systems to provide humidity parameters. To this end the characteristics of geodetic reference networks (IGS, EUREF) have been considered. To serve as a starting point, generic requirements for humidity observations, independent of the observing system used, have been gathered and are presented in Section 3. These basic user requirements have been gathered from WMO documents summarising the needs of several user communities for meteorological products [RD.1]. Requirements for humidity observations specific to the GPS observing system under study are then given in Section 4. These user requirements have been discussed and refined at several occasions with the help of COST-716 Working Groups 2 and 3 and the COST-716 Workshops. Finally, Section 5 shows specific requirements for the TOUGH demonstration data products.

2 Ground based GPS data processing

2.1 GPS signal processing to delay parameters

Global Positioning System (GPS) signals are delayed due to ‘neutral’ molecules in the atmosphere. In high precision geodetic applications this delay is estimated along with the geodetic parameters by introducing so-called Zenith Total Delay (ZTD) parameters [RD.5]. 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.6]. 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 GPS signals, the slant total delays to these GPS satellites are modelled with the help of an *a priori* estimate of the Zenith Hydrostatic Delay (ZHD_0) and *a priori* functions mapping the hydrostatic and wet delays to the slant direction. The mapping functions most commonly used for GPS are those derived by Niell by ray-tracing several years of radiosonde profiles. The Niell mapping functions are functions of elevation, latitude, altitude and day of year [RD.7].

$$STD = mf_{hyd} \times ZHD_0 + mf_{wet} \times ZWD$$

ZHD can be approximated using an estimate or, more precisely, an exact measurement of the pressure at GPS antenna height [RD.8]. However, during the GPS data processing stage usually no accurate ground-pressure measurements are available to compute the ZHD, and thus an approximated value is computed using a standard atmosphere. The effect on ZTD, via the effect on the estimated ZWD, may be neglected if ZHD and ZHD_0 are sufficiently close.

$$\begin{aligned} ZTD = ZHD + ZWD &= ZHD_0 + ZWD + \left[\frac{mf_{hyd} - mf_{wet}}{mf_{wet}} (ZHD - ZHD_0) \right] \\ &\cong ZHD_0 + ZWD \end{aligned}$$

GPS processing centres generally have different ways to compute ZHD_0 and sometimes use different mapping functions. Therefore, ZTD and not the estimated ZWD, is the preferred quantity to be exchanged. The ZTD itself can then be assimilated into a numerical weather prediction model, or the ZWD itself can be extracted from the ZTD by subtraction of a more accurately computed ZHD using estimates or exact measurements of surface pressure from either nearby synoptic reports or from NWP models.

Also the way in which the ZWD is modelled, and therefore ZTD, can be different for different GPS processing centres. The ZWD is modelled in some of the GPS 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 GPS data is usually provided at 30 second intervals using hourly files. However, some of the processing centres choose to decimate the GPS data into intervals of e.g. 5 minutes.

2.2 Characteristics of GPS 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 GPS network. The network of the International GPS Service (IGS) is a world-wide network of 200–300 receivers and is mainly used to estimate precise satellite orbits and satellite clock parameters for the GPS satellites. Other parameters that are estimated are the daily station coordinates, the 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 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, below the cm level accuracy level for the ground based stations and at the cm 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 Earth Rotation Parameters (ERP) are used for instance in the EUREF Permanent GPS Network (EPN), a regional densification of the IGS network in Europe of about 200 receivers. The EPN provides daily coordinate time-series, and plays therefore 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, in total, 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.

2.3 GPS network processing strategies

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

1) Network approach using zero or double difference
2) Precise Point Positioning (PPP) approach

2.3.1 Network approach

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

The zero difference and double difference methods in theory give identical results, although the implementation in software may result in small differences. The main advance 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 time-behaviour of parameters such as ZTD.

The domain of the GPS 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 ZTD's can be estimated only when the network is covering a reasonable 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.

