Tropospheric Delay Prediction in Wide Area Augmentation Systems Using Numerical Weather Fields

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ABSTRACT

For wide area augmentation system monitoring stations like the so-called RIMS of future EGNOS, the expected accuracy of smoothed pseudo-ranges is in the decimeter range. This means that tropospheric delay modeling is not unimportant as such propagation delays are in the order of about 2.5 m in zenith direction and a factor of 3 higher for elevations as low as 15 degrees. Normally, delay estimation is carried out using surface meteorological measurements. Some considerations point to omission of meteorological sensors at RIMS site due to economical reasons. Therefore, the troposphere is to be modelled by usage of default models like the MOPS approach which uses mean latitude-dependent and seasonally varying meteorological parameters as input. This study evaluates such models and those taking in situ measurements into account. Results indicate that the uncertainties are up to 10 centimeters in zenith direction and for MOPS the situation can be worse. The very idea of this investigation is to get rid of this dilemma by using numerical weather fields which allow to interpolate all necessary site data and also permit the integration of vertical refractivity profiles above the GPS antenna. This approach directly leads to zenith wet delays. Comparative studies of analysis fields reveal an accuracy that almost always outperforms common troposphere models in use.

INTRODUCTION

Microwave signals as used by navigation satellite systems like *GNSS* suffer from atmospheric propagation delays in transit, namely ionospheric and tropospheric delays. It is well known that the first is frequency-dependent and can be eliminated by simultaneous measurements on two frequencies whereas the latter reaches a magnitude of about 2.5 m in zenith direction (or about 25 m at an elevation angle of 5°) and cannot be compensated that easily.

The error budget for the troposphere error can be summarised as follows: The troposphere *delay being modelled in zenith direction* consists of a hydrostatic component that is responsible for about 90% of the total delay and a wet component. The first can be computed accurately by pressure measurements at the antenna site (and information about latitude and height of the station). The latter is highly variable and it is almost impossible to model it solely from surface measurements. Therefore, available troposphere models are rather inaccurate as far as this part of the tropospheric propagation delay is concerned and can have errors of sometimes up to 2 decimetres. Second, the zenith delay is to be *referenced to slant direction*, i.e. to the elevation angle under which the corresponding satellite is seen. This is done by application of a mapping function which is increasingly inaccurate with decreasing elevation. Satellites below zenith transmit signals that traverse greater part of the troposphere causing higher propagation delays. One has always to consider both effects: Errors of the zenith troposphere delay and errors of the mapping function which lead to increased slant path uncertainties. Elevation-dependent weighting of the *GNSS* measurements is useful due to this reason. This paper primarily deals with accuracy assessments of troposphere delays mapped into zenith direction.

The simplest approach to estimate the tropospheric error is to assume certain standard atmosphere values, to reduce them to the antenna site and to feed them into conventional models. The model presented in MOPS [1998] is an example based on this principle, although it implies some enhancements. Instead of applying default meteorological values taken from the standard atmosphere, latitude-dependent mean values are employed including modelling of seasonal variations. The advantage of such an approach is mainly that no measurements are needed which is practical for a lot of applications and cost-effective.

Most standard tropospheric delay models are based on the assumption that it is possible to model both the hydrostatic as well as the wet delay with sole knowledge of surface meteorological measurements. This approach is only partly sufficient, namely for modelling the hydrostatic component. The differential hydrostatic delay can be expressed as

$$dZHD = k_1 \cdot \frac{P_d}{T} \cdot 10^{-6} \cdot dh \qquad (1)$$

$dZHD$: differential hydrostatic delay in zenith direction
k_1: hydrostatic refractivity constant (77.6 K/hPa)
P_d: dry pressure in [hPa] (sum of P_d and partial water vapour pressure e yields the total pressure P)
T: temperature in [K]
dh: differential height increase

and integrated using the laws of hydrostatic equilibrium[1]. The well-known and highly accurate SAASTAMOINEN hydrostatic model is used by many authors, see e.g. BEVIS [1992], mainly depends on surface total pressure

$$ZHD = \frac{\left(2.2779 \pm 0.0024\,[mm]\right) \cdot P_S}{1 - 0.00266 \cdot \cos 2\varphi - 0.00028 \left[\frac{1}{km}\right] \cdot h} \qquad (2)$$

ZHD: zenith hydrostatic delay in [mm]
P_S: total pressure at surface/antenna site in [hPa]
j: geographic latitude of the site
h: ellipsoidal height in [km]

and takes the impact of the gravitational force on the delay into account which can be computed depending on the site latitude and ellipsoidal height.

Unfortunately, it is not possible to find a model as easy as the hydrostatic one for the wet component since the water vapour distribution is highly variable and unpredictable by surface measurements, although a correlation can be found mainly between the surface partial water vapour pressure and the zenith wet delay which MENDES [1998] found to be

$$ZWD = 12.2\,[mm] + 9.43 \left[\frac{mm}{hPa}\right] \cdot e \qquad (3)$$

ZWD: zenith wet delay in [mm]
e: partial water vapour pressure in [hPa]; e is a function of relative humidity and temperature

An assessment of this model is given here and, actually, the accuracy is better in comparison to the MOPS model. Nevertheless, the most accurate way to determine wet delays is to integrate the wet refractivity profile given by

$$ZWD = 10^{-6} \cdot \int_{h_{Antenna}}^{\infty} \left[k_2' \cdot \frac{e}{T} + k_3 \cdot \frac{e}{T^2} \right] \cdot dh \qquad (4)$$

ZWD: zenith wet delay in [m]
k_2': refraction coefficient, about 22.1 K/hPa
k_3: refraction coefficient, 370100 K²/hPa
e: partial water vapour pressure in [hPa]
T: temperature in [K]

This has been practised for high-precision applications, in VLBI for instance, by using the information of radiosonde launches, but we can apply the same algorithm to 3d-numerical weather fields in a very analogous manner[2]. A detailed discussion about the coefficients of the refraction formula can be found in BEVIS [1994].

Description of Numerical Weather Model

The numerical weather model used for this study is the *NOAA/NCEP* model[3] of the Global Data Assimilation System *(GDAS)*. *NCEP* processes data from a variety of operational measurements and has developed numerical forecast models which are used together with the assimilated data for the production of analysis and forecast fields. A list of observational data sources assimilated is given by HUANG [1995] and consists - among others - of surface marine and land observations, *TIROS* operational vertical sounder *(TOVS)* temperature retrievals and rawinsonde observations.

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[1]) see SPILKER [1996], page 533 for further details

[2]) Actually, the only practical difference is that radiosonde profiles usually have a higher vertical resolution in comparison to the weather model used for this investigation.

