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Validation of SBAS MOPS Troposphere Model over the EGNOS Service Area

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Summary

The European Geostationary Navigation Overlay Service (EGNOS) delivers corrections to GPS receivers for ionospheric delay, satellite position errors and satellite clock errors via EGNOS satellites navigation messages. Next to these corrections, integrity data for the satellites is embedded in the navigation message. Geostationary communication satellites broadcast these messages, also delivering GPS-like ranging signals which can be used to augment the position solution computed by the user receiver.

EGNOS is a Space Based Augmentation System (SBAS) providing functionality and data fully compatible with the United States operated Wide Area Augmentation System as specified in the RTCA Minimum Operational Performance Standard (MOPS). Correction for the tropospheric delay by the receiver is defined in this standard through a fairly simple model using estimated receiver position, satellite elevation and day of year only.

When the actual troposphere deviates heavily from the model, the remaining tropospheric delay error, and hence the pseudorange error, may exceed the error limit as specified in the MOPS, which may result in hazardous misleading position information provided to the user.

In order to verify the performance of the model, a priori knowledge about the magnitude distribution of the actual tropospheric delay is required. Also during the validation of EGNOS it has to be determined if an abnormal pseudorange error is due to an abnormal tropospheric delay error.

The paper starts with a short introduction to the MOPS corrections, with the emphasis on the tropospheric delay model.

Next the MOPS tropospheric correction model performance is compared to the performance of other models published in the last two decades.

Actual tropospheric delay data of a large number of GPS reference stations distributed over the western and southern part of Europe has been used to assess the performance of the MOPS model.

The paper ends with conclusions of both the theoretical and the practical assessment, and gives recommendations for the reduction of the remaining tropospheric error by applying an improved model.

The paper is based on work performed by the Netherlands National Aerospace Laboratory NLR and Delft University of Technology as part of a contract awarded by the European Space Agency.

Contents

(24 pages in total)

1 Introduction

To verify functionality and performance of the EGNOS signal various measurement campaigns are currently being undertaken by industry, the European Space Agency and several other organisations throughout Europe. Most of these activities are related to the EGNOS signals that are available since the start of the year, or the signals of its predecessor, the EGNOS System Testbed. Effects that have an impact on the quality of the collected data have to be known when assessing the measurement data. Several different error sources are known to have an effect on GPS ranging accuracy, like ionospheric errors, multipath, etc, which influence the performance of EGNOS. This article presents the analysis of errors in the receiver for the tropospheric delay due to uncertainties and fluctuations in the atmosphere. It can be noted that these effects are relevant for both EGNOS and GALILEO. Therefore results from the present study could be considered as a forerunner of similar investigations carried out on world global scale for the GALILEO Satellite Navigation System.

EGNOS delivers to the user corrections for ionospheric delay, satellite position error and satellite clock error. In EGNOS the correction of the tropospheric delay is to be carried out by the user with the tropo delay model as described in the SBAS MOPS (the 'MOPS model'.) as defined in Ref. 1.

This model, as the majority of tropospheric delay correction models, follows a two step procedure. First the tropospheric delay is computed in the zenith direction. This value is called 'Zenith Total Delay' or ZTD. ZTD values are in the order of 2 to 2.4 meters. Next a 'mapping function' corrects for the actual satellite angle with respect to the zenith direction. A mapping function multiplies the ZTD by a factor of one for satellites at zenith, to more than five for satellites below 10 degrees elevation.
ZTD models are often split into a component for the hydrostatic delay (Zenith Hydrostatic Delay, ZHD) and for the wet delay (Zenith Wet Delay, ZWD). The hydrostatic delay is caused by a mixture of dry air and water vapour, which is considered to be in hydrostatic equilibrium. The remaining (wet) delay is caused by water vapour alone.

The MOPS model is based on estimating tropo delay using surface meteorological data and lapse rates, in a way similar to the Hopfield and Saastamoinen models (Ref. 2, 6). However, in the MOPS model, input meteorological parameters and lapse rates are contained in small tables sorted according to latitude belts. These model characteristics introduce a certain amount of error and when the troposphere deviates heavily from the MOPS model, the unmodelled tropospheric delay error, and hence the pseudorange error, may exceed the allowable error level as specified in the MOPS. This should not happen in any case, since the information of EGNOS should be 'safe'. Knowledge about the magnitude distribution and outliers of the unmodelled tropospheric delay error provides insight into the quality of the MOPS model.

The validation of the MOPS model has been based on the review of models, measurement techniques (like radiometric measurements, and GPS based assessment) and current datasets of meteorological data (like radiosonde, products from Numerical Weather Prediction (NWP) systems and surface measurements). For the scope of the validation the main issues that have been considered are:

- the quality of the data in terms of accuracy;
- the spatial distribution of the available data;
- the timeliness and availability.

Hence the validation of MOPS over the area covered by EGNOS has been carried out by using International GPS service (IGS) related European Reference Frame (EUREF) datasets. The statistical distribution of the errors, taking into account also latitude dependence, has been derived. As well recommendations for the improvement of this type of model for use in GALILEO are proposed.

2 Comparison of MOPS model to other models

The actual tropospheric delay in the (pseudo) range measurement is a function of the zenith delay and the elevation of the satellite at the user site. In the following section ZTD models are identified and the performance of the MOPS model is compared with other models. In section 2.2 relevant mapping functions are identified, and again serve as comparison for the MOPS mapping function.

Mapping functions describe the relation between zenith delay and elevation. This statement holds only for an atmosphere that is homogeneous in the horizontal plane. In practice this is not the case. Therefore, three possible causes for differences between the delay computed from the MOPS and the actual observed delay could be identified

1. errors in the modelled (hydrostatic and wet) zenith delay
2. errors in the mapping function used by the MOPS
3. errors in the mapping function due to horizontal a-symmetries in the atmosphere

We will show in sect. 2.2 that the third source of error can be ignored safely in view of the size of the first two error sources. However, strong variations in the atmosphere giving lead to a-symmetries will also lead to strong variations in the zenith delay as function of time and place that are not accounted for in the MOPS model. They therefore contribute to the first type of errors.

