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| **WORLD METEOROLOGICAL ORGANIZATION**  **\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_**  **COMMISSION FOR INSTRUMENTS AND**  **METHODS OF OBSERVATION**  **EXPERT TEAM ON NEW TECHNOLOGIES AND TESTBEDS**  **(ET-NTTB)**  **First Session**  Geneva, Switzerland 4 – 7 March 2013 |  | CIMO/ET-NTTB-1/Doc. 4  (11.II.2013)  \_\_\_\_\_\_  ITEM: 4  Original: ENGLISH ONLY |

**GUIDANCE ON METEOROLOGICAL USE OF GNSS**

**Guidelines on operational use and data exchange protocols for GNSS water vapour**

(Submitted by Siebren de Haan)

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| **Summary and Purpose of Document**  The document presents draft guidelines on operational use and data exchange protocols for GNSS water vapour. |

**ACTION PROPOSED**

The meeting is invited to review the material provided in this document. The meeting will further be invited to identify whether it is suitable as guidance to Members or whether additional work/activities need to be carried out to provide appropriate guidance on GNSS water vapour to Members. The meeting will be invited to consider how to best reflect these practices in the CIMO Guide and agree on necessary follow-up actions.

**Guidelines on operational use and data exchange protocols for GNSS water vapour**

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| **Author** | **Version** | **Date** | **Document** |
| Siebren de Haan (KNMI) | Draft | 20/11/2009 | CBS-CIMO Remote Sensing/Doc. 4.1(6) |
| Jonathan Jones (UK MetOffice) | 1.0 | 14/10/2011 |  |
| Siebren de Haan (KNMI) and Jonathan Jones (UK MetOffice) | 1.1 | 11/02/2013 | CBS-CIMO/NTTB Doc XX |

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# Purpose of this document

**This document intends to define a set of common minimum requirements with regards to processing GNSS data with specific emphasis on problems associated with access to data from individual sites, and to satellite orbits and clock estimates**.

# Preface

The Global Positioning System (GPS) as deployed by the Department of Defence of the United States of America has been in operation since the early 90’s of precious century. At the time of writing, new systems are being installed or revived (GLONASS, GALLILEO, COMPASS). Together they form the Global Navigation Satellite System (GNSS). While using the GNSS for very accurate positioning new ways have opened for observing atmospheric humidity. This is achieved by carefully examining and separating the error sources in the transmitted GNSS signals.

This document is trying to formulate guidelines for operational use of water vapour observations from GNSS. The guidelines are based on the current experiences, which resulted from research on the meteorological application of GNSS water vapour observations. In essence, these guidelines could and should be revised when new insight has been gained through research and/or practice.

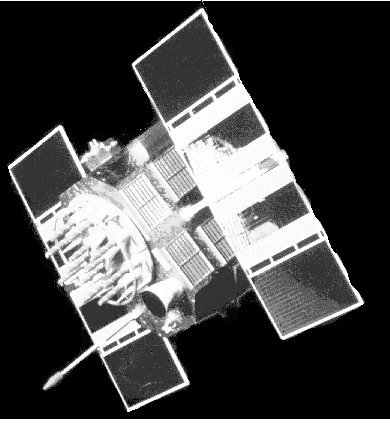
Furthermore, this document describes protocols on exchange of GNSS water vapour data. In addition, these definitions can be regarded as the current state of these protocols and should be revised in the (near) future.

# 1. Introduction

The Global Navigation Satellite System (GNSS) consists of the US GPS, the Russian GLONASS, and in the (near) future, the European GALILEO and the Chinese COMPASS. A GNSS consists of a constellation of satellites transmitting a radio signal (the space segment), ground-based or space-borne receivers (the user segment), and a network of control and monitoring stations (the ground segment). The primary observable is the time of arrival of the transmitted signal. The ionosphere and the neutral atmosphere along the signal path influence this observable. The influence (or delay in arrival time) of the ionosphere is dispersive (i.e. frequency dependent) while the influence of the neutral atmosphere depends on the refractivity along the signal path.