[3]) *NCEP:* National Center for Environmental Prediction, formerly *NMC*
NOAA: National Oceanic and Atmospheric Administration, USA

For this study, mainly final analysis fields have been used which are created each 6 hours, have a horizontal resolution of 1° x 1° and a vertical resolution of 26 geopotential height layers (1000 ... 10 hPa), 26 temperature layers (same pressure levels as for geopotential height) and 21 relative humidity layers (same pressure levels, but ends at a height of 100 hPa). Some more details are displayed in
Figure **1**.

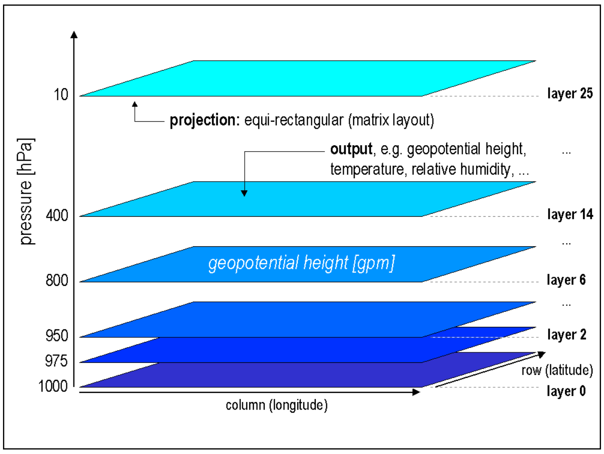

Figure 1 - *Data representation in global numerical weather fields as used for this investigation.* *The data in the output fields are organised in 3 dimensions. 26 vertical layers contain geopotential heights for the corresponding pressure levels as well as temperature. Relative humidity is given for 21 vertical layers. In horizontal direction, the data are stored in matrix layout (i.e. equi-rectangular projection is used) with 181 rows and 360 columns corresponding to a resolution of 1° x 1°.*

Tropospheric Database

The Institute has established and still maintains a tropospheric database where the zenith neutral delays from more than 100 stations of the IGS network are separated into hydrostatic and wet components. Moreover, the zenith wet delays are converted into integrated water vapour and archived for analysis purposes. For separation and conversion, meteorological data are needed and those either come from surface measurements taken at the IGS tracking stations (only in very few cases) or, for all sites with missing meteorological data, the needed information is extracted from the numerical weather fields. This database is used for the following comparisons: the GPS-derived delays serve as reference data. Since the hydrostatic component can be determined with a standard deviation of usually less than 3 mm, the GPS wet delays have an accuracy of about 5 to 15 mm.

Data Extraction from Weather Fields

In brief, the data extraction strategy from numerical weather fields as used for the work depicted in this paper can be summarised as follows:

1. Horizontal interpolation is performed for each of the vertical layers. In this way, the vertical profile above the GPS tracking station is extracted. Interpolation is carried out using a weighted nearest neighbour algorithm. The weight is defined by the reciprocal squared distance from the antenna site to the neighbouring model grid point. All 4 grid points in the vicinity of the GPS tracking station are used.
2. Vertical interpolation is performed to derive surface meteorological data. Pressure data are interpolated by exponential functions. For temperature and relative humidity, linear interpolation is adequate and applied.
3. The wet refractivity profile is integrated using formula (4). In this way, the zenith wet delay is derived.
4. Extra information is extracted, e.g. the height of the tropopause, the temperature lapse rate (linear least-squares fit of the temperature profile up to the height of the tropopause), the water vapor scale height and the mean temperature of the atmosphere (for accurate conversion of the zenith wet delay into integrated water vapor).

SURFACE METEOROLOGICAL DATA

Before a detailed look at some tropospheric delay models is given, a quality assessment for the surface data extracted from the numerical weather fields should be made. Some IGS stations are equipped with meteorological sensor packages. The pressure sensors usually have an accuracy of about 0.5 hPa or less, but for some stations, the height reference was obviously erroneous. It has been tried to exclude such measurements from any comparison, but as an offset of 10 meters height only causes an error of 1 hPa in pressure, there still remains some uncertainty.
Table ***1*** presents the results for all three types for surface observations and
Figure ***2*** shows the biases and standard deviations in surface pressure for selected - predominantly European - sites. Please refer to the IGS web site *http://igscb.jpl.nasa.gov/* to get more information about the location of these stations.

For all practical purposes, the surface pressure is the most important measurement. Formula (2) shows that it is the only meteorological information needed to estimate the hydrostatic zenith delay - the major contributor to the zenith neutral delay holding a ratio of about 90%. For high-precision applications in GPS meteorology, an accuracy of less than 1 hPa is wanted which allows the determination of the hydrostatic component with an uncertainty of better than 3 mm for average situations. In any case, it becomes evident that the hydrostatic delay is not the problematic part of the tropospheric propagation delay. Even for tracking stations like *STJO* or *CHUR* showing a bias of 1.6 hPa, the hydrostatic delay can be determined with a precision of better than 4 mm. The standard deviation, a bias-reduced value, is between 0.5

and 0.6 hPa for the major part of the stations.

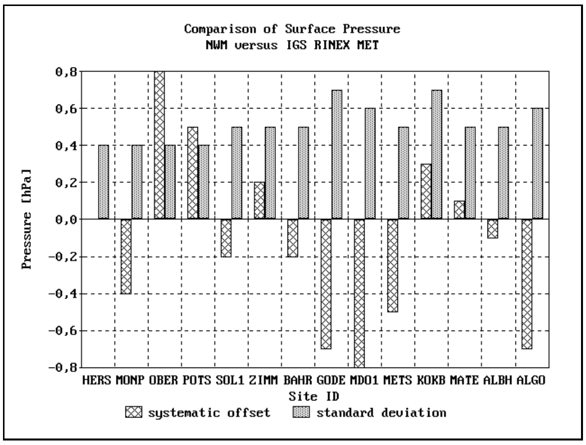

Figure 2 - Surface pressure comparison. *The diagram shows biases and standard deviations for selected IGS sites. In most cases, the standard deviation reaches the desired level of about 0.5 hPa which results in an error being less than 2 mm for the hydrostatic component. Systematic errors are obviously present, but in most cases they are tolerable. A few sites, however, show long-term offsets in the range of 1 hPa (see table).*

Conventional wet delay models usually employ surface temperature and relative humidity for deriving the wet delay.