2.1 Zenith Total Delay models

Table 1

Method	accuracy (cm RMS)	remarks
Measurement	0.5 - 2.0	GPS network, radiosonde, etc.
numerical weather model	1.5 - 3.0	HIRLAM, GDAS, ECMWF
model using meteo data	2.5 - 4.0	pressure, temperature, humidity
global model	4.0 - 6.0	lat, lon, height, date/time

ZTD data may be derived from actual measurement, from NWP models, from models using locally measured meteo data, and from global models ('blind models'). Schueler (Ref. 16) identifies the ZTD sources and estimated accuracies in table 1.

The MOPS model belongs to the 'global (blind) model' category since it uses latitude, height and day of year as input only. The RMS accuracy is therefore expected to be in the order of 4 to 6 cm. This figure is confirmed by the analysis carried out in the framework of this report. The MOPS however specify the 'tropospheric vertical error' (σ_{TVE}) as 0.12 m. In view of the above this seems to be a conservative error estimate.

In order to assess the accuracy of the MOPS model, a source for reference or 'truth' data is required. This data is preferably a factor 10, but at least a factor 3 better. According to the above table actual measurement data is therefore the preferred source of reference. There are a number of disadvantages associated with this choice:

1. it takes hours to days before measured data becomes available
2. data is only available for the measurement locations
3. instrumental errors may exist, in particular unknown biases or calibration errors.

For a statistical analysis the disadvantages of 1 and 2 are no problem. Also, best engineer's estimates of bias errors are available, which are supported by limited measurements. But for (near) real-time assessment of the MOPS model error anywhere within the coverage area of EGNOS the measurement method alone fails. Numerical weather predictions could very well be the only applicable source, possibly with actual delay measurements from ground GNSS stations assimilated.

In the framework of EGNOS validation not only the accuracy figures (such as average, standard deviation and 95% error) are required, but also the time interval between measurement and availability of the data is an important parameter for problem solving.

Sources of reference data for the MOPS model are:

1. delay from measurements,
2. delay computed from numerical weather models, and
3. delay computed from models using surface meteo data.

The distinction between these sources is not so important as it might seem at first, since all these approaches are based somehow on measurements. A more important distinction is the quality of the data in terms of accuracy, the spatial distribution of the available data, timeliness, reliability and availability.

Sources of reference data and their relevant characteristics are identified in the following section.

2.1.1 Meteorological data measurement

Synoptic measurements:

Pressure, temperature and relative humidity measured at synoptic sites on the Earth's surface can be used to compute the delay using empirical models for the delay. This method works well for the hydrostatic component of the delay, which only depends on the surface pressure. The error in the hydrostatic zenith delay, computed from the model developed by Saastamoinen (Ref. 6), is estimated to be about 0.5 cm. However, the wet component of the delay, although much smaller, is more difficult to predict from surface measurements only. The error in the delay is typically 2.5-4 cm rms, but occasionally the errors can be significantly larger due to ground-proximity effects (mist, inversion, etc), which are not representative for the whole atmosphere. Therefore this data source does not meet the accuracy requirements.

Radiosondes:

In order to compute the delay more accurately the height profile of pressure, temperature and humidity are needed. Radiosondes provide those profiles. A radiosonde is basically a balloon with a meteorological and communication package to transmit the measurements to the ground. Screening of the data for outliers is important. The accuracy of the thus derived delay is about 1-1.5 cm rms, which meet the requirements. The spatial distribution of the measurements is not very good. Radiosondes are only launched from a few places in Europe and only 1-4 times per day. The timeliness of the data is in general very good, as radiosondes are still a primary source of data from numerical weather prediction. Radiosonde data is made available on the GTS (Global Telecommunication System) operated by meteorological institutes and is in general available from meteorological institutes. On the GTS typically only the characteristic levels are broadcasted, this has a slight impact on accuracy. For the best possible accuracy the full measured profile should be used, but availability of this data is not very good. Also, all radiosondes are launched at the same time in the GMT time scale, which can lead to serious aliasing effects with respect to actual meteorological conditions for certain areas of the world.

Radiometers, Lidars, etc.:
Radiometers and Lidars can provide direct measurements of water vapour. If combined with pressure and temperature measurements the delay can be computed. The accuracy is in general better than about 1 cm rms. Unfortunately, these instruments are only found at a few research sites and availability and timeliness of this data is a problem. Furthermore, radiometers cannot operate in the presence of precipitation; Lidars can not operate in the presence of cloud cover.

2.1.2 GPS derived tropospheric delay

Networks of permanently operating Global Navigation Satellite System (GNSS, e.g. GPS) receivers can provide direct measurements of the tropospheric delay.

International GPS Service (IGS):
This is a global network of about 300 continuously operating GPS receivers (http://igscb.jpl.nasa.gov/). The main product of IGS is precise satellite orbit and clock files. IGS also routinely produces maps of the ionospheric delay and files with the tropospheric delay estimated at the GPS stations. Since 1997 the IGS regularly generates a combined tropospheric product on a weekly basis for more than 150 sites. The quality of the product is at the level of 3 to 6 mm in ZTD. The agreement of the GPS results with the Water Vapour Radiometer at Potsdam is at the 6-7-millimetre level. The standard deviation of the difference approaches 3 millimetre; the bias has a level of 6 millimetre and shows some long-periodic characteristics. The sampling interval is 2 hours. Weekly files with combined ZTD for individual sites of the IGS network are available from the GeoForschungsZentrum (GFZ), Potsdam, with a delay of 2-4 weeks (ftp://ftp.gfz-potsdam.de/pub/igstrop). See also http://www.gfz-potsdam.de/pb1/igs_trop_wg/index_IGS_TROP_WG.html.

European Reference Frame (EUREF) Permanent GPS Network (EPN):
The EPN is a permanent GPS network created by the International Association of Geodesy Subcommission for Europe. Its primary objective is the creation and maintenance of the European Terrestrial Reference System ETRS89. The EPN is also the European densification of

the network operated by the IGS. As such, the EPN uses the same standards and exchange formats as the IGS. The network consists of about 140 receivers (status 2002). Starting in April 2001, the EPN is also computing a combined tropospheric delay product for its 16 analysis centres similar to the IGS (Soehne et al, Ref. 13). The files can be found at http://igs.ifag.de/root_ftp/EUREF/products/, using the same format as IGS. The consistency values are very similar to those of the IGS and can be found on a weekly basis in the summary files. The sample rate for the ZTD is one hour. The weekly files become available in 3-4 weeks.