For precise positioning (i.e. with millimetre accuracy), the atmospheric term is an error source, which needs to be estimated to obtain the acquired accuracy. There are of course other error source terms, which play a crucial role with respect the accuracy of precise positioning. Other sources of error are satellite positions, satellite clock error, receiver clock error, ionosphere and noise. This atmospheric delay is mapped to zenith in the processing and is called Zenith Total Delay (ZTD) expressed generally in meters or millimetres.

The current GNSS networks (at least in Europe) used for meteorology rely on access to regional positioning networks.



**GNSS site**

**GNSS satellite**

***Ionosphere***

***Atmosphere***

*position*

*clock*

*antenna phase*

*dispersive:*

*frequency dependent*

*excess path due to refraction (ZTD)*

*frequency dependent*

*position*

*clock*

*multipath*

**Figure 1**: The GNSS constellation and error sources.

## 1.1 Atmospheric observables from GNSS

Figure 1 shows the error sources related to the GNSS system. The ionospheric error is due to the dispersive nature of the ionosphere. By combining the observations from two different frequencies, this error can be eliminated (in a first order approach). The atmospheric error is due to the refractivity and is given by:

,

where the refractivity *N* is given by:

.



with pressure *P*, temperature *T*, and water vapour density *e*. The ZTD can be separated into a hydrostatic part (Zenith Hydrostatic Delay, *ZHD*) and “wet” part (Zenith Wet Delay, *ZWD*) using Saastamoinen (1972), that is:



*P0* is the surface pressure, *λ* is the latitude of the GNSS receiver and *H* is the height of the receiver. The *ZWD* is related to the total amount of water vapour overlying the GNSS site and can be estimated by:



*Tm* is an approximation of the mean temperature in the column of air above the GNSS receiver. See Bevis (1992) for more details.

Ideally the surface pressure and temperature sensor would be collocated.

It is also possible to infer slant observations, i.e. the atmospheric delay along the individual signal path. For a network solution, this requires additional processing.

## 1.2 Processing GNSS data

The atmospheric observable from GNSS observations is *ZTD* and is estimated using observations from static GNSS sites. Together with the atmospheric term, an estimate of the clock errors and position is obtained.

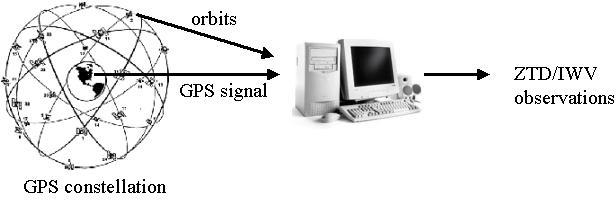


Figure 2: Processing GNSS

There are two main methods used for processing GNSS data:

1. *Network solution*

Using so-called Double Differences (DD), the clock errors of both the satellites and receivers are eliminated. A large network is necessary to obtain absolute estimates. Observations of a network of receivers, gathered over a certain time window (e.g. 12 hours), are necessary to determine the position of a receiver very accurately. The determination is performed using GNSS processing software, which estimates the position of the receivers in the network and, simultaneously, the atmospheric correction or atmospheric delay.

1. *Precise Point Positioning*

For this method, the orbits and satellite clocks are estimated using a separate scheme and then used as a priori information to estimate the position of the receiver and atmospheric term. This method requires very accurate and stable satellite information but has the advantage of being completely scalable with respect to the number of GNSS sites in the processing scheme.

## 1.3 GNSS quality issues

The quality of the GNSS observation can be affected by a lot of sources, amongst which are:

* Network configuration (stability/coverage)
* Accuracy of the orbits (and/or clocks)
* Method of processing
* Models used in the processing (different Ocean Tide Loading models etc)

Quality of observations is an important issue and monitoring the observations is therefore very important. The accuracy of ZTD depends on the processing parameters, such as processing time window, elevation cut-off angle, and update frequency and quality of a priori coordinates. Another import factor is the network quality (stability and types of receivers) as well as accuracy of the satellite orbits.