Table ***1*** suggests a standard deviation of less than 2 K for the temperature and also shows that the biases are within acceptable limits. *YELL* is a bit out of boundaries with a long-term bias of almost 4 K. The same statement is *not* true for the comparison of relative humidity. Quite a number of stations show heavy biases. In a few cases, theses biases can be definitely traced back to erroneous measurements of the IGS meteorological sensors. This is undoubtedly true for *KOKB*: for many days, the sensor reads a relative humidity of 0.5% which is almost constant over the whole day. This value is not considered to be reliable, but it is not easy to detect such corrupted data sets by the database analysis routines. Apart from poorly performing humidity sensors[4] there are some other reasons that can lead to strong biases in relative humidity, for example extrapolation problems in the numerical weather model. Extrapolation problems are also one reason for the relatively large pressure bias at *OBER*. This station is located near Munich, Germany. In the south, the model grid points are covering the Alps and therefore, vertical extrapolation problems may occur. This problem is mainly related to the limited resolution of the numerical weather model. On the other hand, the humidity sensors can be highly influenced by micro climate which is not at all representative for the vertical atmospheric profile although this is exactly what is necessary to determine the wet delay with help of conventional models. In such cases, the data extracted from the numerical weather fields certainly can have offsets in comparison to the in situ measurements though they should be expected to be better suited for application in wet delay models.

TROPOSPHERIC PROPAGATION DELAY MODELS

The following paragraphs try to assess the quality of selected troposphere delay models. The validation period ranges from June, 1999 up to March, 2000. At least one example is given for each type of model *(ZND/ZTD, ZHD* and *ZWD)* beginning with the zenith total or neutral delay. It should be pointed out that models requiring meteorological data have been supplied with these information by the numerical weather model because it is the aim of this investigation to show how the use of numerical weather fields can improve the delay estimation in the sense that no meteorological sensors are needed. This can be important as far as the interpretation of results is concerned since the previous section showed clear discrepancies between the surface humidity measurements and those extracted from the numerical weather fields.

To repeat the essential outcome of the introductory paragraph, there are two basic strategies to make use of numerical weather models for delay estimation. The first one is the extraction of surface data which are then used in conventional delay models and the second approach couples much more tightly to the weather model as it directly integrates the refractivity profile. It should be expected that this method is the most accurate strategy in this context.

Total Delay Models

An example for this class of models is the SAASTAMOINEN *ZTD* model. SPILKER [1996] describes this model. Here, the unrefined version has been used receiving meteorological inputs in form of total pressure, temperature and relative humidity referenced to the GPS antenna height. Figure 6 shows the RMS diagram where the reference data are the GPS-derived neutral delays in zenith direction. The diagram is very similar to those for the wet models presented hereafter and, indeed, it can be assumed that the major contribution to the error budget comes from the wet delay uncertainties.

Hydrostatic Delay Models

A brief comparison of hydrostatic models is presented here as well, although section 2 already revealed that hydrostatic delays are not the critical point in tropospheric propagation delay estimation. The surface pressure from numerical weather fields of medium resolution as used for this investigation has a sufficient accuracy to allow *ZHD* computation with an accuracy of about 3 mm.

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[4]) Humidity sensors need ongoing calibration; a well-calibrated device should be able to measure relative humidity with an accuracy of about 5% and better.

Of course, the hydrostatic refractivity profile could also be integrated in the same manner as it is done for the wet component, but there is one crucial difference between both types: whereas the wet component receives contributions throughout the tropopause up to a height of approximately 12 km, the hydrostatic component is influenced up to the height of the stratosphere. The weather model used here covers the whole vertical column responsible for wet delay, but it ends at a height of 10 hPa (less than 30 km) which is not sufficient for hydrostatic delay computation by profile integration. Nevertheless, this problem can be solved: above the final height of 10 hPa the remaining contribution of the stratosphere to the zenith hydrostatic delay can be estimated with formula (2) which yields about 2 cm (!).

In any way, the surface model of Saastamoinen given with formula (2) is sufficient and used here as a reference. It is commonly used in high-precision GPS meteorology where it proved to be of high accuracy. The hydrostatic model of Hopfield (Figure 5, inputs: temperature and relative humidity) and the MOPS hydrostatic component (Figure 4) are compared with this reference model.

Generally speaking, there is - in mean - only a slight difference of less than 5 mm between the reference and the Hopfield model, but the plot shows clear systematic tendencies which are not too unexpected as the Saastamoinen model takes gravity acceleration into account whereas the Hopfield approach does not. The difference of a nominal, non-gravity corrected hydrostatic delay of 2.4 m between the equator and the pole is about 1.3 cm according to formula (2) and corresponds to Figure 5. At the equator there is the best fit, at the poles the discrepancies are highest.

The MOPS model does not perform very good as depicted in Figure 4.
Figure ***3*** was added to the paper in order to clarify the spatial (i.e. latitude-dependent) properties of the systematic MOPS errors. For the southern hemisphere, there are some dramatic offsets which are mainly related to IGS tracking stations located at Antarctica (e.g. *DAV1, MCM4, MAW1*). A closer look at the tropospheric database showed that this model has tremendous difficulties in predicting a proper value for the pressure at antenna site here. To give an example, *MCM4* is located at a latitude of -77.8° and an ellipsoidal height of 98 m (geoid height is -53 m). On 2000/03/31, pressure near 980 hPa was extracted from the numerical weather model. The Saastamoinen *ZTD* model agreed at the level of 15 mm to the GPS-derived neutral delays, so the pressure from the weather fields is apparently of good quality. In contrast to that, the MOPS model predicts a pressure which is clearly too high and therefore computes a hydrostatic delay being much larger than the actual value leading to negative biases when compared to the reference model. For most other sites on the globe, the performance is better, but there is a factor of 4 between the global RMS of 1.6 cm in comparison to 0.4 cm for the Hopfield model.

Wet Delay Models

The pages at the end of this paper show diagrams for the accuracy assessment on four wet delay models. The RMS (root-mean-square) diagrams in Figure ***7***+ include systematic deviations, in the standard deviation diagrams (Figure ***11***+), offsets are eliminated and in Figure ***15***+ the systematic effects are displayed in relation to the site latitude. Each dot represents the mean value for one specific site of the IGS tracking network for the whole validation period from June, 1999 to March, 2000.

The following models have been assessed: the wet component of the MOPS model, the Hopfield and Mendes[5] models representing the *"surface approach"* and the vertically integrated wet delays from the numerical weather model.

For the *MOPS model*, the linear RMS trend function (dashed line) suggests an accuracy of only 8 cm at the equator, but Figure 10 undoubtedly shows that there are also a lot of sites at latitudes of 30° to 40° which perform rather poorly. The results obtained for *Hopfield and Mendes* are similar. Clearly, the results are better than in the MOPS case and again, RMS drops down for higher latitudes due to the fact that the tropics are the climate zone with highest humidity and therefore, the delays are largest there. The more the poles are approached, the more the delays decrease. As most errors in wet delays are no constant biases, but predominantly relative errors, the absolute accuracy increases with higher latitude - for the relative accuracy this statement is not necessarily true. In global average, a RMS of 3 cm for the Hopfield as well as the Mendes model can be stated. The linear trend analysis suggest an accuracy of about 5 cm at the equator. Last but not at least, it becomes evident that the *vertical integration approach* performs best - the RMS at the equator is more than twice as good as for the previous model and 3-4 times better than for the MOPS model. The decrease of RMS with increasing latitude is much weaker, so there is a better “global stability” of the solution. The linear accuracy functions of type

$$\sigma(\varphi) = \sigma_0 + q \cdot |\varphi| \qquad (5)$$

$s(j)$: latitude-dependent RMS
s_0: RMS at the equator
q: RMS decrease factor
j : latitude of site in degrees

are given in table 2.