COST-716:
In 1999 the European action COST-716 was started to investigate the exploitation of ground based GPS for climate and numerical weather prediction applications (COST is the French acronym for European co-operation in the field of scientific and technical research). The network consists presently of over 400 GPS stations in Europe, of which several are processed by more than one analysis centre. The overall consistency between the GPS solutions is about 5-6 mm for the Zenith Delay (1 kg/m^2 in Integrated Water Vapour). For more than 75% of the stations the estimated ZTD is arriving at the UK Meteorological Office within 1^h45^m. The ZTD is routinely converted into Integrated Water Vapour) at the Royal Netherlands Meteorological Institute. For the conversion the pressure and temperature measured at GPS site, if available, or the pressure and temperature from nearby synoptic sites is used. The COST-716 action has finished officially in March 2004, but the network continues to be operated in the EU TOUGH project.
The GPS results have also been compared to the ZTD computed from Radiosondes. The agreement between ZTD from GPS and radiosonde is roughly between 10 and 15 mm for the near real-time processing for nearby stations, and slightly better for post-processing. The bias between GPS ZTD and radiosonde is between 5 and 20 mm, depending on the station and the GPS processing centre. The near real-time estimates have been compared with estimates of the EUREF Permanent Network, showing an agreement in the range of 5-14 mm rms and biases in the range of 2-8 mm depending on the type of software used. Comparisons against the High Resolution Local Area Model (HIRLAM), an NWP model, showed an rms error in the range of 10-20 mm depending on the station, with a station dependent bias generally below 10 mm (http://www.knmi.nl/samenw/cost716/GPSvsHIRLAM.html).

2.1.3 Numerical weather prediction models

NWP models can provide tropospheric delay in a similar way to radiosonde data by integrating refractivity profiles computed from pressure, temperature and humidity profiles provided by the NWP model. NWP models are usually parameterised in term of a horizontal grid and a limited number of vertical layers. The typical grid size depends on the domain of the model and the available computing power. Typical values are e.g. 20 km for the grid size and 35 layers. NWP

models are based on actual measurement data, and it is fair to say that in the limiting case the model is as good as the data that has gone into it. The main advantage of NWP models is that they are able to assimilate and combine different sensor types, e.g. surface meteorological data and radiosondes, and that they are not bound to the location of the sensor and time of observation. The wet delay is computed by integrating the wet refractivity computed from the temperature and humidity profiles, whereas the hydrostatic, or dry, delay is computed from the surface pressure in the model assuming hydrostatic equilibrium. Alternatively, the dry delay can also be computed by integrating the dry refractivity computed from the pressure profile in the NWP model, extended by a model for the upper part of the atmosphere and taking into account the difference between the surface as modelled in the NWP and the actual surface. The main advantage of using an NWP model is that in principle it can provide delay estimates at any time and place in the domain of the model, and can be used to evaluate the actual delay in real-time using the prediction capabilities of NWP models. The accuracy of the tropospheric delay computed from a NWP model is typically 1.5-3 cm. Comparisons of the HIRLAM against COST-716 data showed an rms error in the range of 10-20 mm depending on the station, with a station dependent bias generally below 10 mm
(http://www.knmi.nl/samenw/cost716/GPSvsHIRLAM.html).
In De Haan et al (Ref. 9) one year of COST-716 data is compared to the European Centre for Medium-range Weather Forecast (ECMWF) model, using 28-day means and standard deviations. The standard deviations show a clear seasonal signal, closely related to the observed Zenith Wet Delay with the standard deviation about 10% of the 28-day mean, which is again in the range of 10-20 mm.

The ECMWF model is a global numerical weather model. The HIRLAM's are regional models operated by several European meteorological agencies. They use the same code-base, but each institute is running a separate instance of the model within their own domain (which is a large part of the European subcontinent). The ECMWF model is convenient for both verifications and possible implementation of future GNSS services.

2.2 Inventory of mapping functions

Mapping functions describe the relation between ZTD and the actual (Slant) Total Delay (STD) between a satellite and a user. Often the wet component of the tropo delay is mapped different from the hydrostatic component. The hydrostatic component in the tropo delay is over 2 m in magnitude in the zenith direction; the wet component is a few decimetres. Therefore the accuracy of the mapping function for the hydrostatic component needs to be far better related to the accuracy of the mapping function for the wet component.

Since the atmosphere is inhomogeneous in both the horizontal and vertical plane, mapping functions require in theory satellite azimuth and elevation as input, but in practice only the elevation is used. A mapping function may also be based on measured atmospheric quantities such as pressure, temperature, humidity and derivatives, or modelled atmospheric quantities using position and date/ time.

Horizontal gradients are not an issue for the mapping functions in the present study. Even in high precision geodetic applications gradient parameters are optional. In Bar-Sever et al (Ref. 17) gradients have been evaluated for 150 IGS sites for a three-month period, showing prevailing north-south gradients for non-equatorial sites with hemispherical asymmetry as should be expected from synoptic temperature gradients. Typical gradients are smaller than 1 mm, which translates to a delay of not more than a few cm at 10 degrees elevation, which is well below the specified MOPS delay error at 10 degrees. In De Haan et al (Ref. 7) a cold front passage in the Netherlands inducing strong horizontal gradients was studied using GPS and NWP. Again, the horizontal a-symmetry of the atmosphere resulted in an excess delay error of not more than 3 cm at low elevations, which is well below other errors in the MOPS mapping function. More of a concern during a cold front passage is the validity of the MOPS model. Near Delft the ZWD dropped from 150 mm to 85 mm over a distance of less than 100 km, and the same drop can be observed in the GPS time series over a period of 4 hours. (The ZWD computed from the MOPS model is 122 mm for 30 Oct 2000, 15:00).
Within the framework of this study horizontal gradients have negligible effect on the accuracy assessment of the MOPS model. Hence the mapping function is only a function of elevation, no azimuth dependency of the mapping functions is considered.

