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IMPACT OF VARIOUS FACTORS ON THE QUALITY OF SITE-SPECIFIC NEUTROSPHERIC PARAMETERS WITHIN GNSS DATA PROCESSING: A CASE STUDY

O impacto de vários fatores na qualidade de parâmetrtos neutrosféricos de estação a partir do processamento de dados gnss

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ABSTRACT

Propagation delays of the signals of global navigation satellite systems (GNSS) caused by the neutral atmosphere are an important accuracy-limiting factor for precise geodetic applications. A common approach to handle the neutrospheric delay is to estimate so-called site-specific neutrospheric parameters (SSNP) within GNSS data processing which are then combined with the predicted model values calculated primarily based on meteorological data. Therefore, the quality of the determined neutrospheric delay depends not only on the factors impacting the GNSS signals but also on data processing strategies. In this paper, the influence of the factors impacting neutrospheric modelling such as baseline length, multipath, observation weighting, ambiguity resolution, and neutrospheric prediction models are analysed and quantified based on the standard deviations of the estimated SSNP. Additionally, an improved observation weighting scheme based on signal-to-noise power ratio measurements is briefly described. Test results indicate that applying this advanced weight model within GNSS data processing, including observations at low elevation, the standard deviation of the estimated SSNP can be improved by nearly 25% compared with the standard elevation-dependent weighting model.

Keywords: GNSS; Neutrospheric Modelling; Observation Weighting; SNR.

RESUMO

Os atrasos na propagação dos sinais dos sistemas de navegação globais por satélite (GNSS), causados pela atmosfera neutra, são importantes fatores que limitam a acurácia de aplicações geodésicas precisas. Uma abordagem comum para tratar o atraso neutrosférico é estimar os chamados parâmetros neutrosféricos específicos da estação (SSNP – *site-specific neutrospheric parameters*) no processamento de dados GNSS, os quais são, então, combinados com valores de um modelo predito calculados principalmente utilizando dados meteorológicos. Portanto, a qualidade do atraso neutrosférico determinado depende não somente dos efeitos que atuam nos sinais GNSS, mas também da estratégia utilizada no processamento dos dados. Neste trabalho, as influências dos fatores que afetam a modelagem neutrosférica como: o comprimento da linha de base, multicaminho, ponderação do peso das observações, resolução das ambigüidades e o modelo de predição neutrosférica, são analisados e quantificados baseando-se nos desvios-padrão dos SSNP estimados. Além disso, um modelo melhorado para a ponderação dos pesos das observações, baseado nas medidas de potência da razão sinal-ruído, é brevemente descrito. Os resultados apresentados nos testes indicam que a aplicação deste avançado modelo de ponderação dos pesos no processamento de dados GNSS, incluindo observações com baixa elevação, pode melhorar os desvios-padrão dos SSNP estimados em torno de 25% comparado com o modelo padrão de ponderação dos pesos dependente de elevação.

Palavras-chave: GNSS; Modelagem Neutrosférica; Ponderação dos Pesos das Observações; SNR.

1. INTRODUCTION

The electrically neutral atmosphere extends from the Earth's surface up to a height of about 80 km and subsumes the troposphere, the stratosphere and parts of the mesosphere. Due to its non-vacuum nature, signals of global navigation satellite systems (GNSS) are delayed when they propagate through this atmospheric layer. The neutrospheric delay depends primarily on meteorological parameters like temperature, air pressure, and relative humidity and can be represented both in time and in metric units. Generally speaking, the zenith path delay of GNSS signals due to neutrospheric refraction amounts to about 7.7 ns resp. about 2.3 m at sea level and it increases to more than 30 ns resp. 10 m for elevation angles of around 10°. The troposphere extending from the Earth's surface up to a height of approx. 10 km makes the greatest contribution to the neutrospheric delay; SPILKER (1996) mentions that about three quarters of the total neutrospheric delay are caused by gases within the troposphere.

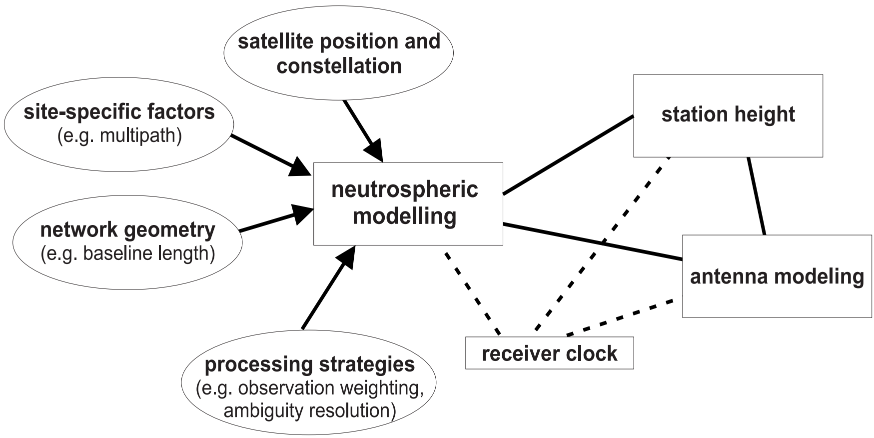
In contrast to the ionosphere, the neutrosphere is not dispersive at microwave wavelengths. Therefore, the neutrospheric delay can’t be eliminated using dual frequency observations. Additionally, the neutrospheric delay is much more site-specific than the ionospheric delay and thus the corresponding neutrospheric modelling within GNSS data processing is more significantly correlated with site-specific effects (e.g. multipath). For high-precision geodetic applications common GNSS software products provide possibilities to handle the neutrospheric delay based on prediction models and so-called site-specific neutrospheric parameters (SSNP). The predicted neutrospheric delay is calculated mainly based on site-related meteorological data and roughly predicts the neutrospheric behaviour, while the estimated SSNP within GNSS data processing approximate reality more accurately and are used as corrections to the predicted model values. Under the circumstance that neither measured nor representative meteorological data are available, a standard atmosphere can be normally applied to derive the above-mentioned site-related meteorological parameters; see ESSA/NASA/USAF (1966) and BERG (1948). Under the assumption of the validity of the standard atmosphere the quality of the determined neutrospheric delay mainly depends on the factors affecting the GNSS signals (e.g. multipath) as well as on the applied data processing strategies (e.g. ambiguity resolution, observation weighting, neutrospheric prediction models). Hence, reliable estimation of the SSNP and accurate determination of the neutrospheric delay require adequate knowledge of the influences of the above-mentioned factors on neutrospheric modelling.