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[5]) see formula (3)

A look at the *standard deviation diagrams* reveals that systematic effects are apparently the most important contributor to the overall error budget expressed in terms of RMS. The standard deviations of all 4 approaches only differ marginally, expect for the vertical integration algorithm where the standard deviation is lowest. Actually, the MOPS model even performs a bit better (about 0.5 to 1.0 mm) in comparison to the surface data models of HOPFIELD and MENDES as far as their standard deviation is concerned.

The *bias plots* show the largest shatter for the MOPS model and the best distribution for the integrated NWM delays. Offsets in the MOPS model can have values of up to 1 dm. It should be stressed that these are results from the long-term comparisons (about 3/4 year), so the biases that can be seen in the diagrams seem to be stable and show a one-sided distribution: they are negative for most tracking stations.

Summary of Assessments

Table 3 gives global mean accuracy figures for the different tropospheric delay types and models/approaches presented here which summarise the outcome presented in the previous paragraphs.

The results obtained for the vertical integration approach are very promising. In global average a RMS of 1.4 cm can be stated and there are only a few sites which have a poor performance. One of them is *GALA* (Galapagos Islands); the reason for this is not yet clear. It might be possible that the numerical weather model does not perform very good in this region due to data scarcity or other reasons connected with local/regional anomalies.

To improve the data extraction algorithm, several modifications have been implemented meanwhile. One important new feature is that model surface data are considered by the program. Moreover, the new algorithm performs vertical interpolation for all four model grid neighbors first and afterwards, the horizontal interpolation takes place. Both modifications serve a good job in overcoming the problems related to extrapolation and first test runs have shown that the biases in relative humidity could be reduced for some sites.

CONCLUDING REMARKS

It could be shown that numerical weather models are useful for tropospheric delay estimation and superior to conventional models in terms of accuracy. This statement is also correct for global models of medium resolution as used for this study which do not place a great burden on memory and hard-disk storage load for modern computer systems as a highly efficient binary data format is used. Under these circumstances, meteorological sensor packages can be omitted. On the contrary, it could be shown that the use of algorithms like the MOPS model making use of default meteorological data might decrease the overall accuracy having in mind that carrier-smoothed pseudo-ranges can have uncertainties in the decimetre range and MOPS delay estimates being as inaccurate as 10 cm or sometimes even more.

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SITE	NUMBER SAMPLES	BIAS PRESSURE	SIGMA [hPa]	BIAS TEMPERATURE	SIGMA [K]	BIAS HUMIDITY	SIGMA [%]
AOML	5184	-0.1	0.8	0.8	0.9	-0	5
HERS	4872	-0.0	0.4	-1.3	1.3	1	6
MONP	3480	-0.4	0.4	-0.9	3.1	7	7
OBER	1152	0.8	0.4	-0.2	2.3	2	10
POTS	3408	0.5	0.4	0.2	1.1	-3	9
SOL1	2040	-0.2	0.5	0.9	1.3	-1	7
USNO	3192	-0.7	0.6	0.4	1.5	-28	6
WES2	3384	1.4	0.6	-0.4	2.2	3	11
ZIMM	4968	0.2	0.5	-0.3	1.5	0	10
AUCK	2472	0.1	0.5	-0.4	1.5	8	7
BAHR	5232	-0.2	0.5	-1.3	2.0	18	11
CHAT	2616	0.0	0.7	-0.8	1.4	7	6
GODE	1296	-0.7	0.7	0.4	3.5	-13	11
MDO1	3984	-0.8	0.6	0.9	2.9	3	15
METS	1872	-0.5	0.5	-0.6	1.4	5	7
FAIR	1728	-0.7	0.6	2.9	2.8	-19	13
KOKB	1344	0.3	0.7	-1.2	1.7	-51 **X**	8
MATE	3336	0.1	0.5	-0.7	2.1	7	12
JPLM	936	-0.4	0.5	0.1	1.8	-3	7
SCIP	24	-0.1	0.5	-1.5	2.4	11	8
ALBH	1224	-0.1	0.5	-0.3	1.1	-11	7
ALGO	1248	-0.7	0.6	0.0	2.3	-10	12
SCH2	1224	-1.5	0.5	-1.2	1.6	-24	8
STJO	1272	-1.6	0.6	-0.6	1.1	2	7
YELL	1224	-0.5	0.4	-3.8	1.9	-16	7
ZWEN	960	1.0	0.6	0.0	1.2	-6	7
NRC1	168	0.8	0.6	-1.2	1.9	-4	6
PRDS	120	-1.4	0.5	-1.2	1.7	-12	10
CHUR	384	1.6	0.4	-2.6	1.6	-25	6
LHAS	24	-1.1	1.3	0.8	2.8	-19	9
MEAN		-0.10	0.55	-0.29	1.78	-1.4	8.7

Table 1 - Comparison of surface meteorological data *as extracted from the numerical weather model with in situ measurements at IGS monitor stations. Hourly values were compared, i.e. there are 24 samples per day.*

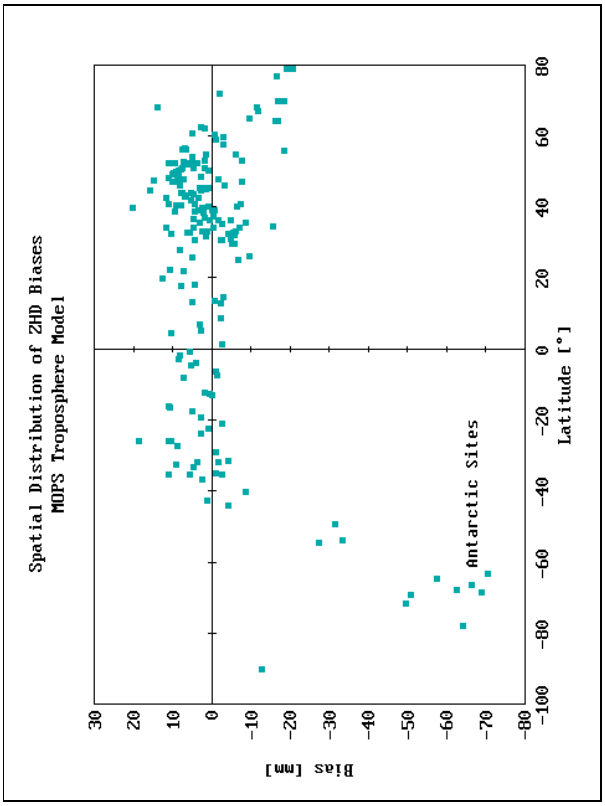
Model	***s_0 [mm]***	***q [mm/°]***
MOPS	70.0 ± 3.1	-0.59 ± 0.07
Hopfield	47.0 ± 1.9	-0.45 ± 0.05
Mendes	46.5 ± 2.0	-0.43 ± 0.05
vertical integration in NWM	21.8 ± 0.7	-0.20 ± 0.02