Mapping functions can be divided into three groups. The first group of mapping functions takes actual measured meteorological quantities as input (Black, Davis, Ifadis, and Herring). They possess good accuracy; their disadvantage is of course the added complexity of having to measure meteorological quantities, such as station pressure, temperature and humidity.
Mapping functions in the second group extract atmospheric quantities from a model (MOPS, Niell). The advantage is simplicity, the disadvantage lies in the fact that actual meteorological parameters, and hence the mapping function, can deviate from modelled parameters.
Third group mapping functions are derived from NWP models. No actual measurements are required, but mapping function data has to be transferred in (near) real time to the user.

2.2.1 Mapping function accuracy

The Davis hydrostatic mapping function is said to be accurate to 2.5 cm at an elevation of 5 deg (Schueler, Ref. 15). If all atmospheric properties are well known, Ifadis claims an RMS figure of 2.2 cm at 5 deg elevation, using surface temperature, pressure and humidity only (Schueler, Ref. 15). Schueler [ibid] reports the accuracy of the Ifadis wet mapping function accurate to 8.5 mm at 5-deg elevation.

Niell (Ref. 3) calculated hydrostatic and wet mapping functions for use down to 3 degrees elevation using ray tracing on radiosonde profiles, and models atmospheric properties with day of year, latitude and height as input. Niell evaluated the accuracy of the mapping functions at 5^o elevation: he found a bias of -2 mm and standard deviation of 8 mm. For comparison, using the same data, he found for Ifadis –3 mm as bias and standard deviation of 11 mm. The errors for the wet mapping function at 5^o elevation were: a bias of –1.8 mm and standard deviation of 2.47 mm, assuming a ZWD of 100 mm. Rocken (ref. 5) found somewhat larger errors for the Niell mapping functions; a bias of -4.6mm and a standard deviation of 23.7 mm for the hydrostatic mapping function, with maxima of -92 and +69 mm. Rocken [ibid] found for the Niell wet mapping function a bias of 4.9mm and standard deviation of 8.7mm, with maxima of –40 and 45 mm.

A more recent development is to use mapping functions derived from NWP models (third group, Niell, Ref. 4, Rocken et al, Ref. 5, De Haan & Van der Marel, Ref. 7). Rocken reports a bias of 0.8 mm and standard deviation of 7.4 mm in the hydrostatic part, assuming a Zenith Hydrostatic Delay (ZHD) of 2.1 m, and 0.15 mm bias and 6.9 mm standard deviation in the wet part, assuming a ZWD of 100 mm (Ref. 5). The effects of a front passage on the mapping function have been investigated in Ref. 7, confirming the previously reported results by Rocken.

2.2.2 Comparison Niell mapping functions with Ifadis mapping functions

The Ifadis mapping functions (based on measured meteorological quantities) have been compared with the Niell mapping functions (based on modelled meteorological quantities) in the following way.
The ZHD was calculated using the Saastomoinen model.
The ZWD was calculated using the Ifadis model.
Both the Slant Hydrostatic Delay (SHD) and Slant Wet Delay (SWD) were calculated using the Ifadis and Niell mapping functions.
The differences between SHD_{Niell} - SHD_{Ifadis}, SWD_{Niell} - SWD_{Ifadis}, and STD_{Niell} - STD_{Ifadis} were calculated.
The following parameters were varied:

- Day of year: 36.5 to 365 step 36.5
- Latitude: 15N to 75N step 15
- Height: 0 and 1000 m, with an ambient pressure of 1013.25 and 898.76 hPa respectively
- Relative humidity: 0 to 100 % step 50 %
- Temperature 0 to 30 Cel step 10 Cel
- Elevation 5 to 30 deg step 5 deg

This calculation produced the following statistics (meters):

Table 2

	Delta SHD	Delta SWD	Delta STD
Average	0.007	-0.002	0.005
St. deviation	0.020	0.007	0.018
Minimum	-0.127	-0.093	-0.127
Maximum	0.320	0.000	0.253

Average and standard deviation are low, but they are somewhat positively biased by the fact that the elevation was varied to 30 deg (at higher elevations the deviations become small). Minimum and maximum values are biased negatively by allowing extreme atmospheric values, e.g. high temperature and 100% humidity. For example, 898.76 hPa, 0 Cel and 0% RH are not very likely in the summer. This will result in significant differences between Ifadis, which uses this data, and the Niell mapping function which is based on average meteorological conditions depending on day of year and latitude. Taking this into account, in general the numbers agree with the comparisons as reported in section 2.2.1, and hence allow the choice of the (convenient) Niell mapping functions as a basis for comparison of the MOPS mapping functions.

2.2.3 Comparison MOPS mapping function with Niell mapping functions

The Niell mapping functions are chosen as reference for the accuracy assessment of the MOPS mapping function. Besides the minor differences found between the Ifadis mapping functions and Niell mapping functions in section 2.2.2, the rationale for this choice is their claimed accuracy, and the Niell mapping functions are the de-facto standards in geodesy. Moreover they are a function of of year, latitude and height only, as the MOPS mapping functions.

For latitudes from 15N to 75N the ambient pressure, temperature and humidity, and ZHD and ZWD are calculated for several values of day of year and station height using the MOPS model. The MOPS model pressure, temperature and humidity are input to the Niell mapping functions. Slant delay is calculated using the Niell mapping functions and the EGNOS mapping function.

Figure 1 gives some typical differences between the MOPS slant delays and Niell slant delays, as a function of elevation, latitude, day of year and station height. The SHD error is plotted in blue for day of year 28 (midwinter), height 0 mean sea level (MSL) and for latitudes 15N, 30N, 45N, 60N and 75N. The SWD error is plotted in purple, and the slant total delay (STD) error in red. The STD error is limited to 15 cm at lowest elevation.

From the accuracy assessment it is concluded that using the Niell mapping functions instead of the MOPS mapping functions, range errors can be reduced, at the cost of more complex mapping functions.