In this paper, the factors impacting neutrospheric modelling such as baseline length, multipath, observation weighting, ambiguity resolution and neutrospheric prediction models are analysed and quantified based on the standard deviations of the estimated SSNP. Sect.2 gives an overview of the factors to be analysed and the correlation among them. In Sect. 3, the GNSS data base and processing strategies used in this case study are described. After that, section 4 provides a detailed analysis of the standard deviation of the SSNP with respect to each factor mentioned above. In Sect. 5, an improved observation weighting scheme based on signal quality measurements is briefly outlined and illustrated considering its impact on neutrospheric modelling. The conclusion and outlook follow in Sect. 6.

2. FACTORS IMPACTING NEUTROSPHERIC MODELLING

Fig. 1 gives an overview of the factors impacting neutrospheric modelling. If SSNP are estimated together with station height and receiver clock parameters a strong correlation among these three parameters is found which depends on the elevation cut-off angle. Under the assumption of homogeneous distribution of satellites above the elevation cut-off angle, the absolute value of the correlation coefficient between SSNP and station height decreases from 98.5% to 83.0% with decreasing elevation cut-off angle from 30° to 5° (ROTHACHER AND BEUTLER 1998). This implies that the correlation among these three parameters can be considerably reduced, if low elevation data are included within GNSS data processing. However, it is commonly known that low elevation data are much more disturbed by atmospheric and multipath effects than data at higher elevation angles. Thus, these observations must be stochastically appropriately handled, for example by applying a realistic observation weighting model. Errors in antenna modelling mainly affect the relative station height and they must be taken into account when cm-level positioning accuracy is desired. Any inaccuracy in station height will inevitably produce errors in neutrospheric modelling. The effects of the site-specific factors (e.g. multipath) vary with the direction of the incoming signals and therefore depend on satellite position and constellation. Thus, the corresponding influences on neutrospheric modelling are short-periodic and can be reduced by increasing the observation periods. Concerning network geometry (e.g. length of the processed baseline), under the assumption of normal atmospheric conditions, neutrospheric effects on GNSS signals can be strongly mitigated for short baselines (i.e. less than 30 km) using differential techniques, due to the similar signal paths through the atmosphere, while for long baselines these effects can't be totally eliminated. This difference implies that for long baselines the neutrospheric effects might be more accurately estimated within GNSS data processing compared to short baselines.

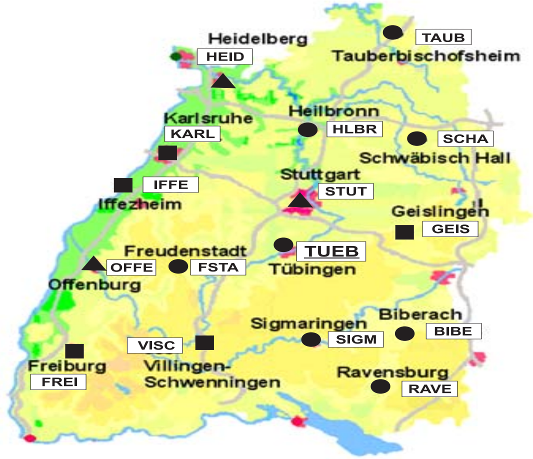
Fig. 1- Factors impacting neutrospheric modelling (MAYER 2006).



3. GNSS DATA BASE AND PROCESSING STRATEGIES

The observation data of all sixteen sites of the SA*POS*® (Satellite *Positioning Service* of the German State Survey) network (www.sapos.de) in Baden-Württemberg (SW-Germany) covering eight days (DOY2004: 186-193) are used for the GNSS data processing. Based on the results of the multipath analysis in MAYER ET AL. (2004), the SA*POS*® sites are classified in three groups (multipath: strong/medium/weak), see Fig. 2.

Fig. 2 - SA*POS*® sites in Baden-Württemberg; triangle/rectangle/circle: strong/medium/weak multipath according to MAYER ET AL. (2004).



The observations data are available with a minimum elevation cut-off angle of 0° and a sampling rate of 15 s. Due to variations of the weather situation within the analysed time span which could affect the data processing in different magnitudes, the processed results for two representative days (DOY2004: 186, 190) are utilised for further analysis. On day 186 the weather situation was normal, while on day 190 heavy rain fall was registered in different areas of Baden-Württemberg (WETTERZENTRALE 2007). Due to the weak multipath impact and the advantageous central location considering baseline length, TUEB (Tübingen) was chosen as reference site for the GNSS data processing from which fifteen baselines are formed to all other SA*POS*® sites. Tab. 1 presents the lengths of the formed baselines and the corresponding multipath impact of the non-reference sites. In Tab. 2 the important parameter settings of the applied standard processing strategy using the Bernese GPS Software 5.0 (BS5) (DACH ET AL. 2007) are listed.

Tab. 1- Multipath impact of SA*POS*® sites in Baden-Württemberg and baseline length..

Multipath	**Multipath impact: weak**						
Site	FSTA	SIGM	HLBR	BIBE	SCHA	RAVE	TAUB
Baseline length [km]	47.7	49.9	70.1	71.8	81.5	91.0	131.0
	Multipath impact: medium				**Multipath impact: strong**		
GEIS	VISC	KARL	IFFE	FREI	STUT	OFFE	HEID
55.6	66.6	72.5	77.7	106.9	30.3	81.8	100.8

Tab. 2 - Important parameter settings of the GNSS data processing using BS5 (standard strategy).