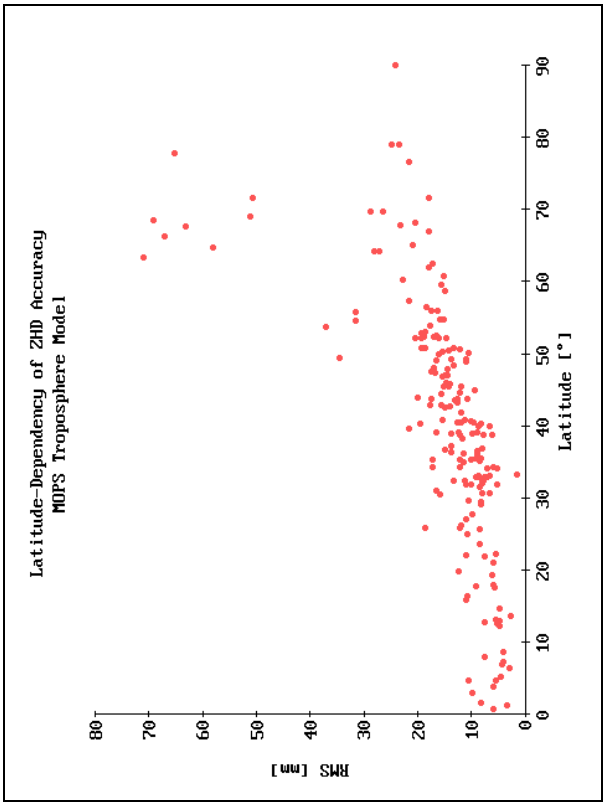
Table 2 - ***Coefficients of the RMS functions*** *expressing the expected absolute accuracy of the different wet delay estimation approaches with dependence on site latitude.*

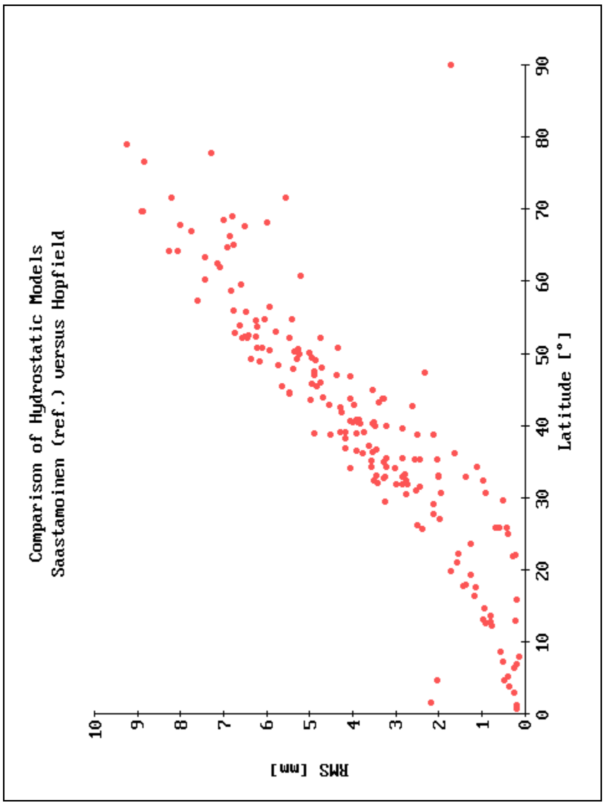
CATEGORY	REFERENCE	MODEL	BIAS	SIGMA	RMS [mm]
ZTD	GPS	SAAS	1.8	12.2	27.7
ZHD	SAAS	HOPF	-3.7	0.2	3.8
ZHD	SAAS	MOPS	-0.7	3.3	15.7
ZWD	GPS	NWM	-1.5	8.7	13.9
ZWD	GPS	HOPF	-0.9	12.4	28.3
ZWD	GPS	MEND	-5.7	12.0	28.3
ZWD	GPS	MOPS	-20.5	11.5	46.6

ZTD..:	zenith total (or neutral) delay
ZHD..:	zenith hydrostatic delay (about 2.3 m, 90% of ZTD)
ZWD..:	zenith wet delay (about 0.15 m, 10% of ZTD)
SAAS.:	SAASTAMOINEN model
HOPF.:	HOPFIELD model
MEND.:	MENDES model
MOPS.:	MOPS model
NWM..:	numerical weather model, i.e. refractivity profile integration
SIGMA:	standard deviation (bias reduced)

Table 3 - Global summary of the accuracy assessment. *Please note that the SAASTAMOINEN ZTD model is not equivalent to the SAASTAMOINEN ZHD model. The latter serves as reference for hydrostatic comparisons.*