2.3.2 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.9]. Therefore, for each station 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 downside 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. In general these parameters are highly correlated. This is a problem in particular for near-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.

2.4 Other issues of relevance for meteorological applications

The ZTD values estimated by GPS are spatially correlated. 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 GPS 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 mm in the estimated ZTD. However, using the wrong antenna type in the GPS 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.

2.5 Estimation of column water vapour

The total water vapour content (IWV or PWV) 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. An estimate of this mean temperature can be made using an empirical formula containing the surface temperature [RD.6]. 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.

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) are forward modelled (via ‘observation operators’) into ZTD-space and the model parajeters adjusted to minimize model and observed ZTD within the *a priori* errors of both. [RD.4] gives an example of a forward operator used within HIRLAM.

3 Generic User Requirements for Meteorological Humidity Data

The COST-716 Action has identified several classes of users, as noted in [RD.1]. For the purposes of the GPS meteorological network development, we present user requirements for two major classes of users – operational meteorology and climate, where operational meteorology has been divided in two sub-classes of use: qualitative, sort-term meteorological application (Nowcasting) and numerical weather prediction (NWP).

For NWP, there exists an implicit requirement that observation errors should be uncorrelated in time and space and the observations should be free of biases. Given the general introduction about GPS processing above, it is clear that the existing ways of solving for tropospheric parameters may introduce unknown correlations and unknown biases. Here, we only discuss correlation- and bias-free observational requirements. Nowcasting applications are more concerned with relative values (horizontal gradients) than with absolute accuracy, so can tolerate small correlations in the network, though discontinuities between networks should be avoided.

In general, *in situ* humidity observations are reported as relative humidity, the ratio of the actual WV pressure to the saturated WV pressure at the same temperature, and presented as a percentage ([RD.10]). The GPS humidity product is the integral of the water vapour density over the pressure (divided by gravity) profile ([RD.4]). 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.

The requirements originating from WMO ([RD1], [RD.11]).are posted in terms of Column Specific Humidity (CSH). Specific humidity, or q(z), is 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.

The vertical path integral of the specific humidity is then given by:

$$CSH = \int_{surface}^{TOA} q(z)dz = \int_{surface}^{TOA} \frac{\rho_v(z)}{\rho(z)} dz \text{ [kg.kg}^{-1}\text{.m]}$$

where TOA represents the top of the atmosphere. The definition of IWV is:

$$IWV = \int_{surface}^{TOA} \rho_v(z)dz \text{ [kg.m}^{-2}\text{]}$$

Both quantities represent some kind of integrated humidity but are not identical. To show the difference between the definitions, both CSH and IWV have been determined using a sample of HIRLAM NWP results. Figure 1 shows a scatter plot of CSH vs. IWV; values of CSH are approximately 10–15% larger than IWV. This difference originates from the relatively large stratospheric contribution of specific humidity. In the remainder of this document we will use the IWV definition, assuming that the ranges of values given in the WMO tables ([RD.11]) are applicable to both CSH and IWV.