Parameter	**Characteristic**
Observations	GPS phase observations; double differences
Sampling rate	180 seconds
Observation weighting model	sin^2E
Elevation cut-off angle	10°
Orbits and earth rotation parameters	Precise final IGS products
Neutrospheric prediction model	Niell model
Mapping function	$MF_{Niell,\,w}$ (NIELL 1996)
Parameter spacing of SSNP	2 hours
Ambiguity resolution strategy	SIGMA strategy (L5, L3)
Antenna calibration	Individual absolute calibration

In order to analyse and quantify the influences of the above-mentioned factors on neutrospheric modelling, SSNP are estimated applying different processing strategies with the corresponding parameter settings. The differences with respect to the standard processing strategy presented in Tab. 2 are related to

- stochastic modelling (observation weighting: $w = 1$ resp. $w = sin^2E$, E: satellite elevation angle)
- ambiguity resolution strategy (SIGMA resp. QIF)
- neutrospheric prediction modelling (Saastamoinen model (SAASTAMOINEN 1973) using $1/sin\ E$
- as mapping function (MF) resp. Niell model with ($MF_{Niell,\,w}$).

The most important characteristics of the applied processing strategies are compared in Tab. 3.

Tab. 3 - Analysed GNSS data processing variants using BS5 (variant1: standard strategy).

Aspect	Variant 1	Variant 2	Variant 3	Variant 4
Observation weighting	$w = sin^2 E$	$w = 1$	$w = sin^2 E$	$w = sin^2 E$
Neutrospheric modelling	Niell $MF_{Niell,\,w}$	Niell $MF_{Niell,\,w}$	Saastamoinen $1/sin\ E$	Niell $MF_{Niell,\,w}$
Ambiguity resolution	SIGMA (L5, L3)	SIGMA (L5, L3)	SIGMA (L5, L3)	QIF (L1, L2)

4. INFLUENCES OF THE FACTORS IMPACTING NEUTROSPHERIC MODELLING

Based on GNSS observation data the SSNP are estimated with a parameter spacing of 2 h within data processing using the BS5. These parameters are site- and time-dependent zenithal corrections added to the predicted neutrospheric delay calculated by means of prediction models (e.g. Saastamoinen model). SSNP are normally modelled in a piece-wise constant continuous way. Detailed information concerning modelling and estimation of SSNP by means of the BS5 is given in DACH ET AL. (2007).

In this section the influences of the factors impacting neutrospheric modelling, for example, baseline length, multipath and data processing strategies including observation weighting, ambiguity resolution and neutrospheric prediction models are analysed and quantified based on the standard deviation of the estimated SSNP. Additionally, the sensitivity of these influences with respect to variations of the weather situation is also taken into account.

4.1 Dependence on baseline length

In order to quantify the effects of baseline length on the quality of the estimated SSNP, the fifteen baselines are classified into three groups concerning the corresponding baseline length. The multipath effects are quantified by introducing the so-called multipath index (MPI) (WANNINGER 2003, MAYER ET AL. 2004). Considering baseline length as well as weather situation, Tab. 4 represents the arithmetic mean values of the standard deviations (MSTD) of the SSNP estimated from daily solutions. The group mean values of the MPI provided by WaSoft (www.wasoft.de) are of comparable magnitude, which implies that the group mean values of the MSTD are representative for the influences due to baseline length.

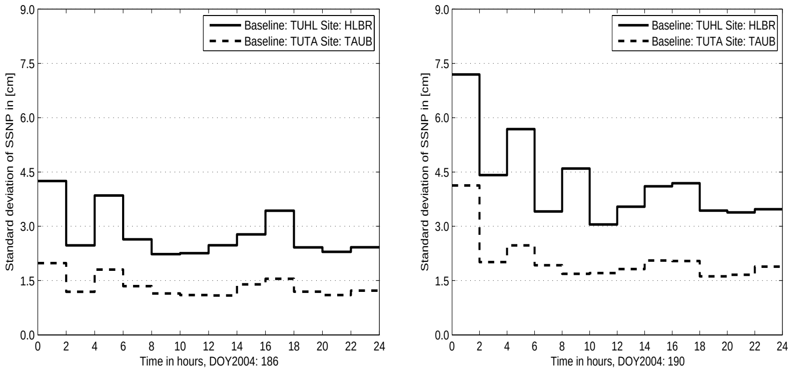
Tab. 4 - Comparison of MSTD of SSNP concerning baseline length and weather situation

30-70 [km], MSTD [cm]				70-100 [km], MSTD [cm]				100-131 [km], MSTD [cm]			
Site	**MPI**	**186**	**190**	**Site**	**MPI**	**186**	**190**	**Site**	**MPI**	**186**	**190**
STUT	23	7.1	8.2	OFFE	13	2.3	3.1	HEID	23	2.1	2.9
GEIS	5	3.0	3.7	KARL	18	2.5	3.5	FREI	7	2.5	2.4
FSTA	4	2.9	4.5	IFFE	4	1.9	3.0	TAUB	4	1.3	2.1
VISC	16	2.8	3.9	HLBR	4	2.8	4.2				
SIGM	5	3.7	4.5	BIBE	5	1.9	2.9				
				SCHA	2	1.8	2.9				
				RAVE	7	1.9	2.9				
Mean	**11**	**3.9**	**5.0**		**8**	**2.2**	**3.2**		**11**	**2.0**	**2.5**

The effects of baseline length on the group mean values of MSTD range between 1.9 cm (DOY2004: 186) and 2.5 cm (DOY2004: 190). The impact of weather variations on short baselines (1.1 cm) is stronger than on long baselines

(0.5 cm). For short baselines the neutrospheric effects on the GNSS signals are eliminated using differencing techniques, so that neutrospheric parameters can't be as accurately estimated as in the case of long baselines. Additionally, the correlation between station height and SSNP affects short baselines more significantly than long baselines. In Fig. 3, the standard deviations of the SSNP are exemplarily visualised for the sites HLBR (Heilbronn) and TAUB (Tauberbischofsheim) on days 186 and 190. The ellipsoidal heights of these two sites are similar (HLBR: 235.42 m, TAUB: 247.97 m), while the distance from TUEB to TAUB (resulting baseline TUTA, baseline length: 131.0 km) is nearly twice as long as the distance from TUEB to HLBR (resulting baseline TUHL, baseline length: 70.1 km).