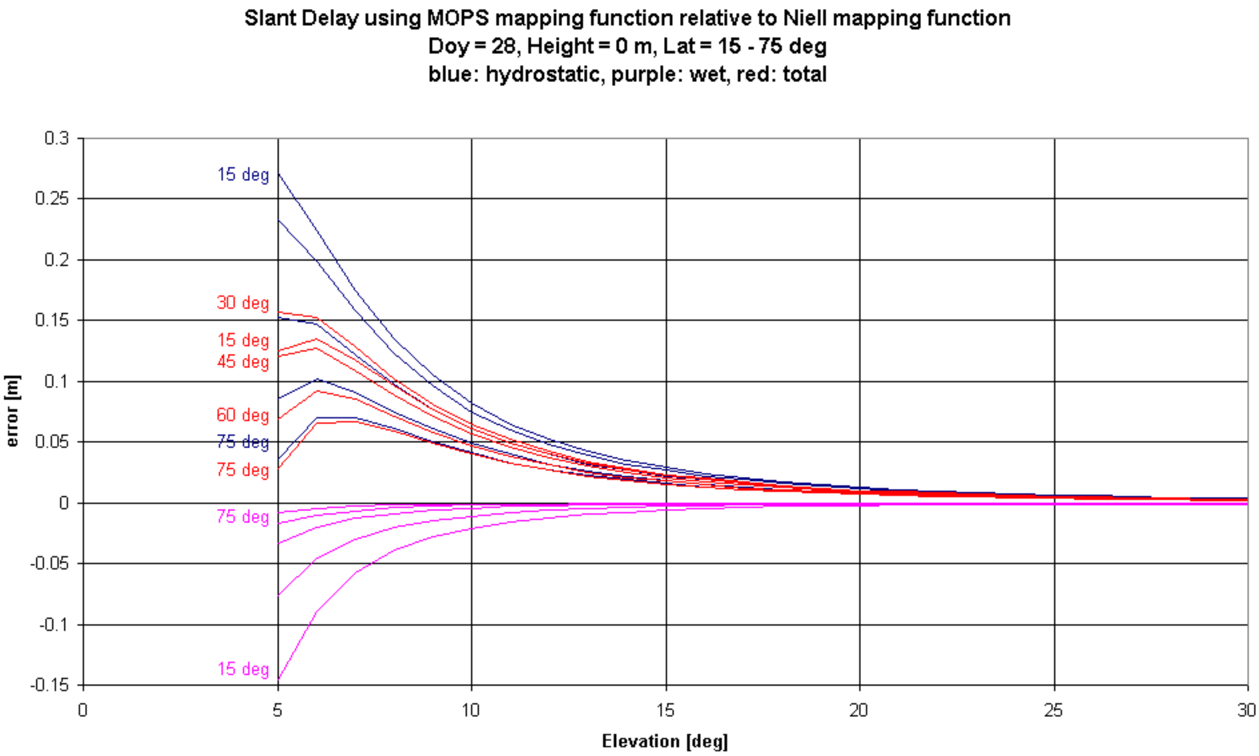

Figure 1 Slant delay error on day of year 28

3 Choice of reference data source and mapping function

For monitoring the performance of MOPS tropospheric model two situations are considered. For (near) real time performance monitoring it is advised to extract zenith delays from the ECMWF model, assimilated with measured meteorological quantities, and to map these into the slant direction using the Ifadis (or Niell) mapping function with meteorological parameters from the model. Zenith hydrostatic delay can be computed using either surface pressure from the model, or direct integration. The wet delay must be computed by integrating a profile from the model. Although it would be possible to compute slant delays directly from the model, this is considered to be too complicated for the proposed application. The advantage is the (near) real time availability of the data; the accuracy however is marginal for the application.

In case the highest accuracy is required, tropospheric delay values derived from a network of GNSS receivers is seen as the best option. The (EGNOS) network could be integrated as a sub network into the EUREF or COST-716 network, with the advantage of having access to a multitude of station observations, while independence of the EGNOS sub network remains guaranteed. The disadvantage is the availability of results; it will take at least one hour before tropo delay data becomes available after the measurement moment using the COST-716 framework and up to 1-2 weeks in the framework of EUREF. However, using a (simple) forward prediction model, ZTD measurements with an age of 1-3 hours can be used to predict the ZTD to the current epoch for real time monitoring of the MOPS tropospheric model. Using data from a weather model like ECMWF data could possibly further strengthen the forward prediction model.
To map zenith delay values to slant delays it is advised to use the Niell mapping functions.

3.1 Performance review of chosen reference data

It has been shown in the preceding sections that the RMS accuracy of the ZTD using NWP models is in the order of 15 - 30 mm. The RMS accuracy of the ZTD determined in a GNSS network is in the order of 5 to 10 mm. The (Niell) mapping functions add another 10 mm to the uncertainty (at 10 deg). Also it will amplify the uncertainties in the ZTD by the square root of the mapping function itself. So the RMS accuracy of the slant total delay at 10 degrees elevation will be 27 mm to 51 mm ($\sqrt{(5^2*5^2+10^2)}\ldots\sqrt{(5^2*10^2+10^2)}$) .

3.2 Statistical performance of EGNOS zenith delay tropo model

For an assessment of the performance of the MOPS model the ZTD solution of the EUREF network has been chosen as the 'truth'. Although no firm evidence about the accuracy of the EUREF ZTD data have been obtained, estimates of the accuracy are: standard deviation of the ZTD data below the 5 mm level, with biases at the 2-3 mm level (Soehne et al, Ref. 14). These accuracy values are at least a factor of three below the estimated accuracy of the MOPS model; hence they can serve as the truth.

The EUREF network exists of 138 stations (status 2002) equipped with geodetic quality dual frequency GPS receivers. The stations are located mainly in the western and southern parts of Europe. Each station sends raw measurements to one or more Local Analysis Centres (LAC); each LAC analyses data of several tens of stations. In principle data of each stations is processed by two or more LACs. The 16 LACs produce hourly values of the ZTD of each station. See http://www.epncb.oma.be/_trackingnetwork/maps.html for an overview of the stations in Europe

Both GFZ Potzdam and BKG Frankfurt produce averages for each station from the ZTD values produced by the individual LACs (Soehne et al, Ref. 14). The files can be found at http://igs.ifag.de/root_ftp/EUREF/products/. This data of the year 2002 has been chosen as reference for the MOPS model performance assessment. In principle this data consists of 138 (stations) * 365 (days) * 24 (values per day) = 1,208,880 values.

In practice less values are processed because of:

- values with an internal accuracy (standard deviation) of more than 15 mm are considered unreliable and are discarded,
- values, which have been calculated from only one LAC, are considered unreliable and are discarded.

After this filtering 1,019,544 values (84%) remained for further processing.