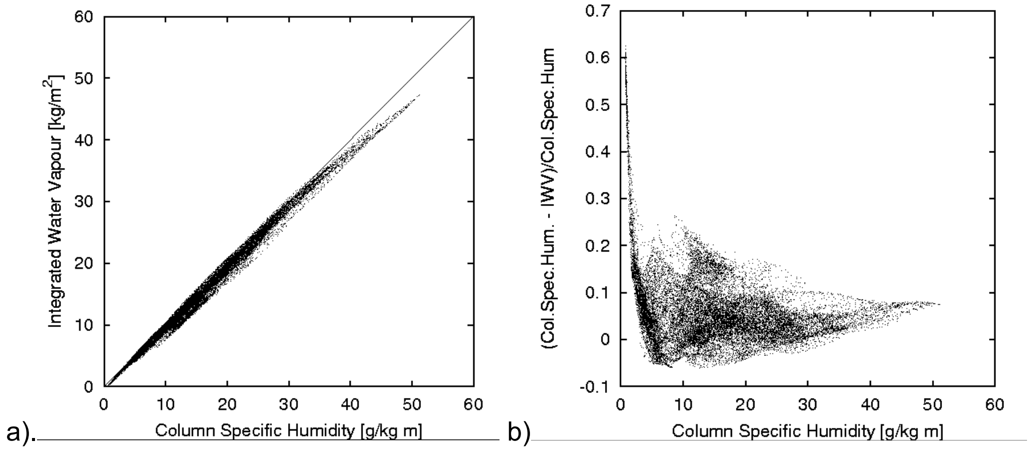

Figure 1. a) Scatter plot of CSH and IWV b) Fractional difference of CSH and IWV with respect to CSH.

3.1 Operational Meteorology

The User Requirements for operational meteorology presented in this document have been extracted from World Meteorological Organisation documentation (WMO database [RD.11]).

A summary of the requirements is shown in Tables 1 and 2. It should be stressed that these requirements are generic, and independent of any particular observing system or technology.

	IWV
Horizontal Domain	Sub-regional
Horizontal Sampling[1)]	5–50 km
Repetition Cycle[2)]	15–60 mins
Absolute Accuracy[3)]	1–5 $kg.m^{-2}$
Timeliness	5–30 mins

Table 1. Generic User Requirements for Nowcasting

	IWV	IWV
Horizontal Domain	Global	Regional
Horizontal Sampling[1)]	50–500 km	10–250 km
Repetition Cycle[2)]	1–12 hrs	30 mins –12 hrs
Absolute Accuracy[3)]	1–5 $kg.m^{-2}$	1–5 $kg.m^{-2}$
Timeliness	1–4 hrs	30 mins – 2 hr

Table 2. Generic User Requirements for Numerical Weather Prediction

Notes:

1) Horizontal sampling in this context means the average horizontal separation distance of observations, and is related to typical nowcasting application (scale of the phenomena) and NWP model resolution.
2) Repetition Cycle is the effective sampling interval at the same location.
3) Integrated Water Vapour is usually expressed in $kg.m^{-2}$ or alternatively as the equivalent height of the precipitable water (PWV) column in mm (1 $kg.m^{-2}$ IWV = 1 mm PWV). To avoid ambiguity with path delay the first notation will be used.
4) Timeliness is the delay from the 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 observations are expected to arrive within the required timeliness value for an operational system.

Error! Reference source not found. explicitly includes users requiring data for regional and/or mesoscale NWP models. In general, the requirements are very similar except that horizontal resolution better than 50 km and timeliness better than 1 hour are preferred for regional NWP applications.

We should note here that User Requirements do not represent a hard cut-off value of 'good/no good'; rather there is often a broad range of acceptability. Where two values are given in the tables, the first one is the target value whereas the second indicates a threshold beyond which data may have marginal use (impact). Data with quality better than the target values may be over-specified, as the additional 'quality' cannot be exploited by the application.

3.2 Climate

Table 3 illustrates in a similar way the generic User Requirements for the climate community, in particular those for climate monitoring and prediction where trends in the past and future are analysed. The noteworthy requirement is for long-term system stability. For climate monitoring it is necessary that the data are homogeneous and do not drift by 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 [Lennart Bengtsson]. For specific (dry) regions these numbers may even be smaller. This is far less than the measurement accuracies of the GPS system at present but 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.

The requirement for timeliness stems from the WMO/GCOS requirements as found in WMO documents ([RD.11]). It may be applicable to some applications, but it is felt that this requirement can in general be relaxed.