Fig. 3 - Comparison of the standard deviations of the SSNP concerning baseline length and weather situation; left: DOY2004: 186, right: DOY2004: 190.



4.2 Dependence on multipath

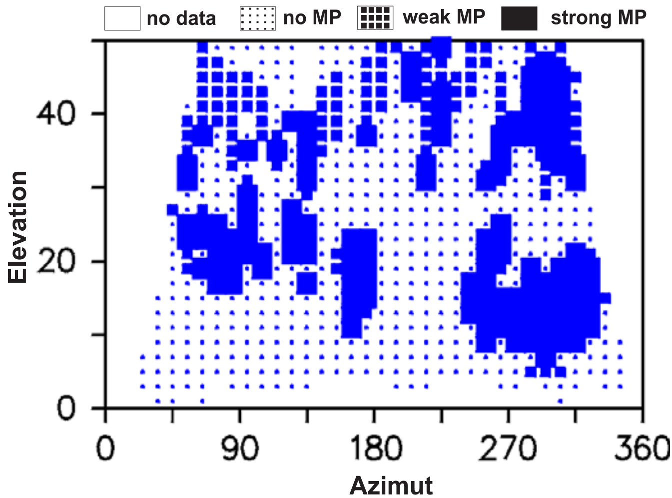
According to MAYER ET AL. (2004), the SA*POS*® sites are classified in three groups concerning multipath (MP) impact. Due to the fact that group mean values of the baseline lengths (BL) are insignificantly different, the influences of multipath on neutrospheric modelling can be analysed analogously using the corresponding group mean values of MSTD, see Tab. 5. Comparing the values in the last row of Tab. 5, the influences of multipath on the group mean values of MSTD vary from 4.7-3.4=1.3 cm (DOY2004: 190) to 3.8-2.3=1.5 cm (DOY2004: 186). The impact of weather variations on the sites with strong (weak) multipath amounts to 4.7-3.8=0.9 cm (3.4-2.3=1.1 cm). Therefore, in contrast to baseline length, the impact of multipath on the group mean values of MSTD is relatively insensitive to weather variations. Furthermore, the differences of the group mean values of MSTD between the classes "MP medium" and "MP weak" are only marginal.

Tab. 5 - Comparison of MSTD of SSNP concerning multipath impact and weather situation.

MP: strong, MSTD [cm]				MP: medium, MSTD [cm]				MP: weak, MSTD [cm]			
Site	BL [km]	186	190	Site	BL [km]	186	190	Site	BL [km]	186	190
STUT	30.0	7.1	8.2	GEIS	55.6	3.0	3.7	FSTA	47.7	2.9	4.5
OFFE	81.8	2.3	3.1	VISC	66.6	2.8	3.9	SIGM	49.9	3.7	4.5
HEID	100.8	2.1	2.9	KARL	72.5	2.5	3.5	HLBR	70.1	2.8	4.2
				IFFE	77.7	1.9	3.0	BIBE	71.8	1.9	2.9
				FREI	106.9	2.5	2.4	SCHA	81.5	1.8	2.9
								RAVE	90.1	1.9	2.9
								TAUB	131.0	1.3	2.1
Mean	**70.9**	**3.8**	**4.7**		**75.9**	**2.5**	**3.3**		**77.4**	**2.3**	**3.4**

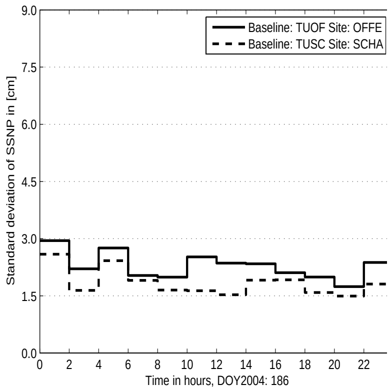
In comparison to other SA*POS*® sites STUT (Stuttgart) has the largest MSTD values which are caused by the shortest baseline length (30.0 km) and the strongest multipath which is exemplarily visualised in Fig. 4 using the corresponding multipath plot generated by WaSoft/Multipath.

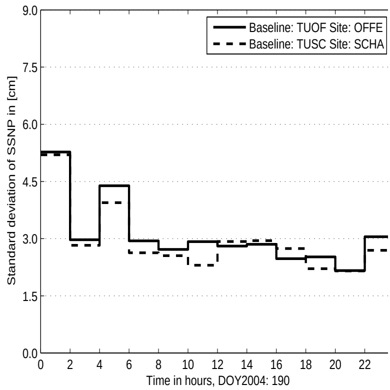
Fig. 4 - Multipath plot of STUT, DOY2004: 186; MAYER ET AL. (2004).



The sites OFFE (Offenburg) and SCHA (Schwäbisch Hall) are particularly suitable for an exemplary visualisation of the influences of multipath on neutrospheric modelling, because using GNSS data of these two sites the baselines related to TUEB have nearly identical length (TUOF: 81.8 km, TUSC: 81.5 km) but different multipath impact (OFFE: strong multipath, SCHA: weak multipath). Fig. 5 shows the corresponding standard deviations of the SSNP. In comparison to day 186, the average level of the standard deviations increases on day 190, while the distance between the solid and the dashed curve, which can be interpreted as the influences of multipath on neutrospheric modelling, slightly decreases.

Fig. 5 - Comparison of the standard deviations of the SSNP concerning multipath and weather situation; left: DOY2004: 186, right: DOY2004: 190.