The quality of the processing is related to

* Quality of the receivers (recording on 2 or more GNSS frequencies)
* Physical location of the GNSS antenna (minimizing multipath, free sky (even at elevations around 5 degrees)
* Knowledge of antenna phase centres (needed for processing)
* Reliability of the data links (reliability)
* Timeliness of the data links (latency)
* Size and coverage of the network (for a network solution)

In case of a network solution, the network should be large enough to guarantee an absolute value of the GNSS ZTD estimate.

Within the EUMETNET-program E-GVAP, a central facility for Active Quality Control will be set up with the aim of continuous monitoring and quality flagging of GNSS estimates for sites with multiple solutions. A feedback file will be generated to support the GNSS-data users.

# 2 Guidelines

The guidelines for operational use are closely related to the operational production of GNSS atmospheric delay observations. As such, we first start with these guidelines.

## 2.1 Guidelines for GNSS Data Processing

1. **Use of standardised processing methods**

The current standard processing software (e.g. Bernese, GAMIT/CLOBK or GIPSY-OASIS) for processing GNSS observations are capable of estimating ZTD with good accuracy in near-real time.

General processing guidelines are:

1. Elevation cut-off angle of < 10 degrees (ideally zero)
2. Use the ‘Niell’ mapping function (Niell,1996) (or equivalent) to map the tropospheric delay from the slant to the zenith
3. Use ocean loading models – which model to use might be dependent on the location of the receiver/network in question)
4. **Satellite orbit and clock quality**

**DD**

For network Double Difference (DD) processing, the quality of the satellite orbits and clocks is paramount to the processing, but also is timeliness. The products made available from the International GNSS Service (IGS) are of increasing accuracy a-posteriori. For NRT processing orbits and clocks equivalent or better than the predicted half of the Ultra Rapid products (IGU) should be used, that is:

Orbit Accuracy => ~5cm

Satellite Clock accuracy => ~3ns RMS, ~1.5ns SDev

**PPP**

For Precise Point Positioning, the quality of the satellite orbits and clocks need to be determined to a higher degree of accuracy than with DD processing. IGU products are not of sufficient quality for PPP, as such most analysis centres employing PPP estimate their orbits and clocks to a higher degree of accuracy. Accuracy of products used for PPP should be:

Orbit accuracy = ~3cm

Satellite Clock accuracy= ~0.1ns

ERP

Earth Rotation Parameters should be used and be obtained from the same source as the orbits and clocks.

1. **Antenna stability and installation**

GNSS-sites used in the processing should be stable and be installed with a long-term intention. The installation of these sites should follow EUREF/IGS guidelines as far as possible (<http://igscb.jpl.nasa.gov/network/guidelines/guidelines.html>). Lesser quality installations are acceptable as long as great care is taken with regards to the installation to eliminate multipath and other sources of error as far as possible. The UNAVCO TEQC utility can be used as a tool for assessing general data (and as such site) quality (<http://facility.unavco.org/software/teqc/teqc.html>) IGS-style log-files should be maintained at all times and be made available to raw data users.

1. **Inclusion of highly stable (IGS or similar) sites for reference**

Almost all processing centres process only regional networks, which limit the possibility to include very distant geodetic reference sites (such as those from the IGS or EUREF networks). Adding stable and accessible geodetic reference sites can monitor the quality of processing monitored by comparison against solutions from other processing centres.

1. **Raw GNSS Data Access Rate**

The frequency of raw data is critical to the quality of meteorological GNSS parameters. The GNSS processing can only use what rate data it is given, as such the epoch rate (frequency) of the raw data is critical

**Timeliness**

The rate at which the raw data can be delivered for processing is critical to the applications of meteorological GNSS products.

**Epoch** **rate**

For NRT applications (hourly processing schemes) an epoch rate of <60seconds is recommended with an epoch rate of <30seconds being considered optimal

For RT applications a data stream is necessary for obtaining the data with minimal time delay, however, an epoch rate of <30sec is recommended with 1Hz being considered optimal

For RT applications the user determines the file length based on the user requirements with 15minute being seen as the minimum requirement

**NTRIP**  
One should note that the receiver and antenna types information are not transmitted with this data stream. Significant errors may occur when maintenance or replacement of components is not detected and acted upon.