	IWV
Horizontal Domain	Regional / Global
Horizontal Sampling	10–100 km
Time Domain	>> 10 years
Repetition Cycle	1 hr
Absolute Accuracy	0.25–2.5 kg.m^{-2}
Long Term Stability	0.02 – 0.06 kg.m^{-2} per decade
Timeliness	3–12 hrs

Table 3. Generic User Requirements for Climate Monitoring and Prediction

4 User Requirements for GPS Meteorology Network Products

From the above generic requirements for total column humidity data, it is clear that the primary goal of the GPS Meteorology Networks should be to provide geophysical (Level 2) products, which meet these. However, from several NWP assimilation trials [RD.3] and the processing practices highlighted in Section 2, it is clear that non-geophysical (Level 1b) products may be the preferred deliverable of the networks for many NWP users. Centres applying variational data assimilation methods may prefer the use of Zenith Total Delay or Slant Delay to the use of Integrated Water Vapour. In case a centre needs Integrated Water Vapour (IWV) that quantity can be derived from ZTD using the methods indicated in Section 2.5. However, in nowcasting and climate monitoring applications there is certainly a need for IWV values rather than ZTD's.

4.1 Operational Meteorology

The main difference with the tables of Section 3 is the introduction of Zenith Total and Slant Delay in Table 5 (Global NWP) and Table 6 (Regional NWP). Also, requirements have explicitly been separated into target and threshold requirements to better illustrate the range of acceptability.

	IWV	
	Target	***Threshold***
Horizontal Domain	Europe to National	
Horizontal Sampling	10 km	100 km
Repetition Cycle[1)]	5 min	1 hr
Integration Time[1)]	MIN(5min, rep cycle)	
Relative Accuracy[2)]	1 kg/m^2	5 kg/m^2
Timeliness	5 min	30 min

Table 4. GPS Meteorology Network Requirements for Nowcasting

	Zenith Total Delay or Slant delay	
	Target	***Threshold***
Horizontal Domain	Global	
Horizontal Sampling	50 km	300 km
Repetition Cycle[1)]	30 mins	2 hrs
Integration Time[1)]	MIN(30 min, rep cycle)	
Absolute Accuracy[3)]	3 mm	10 mm
Timeliness	1 hr	2 hrs

Table 5. GPS Meteorology Network Requirements for Global Numerical Weather Prediction

	Zenith Total Delay or Slant delay	
	Target	***Threshold***
Horizontal Domain	Regional	
Horizontal Sampling	30 km	100 km
Repetition Cycle[1)]	15 mins	1 hr
Integration Time[1)]	MIN(15 min, rep cycle)	
Absolute Accuracy[3)]	3 mm	10 mm
Timeliness	30 min	1h:30min

Table 6. GPS Meteorology Network Requirements for Regional Numerical Weather Prediction

Notes:

1) Requirements for repetition and integration time stem from a requirement that (time) samples should be uncorrelated.
2) Relative accuracy required for quantitative analysis.
3) Absolute accuracy should be better in wintertime.

4.2 Climate

A climate user is probably not only the end user of a climatological product. Therefore a climate user will not only be interested in time- and space-averaged values but preferably in the values in full resolution in time and space as specified in Table 7. 3D analysed fields from NWP assimilation may be one option for deriving gridded data but as long as the influence of the NWP model on the result is still a matter of discussion this should not be the only option. The climatologist will always be interested in the most independent data.

Climate users are unlikely to make direct use of Zenith or Slant delays; they are more likely to either use time- and spaced-averaged individual water vapour columns, or use 3D analysed fields, which have assimilated GPS ground-based meteorology data via NWP systems. Table 7 reflects the average requirements for any realistic network of GPS ground receiver equipment.