4.3 Dependence on observation weighting

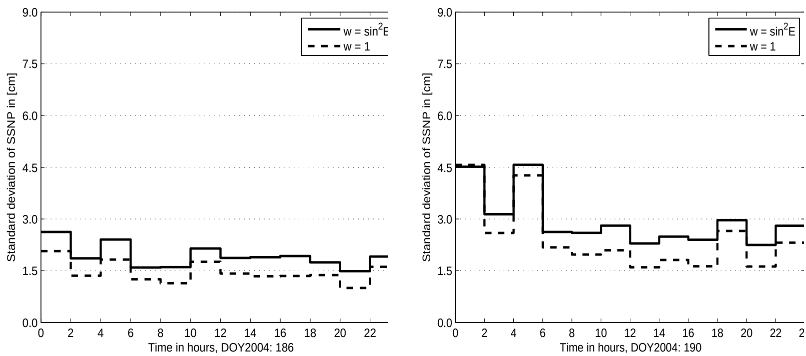
Due to satellite geometry and site-specific factors as well as atmospheric effects, the quality of GNSS observations is variable. It is well known that low-elevation data are much more disturbed by atmospheric effects than data at higher elevations, as well as being more subject to multipath. Within GNSS data processing using the BS5, the variability of observation quality can be taken into account by means of an elevation-dependent observation weighting model ($w = sin^2 E$). Tab. 6 represents the resulting MSTD of the SSNP compared with the corresponding values applying a uniform observation weighting model ($w = 1$) which indicates that the variability of observation quality is omitted within GNSS data processing and all observations are equally treated. The difference Δ of MSTD concerning observation weighting is computed by means of $\Delta = MSTD_{SSNP,\, sin^2 E} - MSTD_{SSNP,\, 1}$.

Tab. 6 - Comparison of MSTD of SSNP concerning observation weighting and weather situation.

Site	Baseline length [km]	MSTD [cm], 186			MSTD [cm], 190		
		$w = sin^2 E$	$w = 1$	Δ	$w = sin^2 E$	$w = 1$	Δ
STUT	30.3	7.1	5.1	2.0	8.2	6.2	2.0
FSTA	47.7	2.9	2.2	0.7	4.5	3.5	1.0
SIGM	49.9	3.7	2.7	1.0	4.5	3.2	1.3
GEIS	55.6	3.0	2.1	0.9	3.7	2.8	0.9
VISC	66.6	2.8	2.1	0.7	3.9	3.0	0.9
HLBR	70.1	2.8	2.0	0.8	4.2	2.9	1.3
BIBE	71.8	1.9	1.4	0.5	2.9	2.3	0.6
KARL	72.5	2.5	1.8	0.7	3.5	2.8	0.7
IFFE	77.7	1.9	1.5	0.4	3.0	2.4	0.6
SCHA	81.5	1.8	1.4	0.4	2.9	2.1	0.8
OFFE	81.8	2.3	1.6	0.7	3.1	2.2	0.9
RAVE	91.0	1.9	1.5	0.4	2.9	2.2	0.7
HEID	100.8	2.1	1.6	0.5	2.9	2.2	0.7
FREI	106.9	2.5	2.0	0.5	2.4	1.9	0.5
TAUB	131.0	1.3	1.0	0.3	2.1	1.5	0.6
Mean	**75.7**	**2.7**	**2.0**	**0.7**	**3.7**	**2.8**	**0.9**

The influences of observation weighting on the arithmetic mean values of MSTD in Tab. 6 vary from 0.7 cm to 0.9 cm. The impact of weather variations applying different observation weighting models ranges from 0.8 cm to 1.0 cm. Fig. 6 shows the effects of both analysed observation weighting models on the standard deviations of the SSNP for the representative site IFFE (Iffezheim).

Fig. 6 - Comparison of the standard deviations of the SSNP concerning observation weighting and weather situation; left: DOY2004: 186, right: DOY2004: 190.



Analysing the magnitudes of the MSTD presented in Tab. 6 and Fig. 6, at first glance the higher MSTD values resulting from applying the elevation-dependent weighting model seem to be confusing. But, this fact can be easily explained. In comparison to the elevation-dependent weighting, a stochastically uniform treatment of all observations by applying $w = 1$ indicates that low elevation data are upweighted and thus contribute more to stochastic modelling within GNSS data processing. It is well known that observations at low elevation play an important role in stabilising the parameter estimation and reducing the correlation between station height and SSNP. Therefore, the lower level of the standard deviations of the estimated SSNP using $w = 1$ is caused by upweighting of low elevation data. Since the observations at low elevation actually are not appropriately handled, this apparent improvement in the estimated SSNP is not realistic.

4.4 Dependence on ambiguity resolution strategy

In order to quantify the effects of different ambiguity resolution strategies on SSNP, two ambiguity resolution procedures (SIGMA and QIF strategy) provided by the BS5 are compared in this case study. The SIGMA strategy resolves the ambiguity parameters at first on the wide-lane linear combination (L5) and then on the ionosphere-free linear combination (L3), while the QIF strategy resolves the ambiguities on L1 and L2 directly. In order to resolve the L3 ambiguities by means of the SIGMA strategy, the L5 ambiguities obtained in the previous step are kept fixed. More detailed information about the ambiguity resolution strategies is given in DACH ET AL. (2007). In Tab. 7 the obtained MSTD of the SSNP using different ambiguity resolution strategies are compared. The difference Δ of MSTD is calculated by means of $\Delta = MSTD_{QIF} - MSTD_{SIGMA}$.

Tab. 7 - Comparison of MSTD of SSNP concerning ambiguity resolution and weather situation.