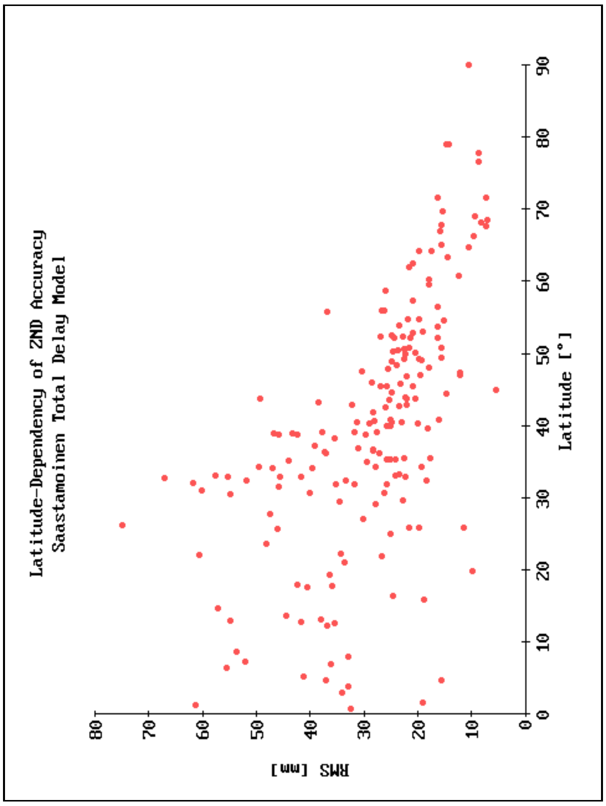
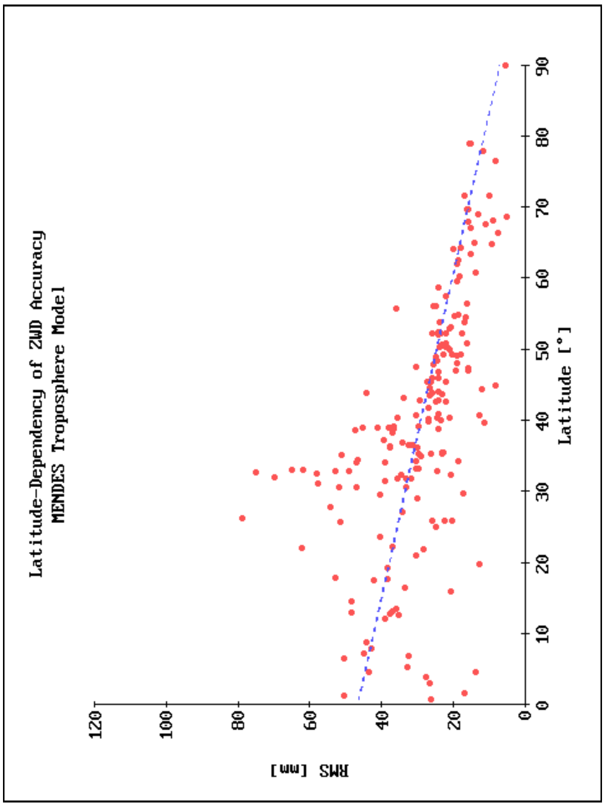
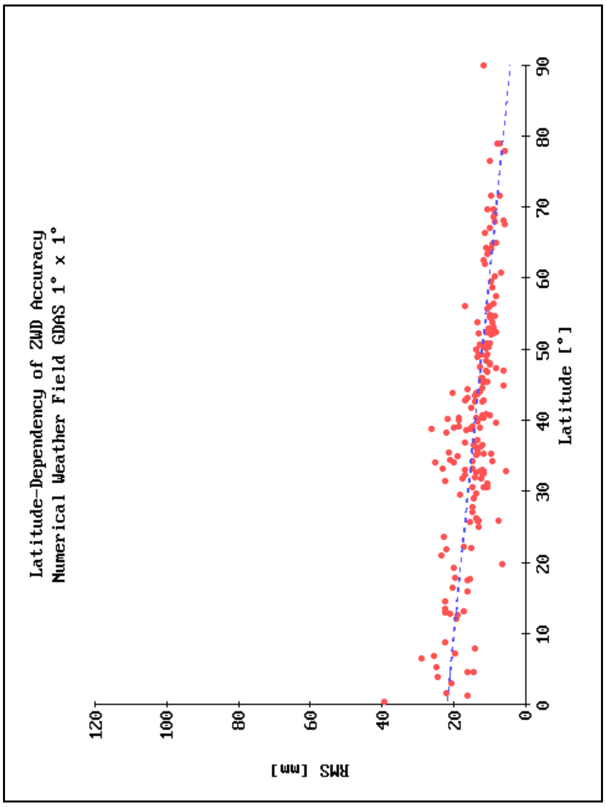
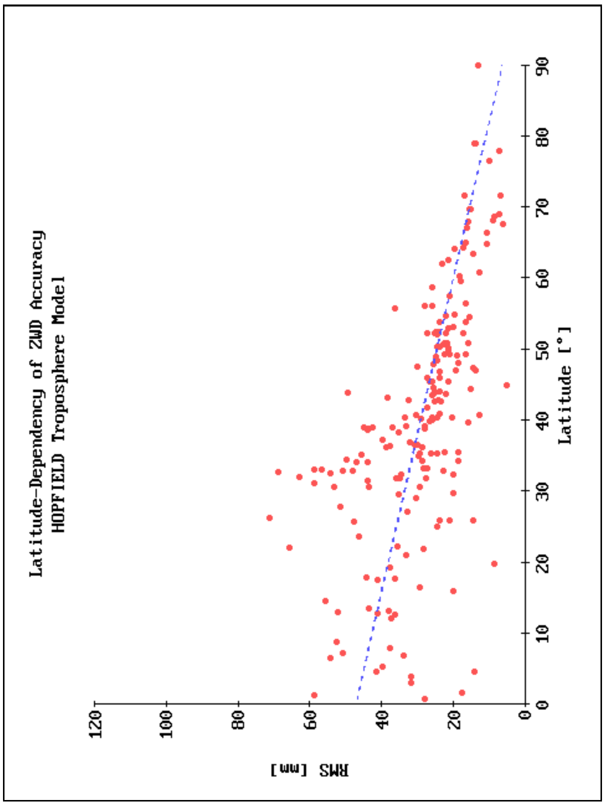


Figure 3 (left, up) - Systematic errors of the hydrostatic component of the MOPS model.
Figure 4 (right, up) - RMS diagram of the MOPS-model (ZHD) related to site latitude.
Figure 5 (left, down) - RMS diagram of the Hopfield ZHD model.
Figure 6 (right, down) - RMS diagram of the Saastamoinen ZTD model