	IWV
Horizontal Domain	All
Horizontal Sampling[1)]	10–250 km; individual stations
Time Domain[2)]	Weeks to many years
Repetition cycle[3)]	1 hr
Absolute Accuracy	1 $kg.m^{-2}$
Long Term Stability	0.04–0.06 $kg.m^{-2}$ per decade
Timeliness[4)]	1–2 months

Table 7. GPS Meteorology Network Requirements for Climate Monitoring and Prediction

Notes:

1) Ideally, data for global studies are sampled in regular 2.5^0 x 2.5^0 or 1^0 x 1^0 grids; Each grid box should have >40 independent observations per day in order to meet the absolute accuracy requirement. For local and regional studies (e.g. Baltex) stations are required every 100–200 km but not necessarily arranged in a grid. Sites chosen must reflect climate areas of interest. For special events (e.g. storms or extreme events) higher network density, e.g. comparable to NWP network density, may be required over the region of interest.
2) For climate monitoring the time domain should be in principle be unlimited. However, for climate studies the time stretch for which data are required may be shortened to several (tens of) years. For special events (see note 1) several weeks may be sufficient. For each of these studies climate accuracy is required, obtained through post-processing of the data using accurate orbit parameters.
3) Daily, monthly, yearly, mean diurnal cycle, mean daily means, mean seasonal cycle, mean yearly means over many (30) years etc. are required. These are best based an hourly repetition cycle.
4) W.r.t. Table 3, timeliness has been relaxed to allow for acquisition of accurate orbit data. This is to obtain the best possible absolute accuracy.

5 Specific Requirements for TOUGH data products

The specific requirements given in this Section pertain to the TOUGH project, in which data processing and dissemination is a demonstrator only. Some requirements may not be appropriate to any future operational scenario, for which modified user requirements can be expected. This is particularly relevant to data delivery and archiving.

5.1 Product Description

The participating analysis centres (ACs) of the GPS meteorology network will provide, as a minimum, Zenith Total Delay, together with supporting data for each of the stations in their network. These will be known as 'Level 2' products. The supporting data include at least time, location, receiver altitude, pressure and temperature at receiver location (if measured or else their estimates, e.g. from interpolated ground observation data or NWP) and quality information. In addition, the Level 2 product will also contain Integrated Water Vapour (if available).

Level 2 products will be available in near-real time for operational meteorology (i.e. all data provided within 3 hours of observation time, on a best efforts basis).

The geographical and temporal coverage of GPS meteorology products will be limited only by the characteristics of the GPS networks available to the ACs

GMP-0101 GPS Meteorology Products shall contain both Level 1b parameters and all required Level 2 parameters.

GMP-0102 The method used to derive ZTD and/or IWV products shall be given corresponding to algorithms described in [RD.6].

TOP-0101 Zenith Total Delays and Slant Delays shall be given in units of metres (m)

TOP-0102 Zenith Total Delays and Slant Delays shall be given in 0.0001 m (0.1 mm) precision.

TOP-0103 (Surface) Pressures shall be given in units of hecto-Pascal (hPa).

TOP-0104 (Surface) Pressures shall be given in 0.1 hPa precision.

TOP-0105 Temperatures shall be given in units of Kelvin (K).

TOP-0106 Temperatures shall be given in 0.1 K precision.

TOP-0107 Relative Humidity shall be given in percent.

TOP-0108 Relative Humidity shall be given in 0.1 percent precision.

TOP-0109 Integrated Water Vapour shall be given in units of $kg.m^{-2}$

TOP-0110 Integrated Water Vapour shall be given in 0.1 $kg.m^{-2}$ precision.

TOP-0111 Receiver altitudes shall be given relative to a reference ellipsoid (WGS-84) in units of m.

TOP-0112 Receiver altitudes shall be given relative to mean sea level (height above EGM96 geoid) in units of m.

TOP-0113 Receiver altitudes shall be given relative to the antenna reference point above benchmark in units of m.

TOP-0114 Receiver altitudes shall be given in 0.001 m (1 mm) precision.

TOP-0115 Receiver latitude and longitude shall be given relative to a reference ellipsoid (WGS84) in units of degrees

TOP-0116 Receiver latitude and longitude shall be given in 10^{-6} deg (~0.1 m) precision

TOP-0117 The observation shall be date- and time-tagged appropriate to the location, and shall include year, month of year, day of month, hour and minute.

TOP-0118 The observation shall be tagged with the GPS site name and unique identifier in the standard IGS-style 4-character format, together with receiver, antenna and radome types in standard IGS style.