Site	Baseline length [km]	MSTD [cm], 186			MSTD [cm], 190		
		SIGMA	QIF	Δ	SIGMA	QIF	Δ
STUT	30.3	7.1	7.2	0.1	8.2	8.2	0.0
FSTA	47.7	2.9	3.0	0.1	4.5	4.6	0.1
SIGM	49.9	3.7	3.8	0.1	4.5	4.6	0.1
GEIS	55.6	3.0	3.0	0.0	3.7	3.8	0.1
VISC	66.6	2.8	2.9	0.1	3.9	3.9	0.0
HLBR	70.1	2.8	2.8	0.0	4.2	4.2	0.0
BIBE	71.8	1.9	1.9	0.0	2.9	3.0	0.1
KARL	72.5	2.5	2.5	0.0	3.5	3.7	0.2
IFFE	77.7	1.9	2.0	0.1	3.0	3.2	0.2
SCHA	81.5	1.8	1.9	0.1	2.9	2.9	0.0
OFFE	81.8	2.3	2.4	0.1	3.1	3.2	0.1

RAVE	91.0	1.9	1.9	0.0	2.9	3.0	0.1
HEID	100.8	2.1	2.1	0.0	2.9	3.0	0.1
FREI	106.9	2.5	2.6	0.1	2.4	2.4	0.0
TAUB	131.0	1.3	1.4	0.1	2.1	2.1	0.0
Mean	**75.7**	**2.7**	**2.8**	**0.1**	**3.6**	**3.7**	**0.1**

Due to different ambiguity resolution strategies the maximum difference in MSTD amounts to 0.1 cm on day 186 and 0.3 cm on day 190. In comparison to the above-analysed factors the influences of ambiguity resolution strategies on the group mean values of the MSTD are less than 0.5 cm and practically insignificant. In addition, for both strategies the impact of the weather situation remains at the same level of about 0.9 cm.

4.5 Dependence on neutrospheric prediction models

The essential difference between the neutrospheric prediction models analysed in this case study (Niell model with $MF_{Niell,\ w}$ and Saastamoinen model with *1/sin E*) is given by the applied mapping functions, because the Niell model also uses the Saastamionen model to calculate the neutrospheric zenith delay. Since for $E >$ 15°all mapping functions can be approximated by *1/sin E* at the first order, the impact of the neutrospheric prediction models on the estimated SSNP is only marginal. In Tab. 8 the resulting MSTD of the SSNP using different neutrospheric prediction models are presented. The absolute difference |Δ| of MSTD is calculated by means of $|\Delta| = |MSTD_{NIELL}\text{-}MSTD_{SAAS}|$.

Tab. 8 - Comparison of MSTD of SSNP concerning neutrospheric prediction modelling and weather situation.

Site	Baseline length [km]	MSTD [cm], 186			MSTD [cm], 190		
		NIELL	SAAS	|Δ|	NIELL	SAAS	|Δ|
STUT	30.3	7.1	6.9	0.2	8.2	8.5	0.3
FSTA	47.7	2.9	2.9	0.0	4.5	4.4	0.1
SIGM	49.9	3.7	3.7	0.0	4.5	4.4	0.1
GEIS	55.6	3.0	2.9	0.1	3.7	3.6	0.1
VISC	66.6	2.8	2.8	0.0	3.9	3.8	0.1
HLBR	70.1	2.8	2.7	0.1	4.2	4.1	0.1
BIBE	71.8	1.9	1.9	0.0	2.9	2.8	0.1
KARL	72.5	2.5	2.4	0.1	3.5	3.4	0.1
IFFE	77.7	1.9	1.9	0.0	3.0	2.9	0.1
SCHA	81.5	1.8	1.8	0.0	2.9	2.9	0.0
OFFE	81.8	2.3	2.2	0.1	3.1	3.0	0.1
RAVE	91.0	1.9	1.9	0.0	2.9	2.8	0.1
HEID	100.8	2.1	2.1	0.0	2.9	2.9	0.0
FREI	106.9	2.5	2.5	0.0	2.4	2.4	0.0
TAUB	131.0	1.3	1.3	0.0	2.1	2.0	0.1
Mean	**75.7**	**2.7**	**2.7**	**0.0**	**3.7**	**3.6**	**0.1**

By comparing the MSTD values in Tab. 8 and Tab. 7 it can be easily recognised that the influences of the neutrospheric prediction models on the arithmetic mean values of the MSTD have the same magnitude as the ambiguity resolution strategy, as well as the impact of weather situation. However, in comparison to ambiguity resolution the MSTD values at the site STUT are more sensitive to the applied neutrospheric prediction models.

4.6 Comparison of the influences of all analysed factors

Based on the group mean values of the MSTD of the estimated SSNP the magnitudes of the above-analysed factors impacting neutrospheric modelling are compared and presented in Tab. 9. In order to take the influence of the weather situation into account, the processing results for both days 186 and 190 are considered and the span is given by intervals.

Tab. 9 - Comparison of the magnitudes of the analysed factors impacting neutrospheric modelling.

Number	1	2	3	4	5
Factor	Baseline length	Multipath	Observation weighting	Ambiguity resolution	Neutrospheric Prediction modelling
Influences on MSTD of SSNP [cm]	1.9-2.5	1.3-1.5	0.7-0.9	< 0.5	< 0.5

Under the condition that the SSNP are estimated using the processing strategies described in Tab. 2 and Tab. 3, the influences of the factors No. 1-3 on the MSTD of the estimated SSNP are significant and vary within a few centimetres. Compared to other considered factors, the impact of baseline length plays the dominant role and is more sensitive to weather situation. Concerning processing strategies, in comparison to ambiguity resolution and neutrospheric prediction modelling observation weighting seems to be the most significant factor. Therefore, an appropriate observation weighting model plays an important role within GNSS data processing. It should be noted that the values given in Tab.9 are only valid within this case study and they might vary due to different data quality, processing strategies and atmospheric behaviour. Moreover, considering other parameters instead of SSNP, the order of the analysed factors given in Tab. 9 may change as well. For example, the applied observation weighting model has the most significant impact on the standard deviation of double difference residuals (LUO ET AL. 2007). In this case study, the average influence of weather variations on the standard deviation of the SSNP amounts to nearly 1 cm.