Using station position and day of year the MOPS ZTD values have been calculated. The differences between the MOPS ZTD values and truth-values have been formed. In the following these differences are referred to as 'MOPS zenith errors'. The following statistics have been calculated for each station and for all stations together:

- average, standard deviation, 95% error, and number of observations
- the distribution of the MOPS zenith errors in bins of 10 mm.

3.2.1 Statistics of all data

The statistics for the full data collection are:

- Number of data points: 1,019,544
- Bias: 5.9 mm
- Standard deviation: 40.5 mm
- 95% error: 87.0 mm.

In Figure 2 the distribution of the MOPS zenith errors are plotted in bins of 10 mm (red). Also the normal (Gaussian) distribution based on the calculated average and standard deviation is plotted (blue).
The actual distribution follows a normal distribution with mean value of 5.9 mm and standard deviation of 40.5 mm very closely.
Compared to the specified MOPS residual tropospheric vertical (zenith) error only 3132 data points (0.31 %) fall outside the -12 cm to +12 cm bins.

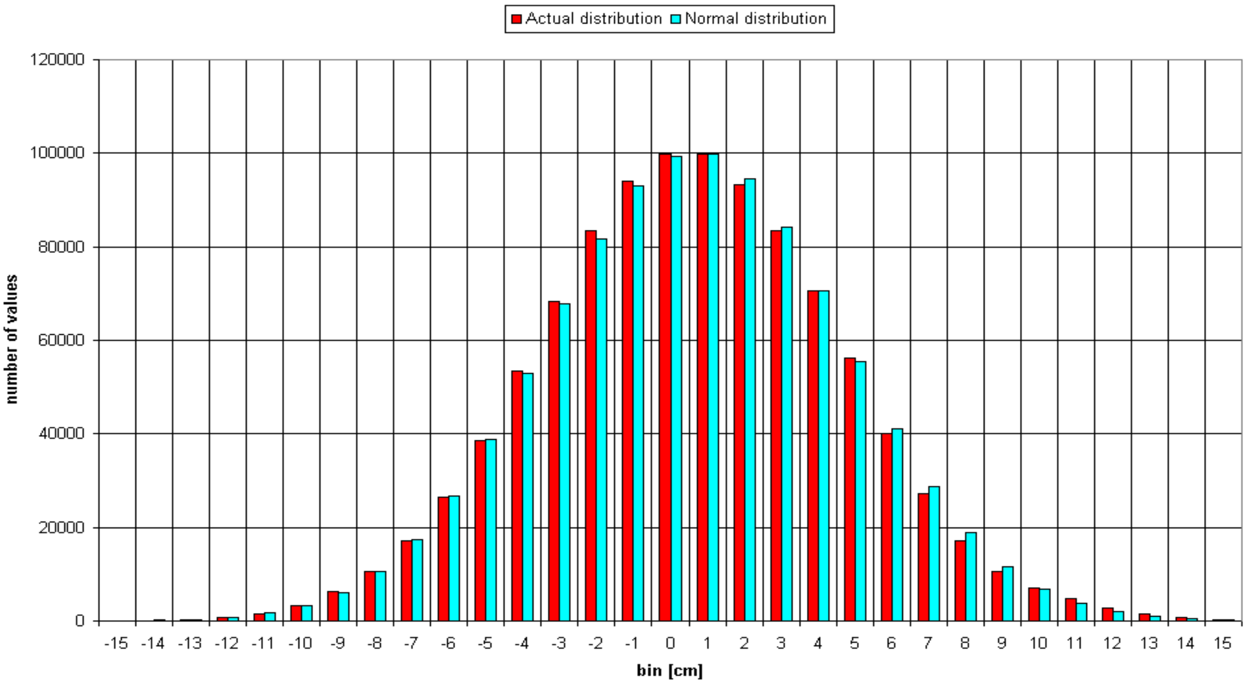

Figure 2 Distribution of MOPS zenith errors

3.2.2 Station statistics - all stations

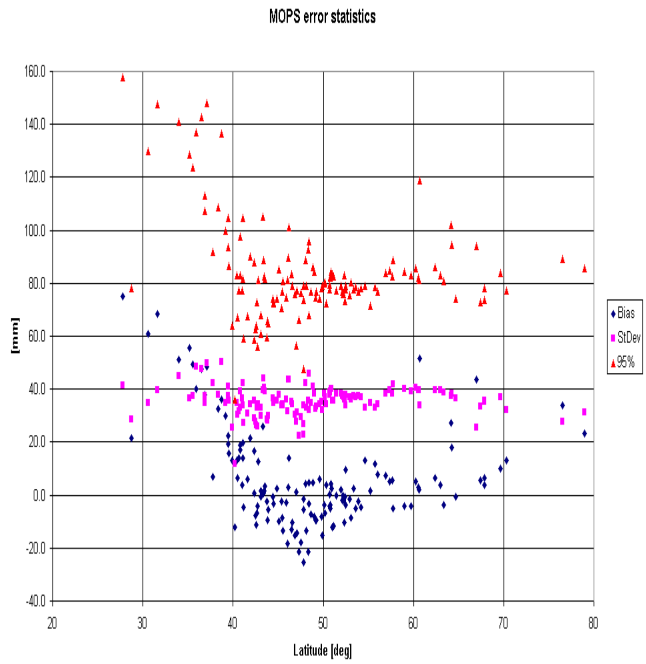

Figure 3 Error statistics vs. latitude

In Figure 3 the MOPS error statistics of each station are plotted as a function of station latitude. Standard deviation of each station is in the order of 40 mm; no clear correlation with station latitude is present. The bias however is close to zero for stations above 40 deg latitude, and increases to about 70 mm with decreasing station latitude. The MOPS model over-estimates the zenith (wet) delay at low altitude. A model tailored to the EGNOS coverage area may remove the bias largely for all latitudes.

3.2.3 Statistics per station

The year statistics for station DELF (Delft - Netherlands) are typical for higher latitude stations:

- Number of data points: 8,592
- Average value of true ZTD: 2413 mm
- Bias of error: 2.0 mm
- Standard deviation of error: 38.5 mm
- 95% error: 79.0 mm.

The MOPS error variation through the year is plotted in Figure 4 on the next page. Seasonal variations are clear. Errors are limited between -10 cm and + 10 cm.