1. **Data** **Gaps**
2. Data gaps are potentially damaging for GNSS processing especially for DD. For PPP, it means that during data gaps no information and short gaps (in the order of one hour) are not a significant problem.

For DD the full NEQ should be available again before data submission.

1. It is a requirement that a full hourly file be delivered for processing
2. If there has been a gap in the access to data from a certain site, this site must have delivered data stably for at least 12 hrs, before ZTDs from the site are again delivered to E-GVAP, or a minimum of 70% of the normally required data in time span 1 hour of the processing must be available.
3. **Quality monitoring**

Add sites close to radiosonde or water vapour radiometer for monitoring*.* Quality control is essential in order to use the GNSS observation in an operational environment. Based on observed atmospheric estimates at common sites this QC can be achieved. Essential is that observations from common processed sites are shared among the other processing centres. When this is the case, a Quality Evaluation should be reported back on regular bases to the data providers.

1. **Notification of processing changes**

A notification to the users in the data-header should be made when an important change in the setup of the processing scheme is applied.

1. **Accuracy of ZTD and IWV**

ZTD for global, regional and local NWP

1. The accuracy of the ZTD estimates should at least 3-10 mm when compared to NWP.

ZTD for Climate Applications (COST716)

1. Absolute Accuracy 6 mm ZTD
2. Long Term Stability 0.25–0.4 mm/decade (ZTD)

IWV for global, regional and local NWP

IWV estimates should have a monthly mean of <1kg/m2 vs. the Total Water Equivalent (TWE) derived from a collocated radiosonde station. The full 2-sec radiosonde ascent data should be used if possible to derive the TWE values and collocation in this instance is regarded as 20km or less. See Appendix A for a method to estimate TWE.

IWV for Climate Applications (COST716)

1. Absolute Accuracy 1 kg/m2
2. Long Term Stability 0.04–0.06 kg/m2/decade
3. **Data Output Formats**

Disseminate the GNSS atmospheric estimates in BUFR on the GTS (or COST716 to a ftp-server) to be included in an Active Quality Control (See par. 1.3)

## 2.2 Guidelines for Operational use

The guidelines for operational use are divided into the different application that is Numerical Weather Prediction (NWP) and Nowcasting (NWC).

### 2.2.1 Guidelines for operational use in NWP

1. Networks for NWP minimal dimensions 100km

2. Latency of the data

Regional models: in general 90 minutes

Global models: several hours

3. Observation frequency depends on the assimilation method

The Observation frequency required is in the range from hourly to every 15 minutes

4. Perform Quality Control

Create black and white list. Important is the difference between actual orography and model orography.

5. Perform bias correction

Due to the difference between actual orography and model orography a bias correction needs to be applied

### 2.2.2 Guidelines for Nowcasting

1. Networks for NWC minimal dimensions 10 – 50 km

2. Latency of the data should be less than 10 minutes

3. Observation frequency should be every at least 15 minutes

4. Perform Quality Control

Create black and white list

1. Possible applications are:
   1. Time series for monitoring NWP forecasts or lightning prediction (Mazany *et al*, 2002)
   2. 2D water vapour fields animations for monitoring severe weather and lightning events (de Haan *et al*, 2008)

### 2.2.3 Guidelines for Climatological use

1. Only use reprocessed data using the latest processing method for consistent ZTD estimates.
2. Report inconsistencies to the processing agency to improve the atmospheric content.
3. Use the formal error (when available) as a baseline quality parameter.

# 3 Data exchange protocols

**GNSS observables (time delay observations)**

1. Raw GNSS data should be exchanged in RINEX or a equivalent formats
2. Method of transport of raw GNSS observables
   1. ftp using the geodetic or dedicated ftp-servers
   2. NTRIP: using broadcasting protocol (see NTRIP-reference)
3. Timeliness of raw GNSS observables

RINEX (or equivalent) data should be available with at most 20 minutes after the observations (ftp)

When data is retrieved through NTRIP a latency of seconds is expected

Centralized NTRIP, including backup, is preferred above ftp

**Processed GNSS data**

1. *Parameters*

The processed data should be distributed with at least the following information

* 1. Site name (4-character ID)
  2. Processing centre/originating centre (4-character ID)
  3. Method of processing
  4. Processing scheme version
  5. Latitude, longitude and height (WGS84)
  6. Time of observation
  7. Estimated ZTD (expressed in 0.1mm)
  8. Estimated error in ZTD (when available from the processing)
  9. (optional) IWV (expressed in 0.1 mm)
  10. (optional) Method of retrieving IWV
      1. origin of pressure and temperature (observation or numerical weather prediction model)
      2. location of the pressure and temperature observation (latitude, longitude, height)

Within the geodetic community, a 4-character identifier is used for the site name.