5. IMPROVING SSNP QUALITY BY MEANS OF SNR-BASED WEIGHTING

Based on the result that among the analysed factors of GNSS data processing strategies (No. 3-5 in Tab. 9) observation weighting plays the most important role in SSNP quality, an improved observation weighting model based on signal-to-noise power ratio (SNR) measurements has been developed at the Geodetic Institute of the University of Karlsruhe (TH). In comparison to the standard elevation-dependent weighting model ($w = sin^2 E$), which is only suitable for undisturbed GNSS signals when a strong correlation between signal quality and satellite elevation angle exits, an improved weighting model should be directly related to signal quality measurements (e.g. based on SNR), and frequency-related weighting of each observation should be possible. Applying the advanced SNR-based weighting model within data processing, the standard deviation of the estimated SSNP can be improved by nearly 25% compared to standard elevation-dependent weighting model. After a brief description of the realisation of the SNR-based weighting model its impact on SSNP quality is illustrated using the dataset introduced in Section. 3.

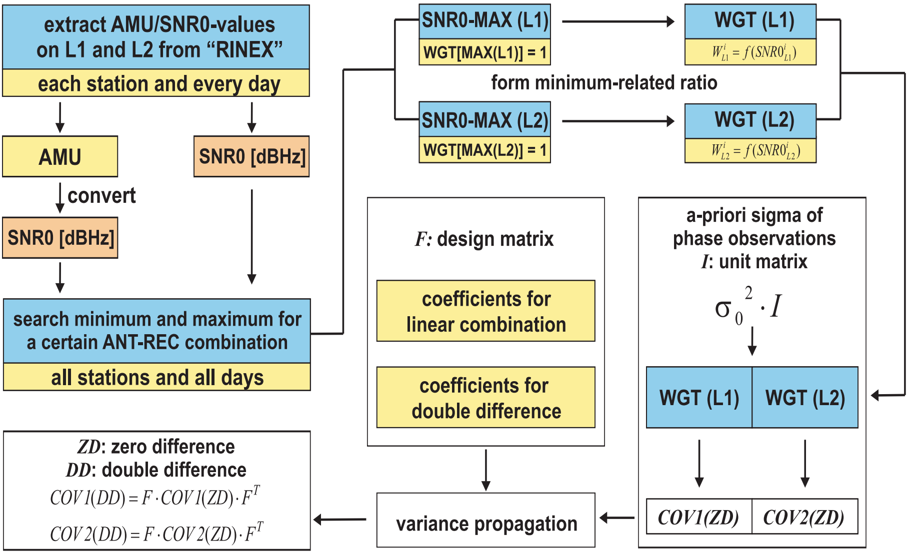
5.1 Realisation of the SNR-based weighting model

In addition to pseudo-range and carrier-phase observations, geodetic GNSS receivers also record signal-to-noise power ratio (SNR) data. Since many signals have a very wide dynamic range, SNR-values are usually expressed in terms of the logarithmic decibel scale and are normalised to signal-to-noise power density ratio (SNR0) with 1 Hz bandwidth. In practice, sometimes the so-called Arbitrary Manufacturer Units (AMU) are used to quantify the signal quality (e.g. Trimble 4000SSI receivers). Using manufacturer-specific formulas, AMU can be converted into SNR0 in [dBHz] (TRIMBLE 1999).

Depending on the measured SNR0 values, the variance of the original phase observations can be computed directly by means of a functional model described in LANGLEY (1997). Applying this functional relation, HARTINGER AND BRUNNER (1999) developed the SIGMA-ε model to handle the relation between atmospheric phase delay effects and satellite geometry. In contrast to the SIGMA-ε model, the SNR-based weighting model presented here is independent from Langley's formula and based on the measured SNR-values directly. The SNR-based weighting model is realised in two steps which are schematically shown in Fig. 7.

In the first step, AMU resp. SNR0 values are extracted from RINEX files which are previously obtained from the binary raw observation data by means of the program TEQC (ESTEY AND MEERTENS 1999). The extracted AMU values are then converted into SNR0 using model- and manufacturer-dependent formulas. In the second step, for all antenna-receiver (ANT-REC) combinations within the network the minimum and the maximum of the obtained SNR0 values are searched on both frequencies and over the entire project. This procedure, carried out in post processing modus, guarantees that the found extreme values are representative for the complete GNSS project (network, observation period).

Fig. 7 - Realisation of the SNR-based weighting model and its contribution to advanced stochastic modelling.

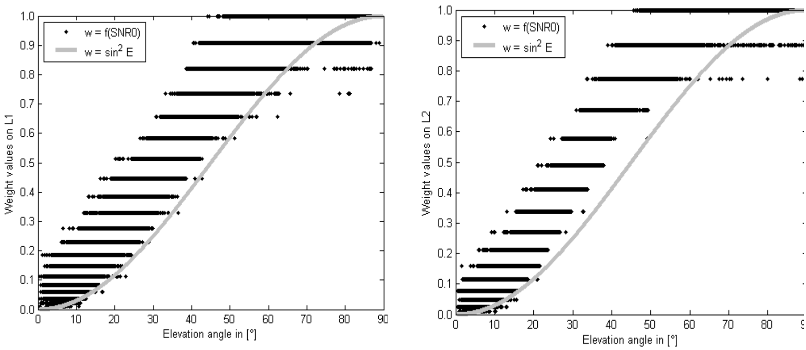


After that, for each L1 and L2 observation an individual weight value (WGT) is calculated by forming the minimum-related ratio between the actual and the corresponding maximum SNR0. Taking SNR0 values of L1 frequency as example, the empirically derived formula,

$$f\left(\mathrm{SNR0}^{i}_{L1}\right) = \left(\frac{\mathrm{SNR0}^{i}_{L1} - \mathrm{SNR0}^{min}_{L1}}{\mathrm{SNR0}^{max}_{L1} - \mathrm{SNR0}^{min}_{L1}}\right)^2 \quad (1)$$

can be applied to calculate L1 weight values for a certain antenna-receiver combination. After forming linear combinations, these frequency-related weight values are used to obtain the diagonal elements of the variance-covariance matrices (COV) of double difference observations by means of variance propagation. The SNR-based weighting model has been experimentally implemented in the BS5 within a case study. The data pre-processing, for example, search for minimum and maximum SNR0 values, is performed in MATLAB. In Fig. 8, for the site HLBR (Heilbronn), the calculated weight values of L1 and L2 observations are visualised.