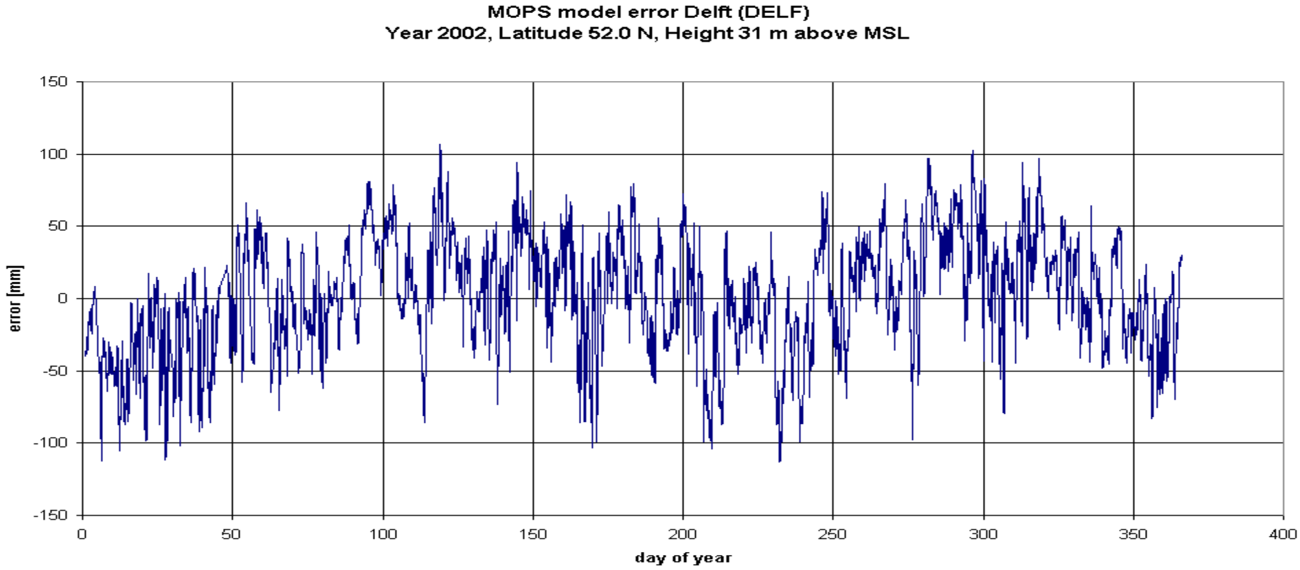

Figure 4 MOPS errors for station DELF

The MOPS errors of station MAS1 (Maspalomas, Canary Islands) are:

- Number of data points: 8,311
- Average value of true ZTD: 2400 mm
- Bias of error: 75.1 mm
- Standard deviation of error: 41.4 mm
- 95% error: 157.8 mm.

The bias value is extremely high. And although the time history in figure 5 (next page) shows some seasonal variation, the bias is nearly always positive, indication a too high MOPS model (wet) delay.

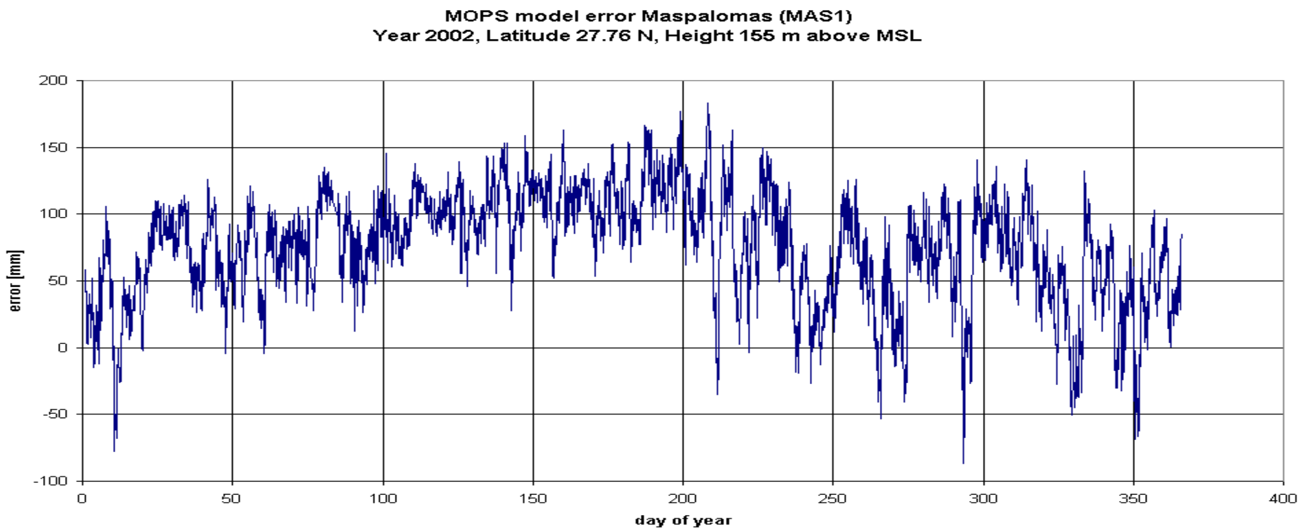

Figure 5 MOPS error for station MAS1

The statistics for DELF and MAS1 are summarised in table 3, together with data for some other a-typical stations.

Table 3

	DELF	MAS1	LAMP	MALL	LLIV
Station latitude [deg N]	52.00	27.76	35.50	39.55	42.48
Station height above MSL [m]	31	155	20	12	1415
Number of points	8592	8311	6926	8663	8143
ZTD average [mm]	2413	2400	2442	2455	2032
ZTD bias [mm]	2.0	75.1	49.2	15.6	- 7.5
ZTD standard deviation [mm]	38.5	41.4	37.3	35.5	27.5
ZTD 95% error [mm]	79.0	157.8	123.8	86.6	62.5

The bias value of station LAMP (Lampedusa, Italy) is rather high and nearly always positive, indication a too high MOPS model (wet) delay for this station on a small Italian island in the southern Mediterranean.
The bias error of station MALL (Palma de Mallorca, Spain) is close to zero, but the seasonal variation (not shown) is again clear.