TOP-019 Quality information shall be provided, both as error estimates for all derived quantities, and as product Q/C data (flags)

A file format meeting these requirements was devised for the COST-716 Action, and subsequently modified for the TOUGH project ([RD.12]).

5.2 Monitoring and Validation

GMP-0201 GPS Meteorology products shall be monitored for delivery metrics such as number of observations and timeless

GMP-0202 GPS Meteorology products shall be validated against NWP models, Radiosonde and Radiometers

RTV-0201 The origin of validation data shall be given

RTV-0202 Real Time Validation products shall be disseminated via the Internet

GMP-0203 A Monitoring and Validation Report shall be disseminated at least annually

OLV-0201 Validation of GPS ZTD and IWV shall be performed by comparison with NWP models, Radiosonde and Radiometers for all GPS site and processing centre combinations in Europe close to other observations

5.3 Interfaces

GMP-0301 GPS Meteorology products shall be available in near-real time to users via the GTS and Internet interfaces.

TOP-0301 Archived products shall be available to users via the Internet

5.4 Dissemination

Dissemination concerns the delivery of near-real time (NRT) products to users.

GMP-0401 At least 75% of GPS Meteorology products shall be disseminated to users within 1h45m of observation time. 100% of data should be available within 3 hours.

GMP-0402 NRT ZTD products shall meet the accuracy requirement for Regional NWP applications

GMP-0403 GPS Meteorology products shall be disseminated via GTS and the Internet

GMP-0404 GPS Meteorology products shall be disseminated via the Internet using the agreed project format (currently CLIMAP V2.0) using standard data compression tools

GMP-0405 GPS Meteorology products shall be disseminated using WMO BUFR (FM94) encoded formats. This is mandatory for GTS dissemination.

5.5 Archiving

Archiving concerns the saving of processed products and its subsequent extraction. Climate users in particular have an interest in extracting and reprocessing the data or to have the archived data reprocessed.

To produce useful and consistent time series and to make any reprocessing feasible each observation should be accompanied by all relevant meta-data. These meta-data should at least include the type of meteorological station (or method of estimation) used to produce P and T, the ZTD solution from the network processing and its error covariances, and an error estimate for the humidity product to 1% level.

In case reprocessing is required addition of the following information to the archived products should be considered:

- Ocean tide model
- Atmospheric tide model
- Receiver, antennae and radome types (and change history)
- Surrounding building information for multi-path
- Orbit processing (JPL)
- Environment information in general

TOP-0501 The GPS Meteorology products shall be archived on a daily basis

TOP-0502 The GPS Meteorology products shall be archived in full RINEX format for ‘raw’ data and in CLIMAP format for processed (ZTD) data. Lossless compression techniques may be employed to reduce storage requirements

TOP-0503 Products shall be archived for at least 10 years after the end of the project, but preferably should be kept indefinitely

TOP-0504 Archived products shall be capable of extraction, with no degradation to the original product quality, on user request

TOP-0505 Tools to (re-)process GPS Meteorology products shall themselves be archived or maintained so as to retain the capability of processing archived products in the future

5.6 Documentation

TOP-0601 Documents shall be in Word and PDF

TOP-0602 Documents shall be labelled with version numbers

TOP-0603 Documents shall be unrestricted and available to all on the Internet

5.7 Portability

Portability refers to the ability of the processing code used at processing centres – at source level – to be implemented at arbitrary sites, which may, or may not, be implemented the same computing platforms.

TOP-0701 Software for processing Level 1b to Level 2 GPS Meteorology products shall use a standard high-level programming language (e.g. C, F90, F77)

TOP-0702 Software shall as far as is practicable use only the standard features of the programming language, avoiding compiler-specific extensions

TOP-0703 Software shall be capable of being ported to a wide variety of host platforms without requiring significant modification to source code

TOP-0704 Software shall be coded and documented to agreed standards with appropriate version control