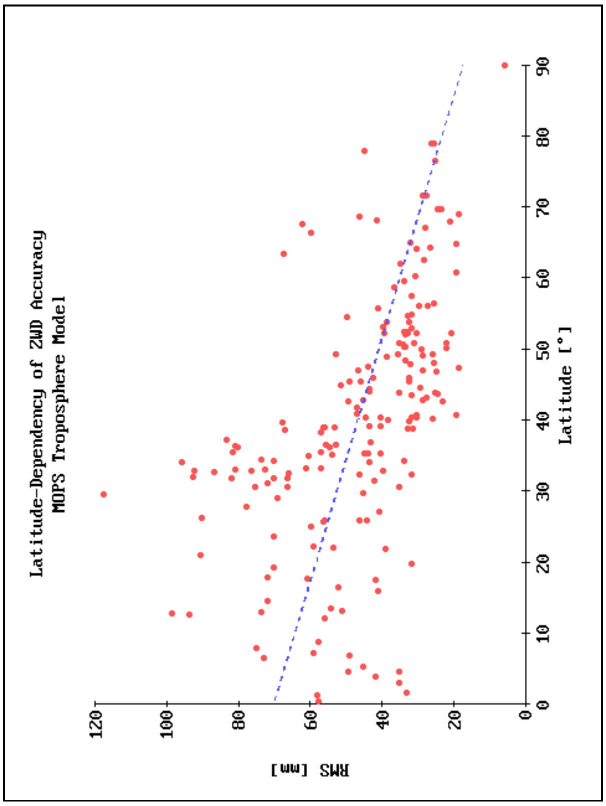
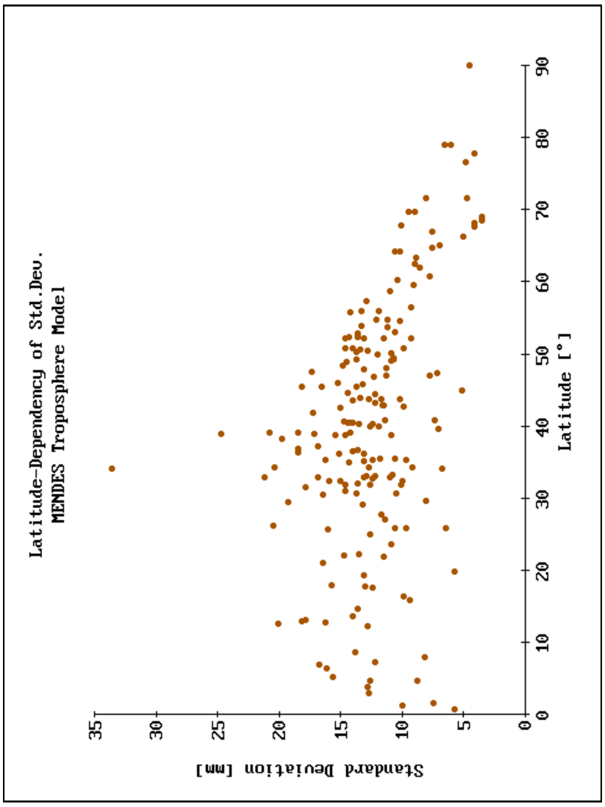
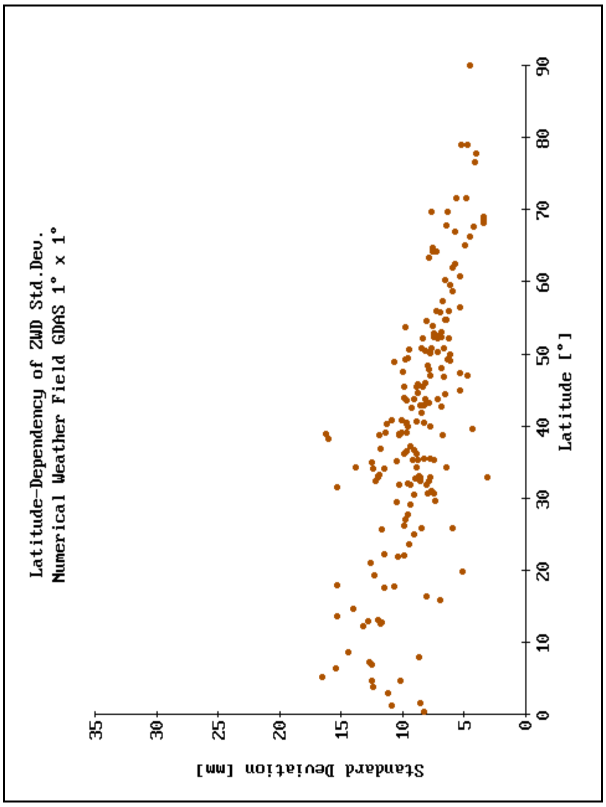
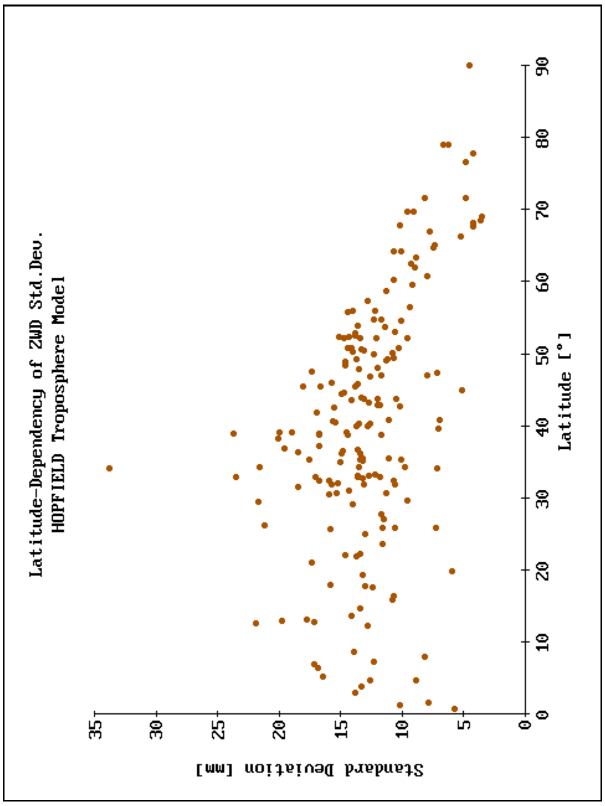


Figure 7 (left, up) - RMS diagram of the MENDES-model (ZWD).
Figure 8 (right, up) - RMS diagram of the integrated ZWD from weather fields.
Figure 9 (left, down) - RMS diagram of the HOPFIELD-model (ZWD).
Figure 10 (right, down) - RMS diagram of the MOPS model (wet component).