A unique identification is possible using the processing centre name and the site name combination. Note that items a-d are required only once per timeslot.

1. *Format*

The processed data should be distributed with at least the following information

* 1. BUFR: method GTS or ftp (see BUFR format)
  2. ASCII: (for ftp-only). An ASCII format description such as the COST716-format (Elgered, 2005) could be used.

# Recommendations

1. For PPP an operational centre should be appointed to disseminate high quality clocks and orbits. This facility should have adequate backup resources or facilities to ensure continuous and guaranteed product delivery.
2. Climate series need to be created very regularly with the best processing methods available. Good knowledge exchanges between different global groups is essential
3. When the EUMETNET-EGVAP Active Quality Control is operational: Before using the data an Active Quality Control file should be checked for applicable data (See par 1.3).

# References and Links

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E-GVAP BUFR format: <http://egvap.dmi.dk/>support/formats/egvap\_bufr\_v10.pdf

COST ASCII format: http://egvap.dmi.dk/support/formats/egvap\_cost\_v22.pdf

Saastamoinen, J. , Atmospheric Correction for the Troposphere and Stratosphere in Radio Ranging of Satellites, *Geoph. Monograph Series*, 1972, **Vol. 15**

### Links:

EUREF: <http://www.epncb.oma.be>

EUREF guidelines: <http://www.epncb.oma.be/_organisation/guidelines/>

IGS: <http://igscb.jpl.nasa.gov>

IGS Site Guidelines: <http://igscb.jpl.nasa.gov/network/guidelines/guidelines.html>

EGVAP: <http://egvap.dmi.dk>

# Appendix A – TWE Calculation

Total Water Equivalent (TWE) is the term used for the equivalent measure of IWV but calculated from radiosonde ascents. The TWE is calculated by successfully incrementing the so-called water equivalent calculated at each 2 second layer of a radiosonde ascent (corresponding to approximately 10m height, depending on rate of balloon ascent) and then simply adding all the incremental layers to determine the total water equivalent for the column. In all the equations below suffix 1 refers to bottom of the layer and suffix 2 refers to top of layer. Firstly we need to calculate the mean vapour pressure for the individual 2 second layers. To complete this we must calculate the Vapour Pressure (VP) from Saturated Vapour Pressure (SVP) for top and bottom of each layer, where t1 and t2 are the temperatures at the bottom and top of the layer respectively,  and is the humidity at the bottom and top of the layer respectively.

For bottom point

 2.22

 2.23

Similarly we need to perform the same calculation for the top of the layer

 2.24

 2.25

Next we must calculate the mean vapour pressure (VPm) and mean temperature (Tm) for the layer which is simply:

 2.26

And similarly we calculate the mean temperature

 2.27

As the layers are relatively thin (~10m) we can assume that by just calculating the mean temperature and vapour pressure we get representative data for the layer. Next we can calculate the so-called water equivalent (WE) for the layer. Firstly we must calculate the depth of the layer which is simply:

 2.28

With  and  being the height at the bottom and top of the layer respectively, and therefore we can calculate the wet equivalent for that layer:

 2.29

Finally we can increment this procedure over successive layers to get the Total Water Equivalent for any radiosonde ascent:

 2.30

This process is carried out up to 12km after which it is assumed that the water vapour content is negligible. For comparison purposes the TWE is assumed to be vertical. The radiosonde flight in reality will hardly ever be vertical but as the radiosonde will generally stay in the same vertical column of air from which it was launched (i.e. the radiosonde is moving horizontally at the same velocity as the air mass itself) we can assume a vertical profile.