Station LLIV (Llivia, Spain) in the Pyrenees at 1415 m above MSL has significantly lower error statistics compared to stations close to sea level. This is probably due to the lower absolute value of the zenith delays. But still the seasonal trend is present.

The majority of station time histories (see the examples above) show a somewhat identical seasonal variation of the MOPS zenith delay error. This suggests that tuning of the MOPS model constants for the EGNOS area might result in reduced errors as a function of day of year.

4 Conclusions, recommendations and suggestions

High accuracy reference data for the performance assessment of the MOPS model are available as zenith delay data delivered by a network of GPS receivers. The data is not delivered in real time, but data is available either with a delay of 1-2 hours or with a delay of a few weeks.

Somewhat less accurate reference data can be derived from NWP models. This data is available in real time.
A number of mapping functions are given, their reported accuracy figures are summarised. Use of the Niell mapping functions to convert the reference zenith delays to slant delays is recommended.

The MOPS model zenith delay values have been compared with high accuracy GPS network derived zenith delays for the year 2002 and for 140 stations in or close to Europe. The conclusions of this comparison are:
The MOPS specify the 'tropospheric vertical error' (σ_{TVE}) as 0.12 m. This specification is met for the ensemble of all stations.
Stations at mid latitudes comply with the above error specification. The statistics for stations at lower latitudes sometimes exceed the specification.
A latitude dependent bias was found for the lower latitude stations.

Based on the conclusions, recommendations for further research are given.
The MOPS zenith delay model latitudinal and seasonal variation parameters can be tuned to the EGNOS coverage area, resulting in a better accuracy of the MOPS model, especially for the lower latitudes, and possible also for high latitudes.
The accuracy of slant delays can be improved by replacing the current MOPS mapping function by e.g. the Niell mapping functions. Although they are more complex in terms of the mathematical formulation, they require the same input (day of year, latitude and height) as the MOPS zenith delay (‘blind’) models.

Although not discussed in this paper it is suggested to investigate if the daily variation of the tropospheric delay can be modelled, which may again increase the accuracy of the MOPS model.

In this paper the performance of the MOPS zenith delay model was evaluated only in a statistical sense for the year 2002. Based on this dataset, the performance of the zenith delay model should be investigated in more detail for a number of interesting meteorological cases, such as a cold front passage, heavy storms or other severe weather.

More research is needed on the (near) real-time performance assessment of the MOPS model. For (near) real time performance monitoring it is advised to extract zenith delays from the ECWMF model, or to use a forward prediction of tropospheric delay values derived from a network of GNSS receivers. It should be investigated weather the EGNOS network can be used

to estimate the ZTD in (near) real-time, or if it would be useful to integrate the EGNOS network as a sub network into the EUREF or
COST-716 networks.

References

1. 'Minimum Operational Performance Standards for Global Positioning System/ Wide Area Augmentation System Airborne Equipment', RTCA/DO-229C, November 28, 2001.
2. Hopfield H.S (1969), Two-Quartic tropospheric refractivity profile for correcting satellite data. J. Geophys. Res., 74(18), 4487-4499, 1969.
3. Niell, A.E. (1996), Global Mapping functions for the atmospheric delay at radio wavelengths, JGR, Vol. 101, No. B2, 3227-3246, 1996.
4. Niell, A.E. (2000), Improved atmospheric mapping functions for VLBI and GPS, Earth Planets Science, 52, 699-702, 2000.
5. Rocken, C., S. Sokolovskiy, J.M. Johnson and D. Hunt (2000), Improved Mapping of Tropospheric Delays, AMS, Vol 18, 1205-1213, 2001
6. 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., Vol. 15, 247 - 251.
7. De Haan, S. and H. van der Marel (2002), The influence on GPS estimates of NWP derived mapping functions, Phys. and Chem. of the Earth 29 (2004) 159-166.
8. Van der Marel, H., for the COST-716 team, The COST-716 demonstration project for the near real-time estimation of integrated water vapour from GPS, Phys. And Chem. Of the Earth 29 (2004) 187-199.
9. De Haan, S and S. Barlag, The use of near real-time GPS-IWV for Operational Meteorology and Nowcasting, GPSMET workshop Japan, 2003.
10. Note on Tropospheric Model Assessment, AM. 1/10/2002
11. Note on RID 402, Tropospheric Model, AM, 19/7/02
12. GALILEO Reference Troposphere Description of Model - Rev. 0-, ESA-APPNG-SPEC/00165-AM, Issue 1, Rev 0, 25.3.02.
13. Handouts ENVISAT meeting RA-2/MWR/DORIS Session, Absolute Range Calibration - Tropospheric Delay, AM, 9-13.12.02
14. Soehne W. and G. Weber (2003), EPN Special Project "Troposphere Parameter Estimation" - Status Report. In: Proceedings of EUREF Symposium, Ponta Delgada, Portugal, June 2002 (in press). (PDF file, 167KB)
15. Schueler, T. (2001), 'On Ground Based GPS Tropospheric Delay Estimation', thesis 2001

16. Schueler, T., Hein, G.W. (2002), 'Tropospheric Services for GNSS Users - Concepts, Status and Future Prospects', International GNSS Symposium, Copenhagen, Denmark 2002.
17. Y Bar-Sever, C Alber, R Ware, F Solheim (1997), 'GPS-Based Estimation of Tropospheric Delay Gradients: Validation and Assessment of Impact on Precise Point Positioning.

Abbreviations

COST	Coopération Européenne dans le domaine de la recherche scientifique et technique
ECMWF	European Centre for Medium-range Weather Forecast
EGNOS	European Geostationary Navigation Overlay System
EPN	European Permanent GPS Network
EUREF	European Reference Frame
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GTS	Global Telecommunication System
HIRLAM	High Resolution Local Area Model
IGS	International GPS Service
IWV	Integrated Water Vapour
LAC	Local Analysis Centre
MOPS	Minimum Operational Performance Standard
NWP	Numerical Weather Prediction
SBAS	Space Based Augmentation System
SHD	Slant Hydrostatic Delay
STD	Slant Total Delay
SWD	Slant Wet Delay
TVE	Total Vertical Error
WVR	Water Vapour Radiometer
ZHD	Zenith Hydrostatic Delay
ZWD	Zenith Wet Delay
ZTD	Zenith Total Delay