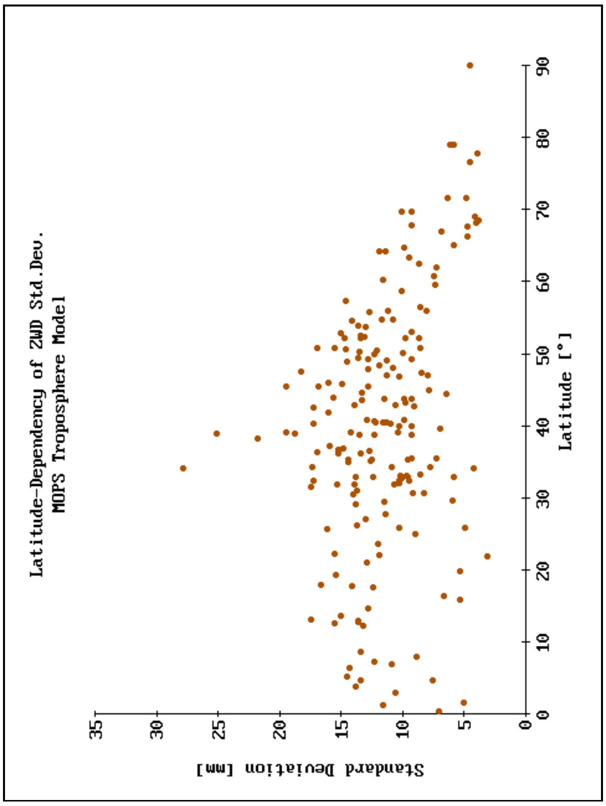
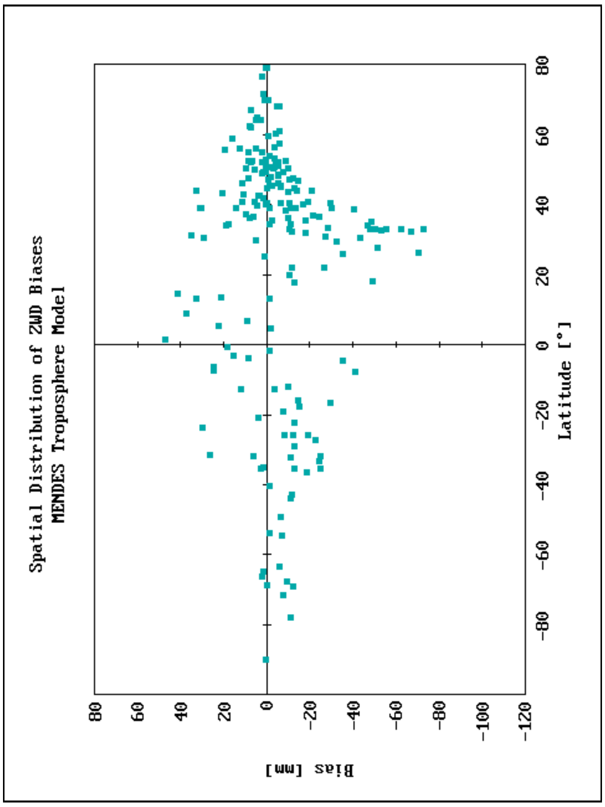
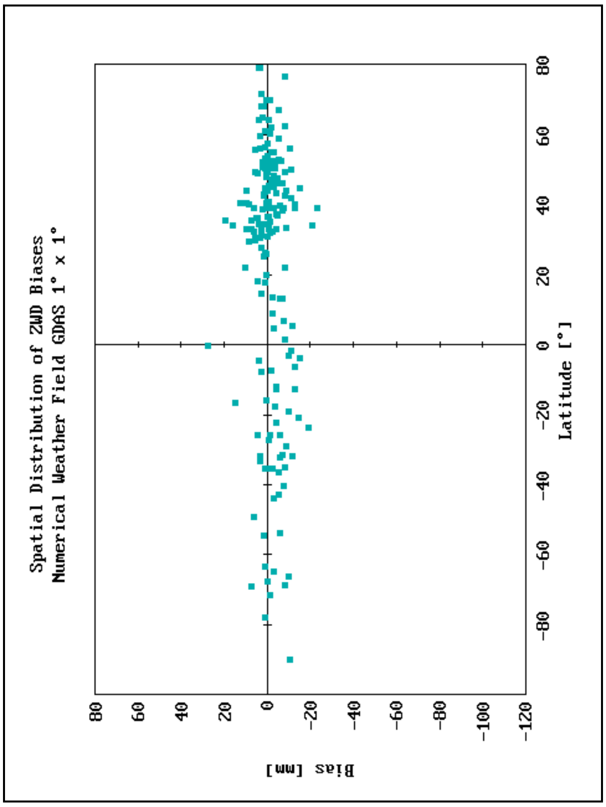
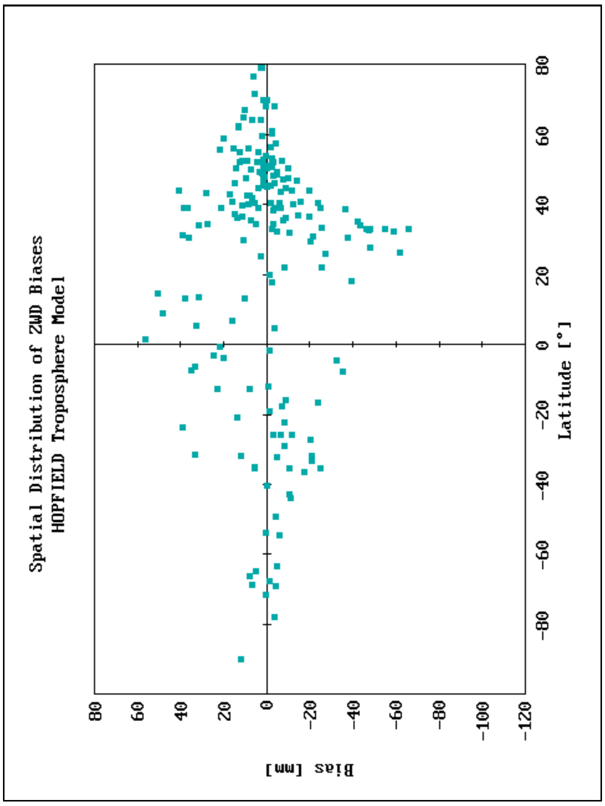


Figure 11 (left, up) - Standard deviation diagram of the MENDES-model (ZWD).
Figure 12 (right, up) - Std. dev. diagram of the integrated ZWD from weather fields.
Figure 13 (left, down) - Standard deviation diagram of the MOPFIELD-model (ZWD).
Figure 14 (left, down) - Standard deviation diagram of the MOPS model (wet component).







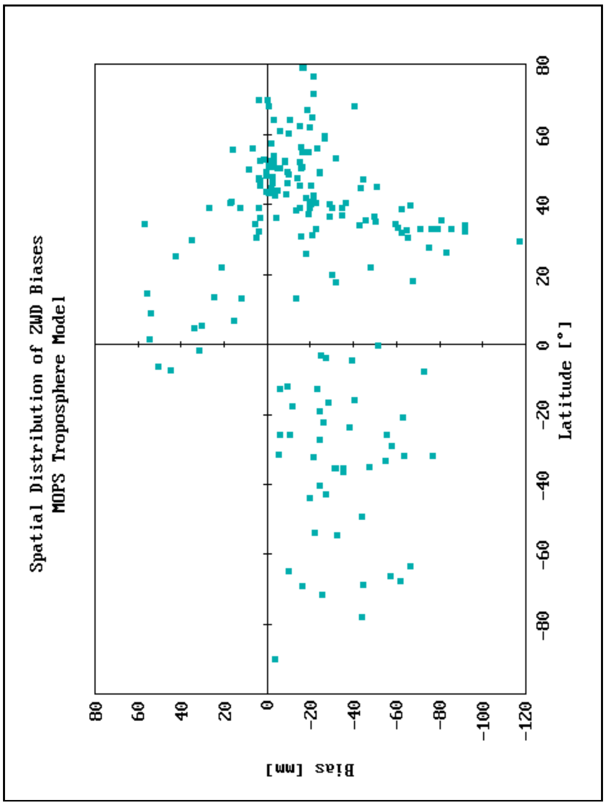


Figure 15 (left, up) - Systematic errors of the MENDES-model (ZWD).
Figure 16 (right, up) - Systematic errors of the integrated ZWD from weather fields.
Figure 17 (left, down) - Systematic errors of the HOPFIELD-model (ZWD).
Figure 18 (left, down) - Systematic errors of the MOPS model (wet component)).