Fig. 8 - Comparison of the weight values of L1 and L2 observations (SNR-based vs. elevation-dependent), HLBR (Leica SR 520, LEIAT503), DOY2004: 186; left: weight values on L1, right: weight values on L2.

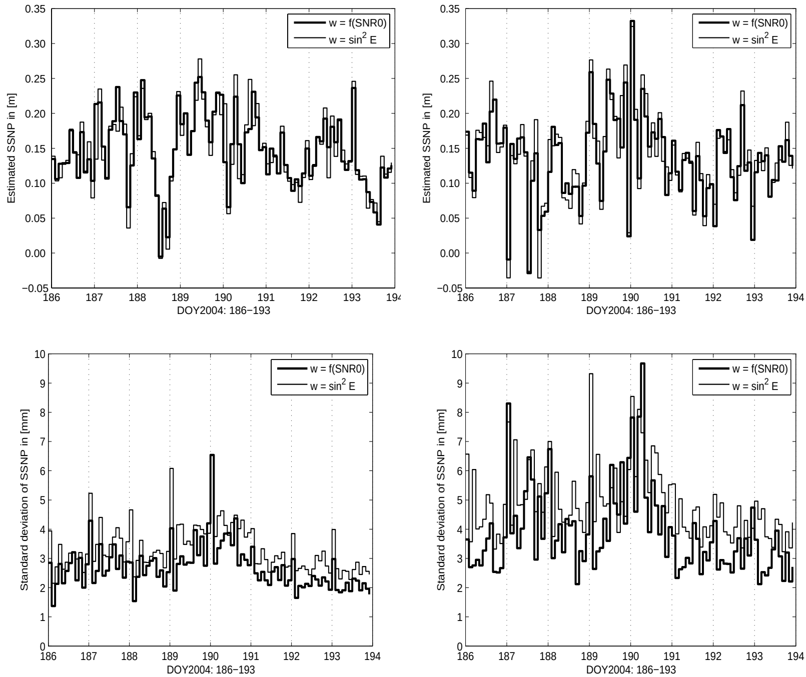


Since the Leica receiver on HLBR delivers integer SNR, the corresponding weight values derived using the SNR-based weighting model represent a stair structure. Additionally, in contrast to the elevation-dependent weighting model, the SNR-based weight values show a much larger bandwidth which has to be taken into account within GNSS data processing. Due to separate registration of signal quality measures on L1 and L2, the SNR-based weighting model is capable to take the frequency-related difference of signal quality into account, although this difference is not significant in the presented example in Fig. 8. Furthermore, in both graphs of Fig. 8, not only low but also medium elevation observations (30°-50°) are downweighted by the standard elevation-dependent weighting model, so that their contribution to parameter estimation is limited. As mentioned before, an appropriate handling of low elevation data plays an important role in estimation of SSNP. Therefore, a realistic observation weighting model which is able to handle observations at low elevations in a stochastically more appropriate way should enable a better quality of the estimated SSNP.

5.2 Effects of the SNR-based weighting model on SSNP

Based on the assumption that the SNR-based weighting model is more suitable for handling low elevation data the elevation cut-off angle was set to 3° within the GNSS data processing. In order to achieve high redundancy, a sampling rate of 15 s was specified instead of 180 s applied in the standard processing strategy (see Tab. 2). For validating the effects of the advanced SNR-based weighting model on the estimated SSNP, the baseline SISC formed by the sites SIGM (Sigmaringen) (fixed) and SCHA (Schwäbisch Hall) as well as the baseline OFHE formed by the sites OFFE (Offenburg) (fixed) and HEID (Heidelberg) are shown as examples. These two baselines have a similar baseline length (SISC: 119.4 km, OFHE: 114.8 km) and orientation (north-south direction) but different multipath impact. According to MAYER ET AL. (2004), in contrast to SIGM and SCHA, OFFE and HEID are strongly affected by multipath effects; see Fig. 2. In Fig. 9, the estimated SSNP and the corresponding standard deviations using different observation weighting models are compared.

Fig. 9 - Effects of the SNR-based weighting model on the estimated SSNP, Leica SR520, LEIAT503, DOY2004: 186-193; upper: SSNP, lower: standard deviations of the SSNP, left: SCHA, right: HEID.



Due to the decreased sampling rate (from 180 s to 15 s) resp. increased redundancy, the mean level of the standard deviation decreases significantly from several centimetres to several millimetres. The average difference of the estimated SSNP is about 1.5 cm, corresponding to approx. 10% of the mean SSNP value.

Considering the corresponding standard deviations in the same way, an improvement by nearly 20% (25%) for SCHA (HEID) can be achieved if the advanced SNR-based weighing model is applied to the data processing. The more significantly the processed baseline is affected by multipath effects, the more considerable are the improvements in SSNP quality. Additionally, the difference of the weather situation between day 186 and 190 can be easily recognised in both graphs of Fig. 9 by comparing the magnitudes of the corresponding standard deviations.

6. CONCLUSION AND OUTLOOK

In this paper, the influences of the factors impacting neutrospheric modelling within GNSS data processing such as baseline length, multipath, observation weighting, ambiguity resolution and neutrospheric prediction modelling were analysed and quantified based on the standard deviations of the estimated SSNP. The results in this case study indicate that baseline length, multipath effects and observation weighting model play a dominant role, their influences on the standard deviation of the SSNP ranging from about 1 cm to about 3 cm. Compared to the other two dominant factors, the impact of baseline length is more sensitive to weather variation. Therefore, these three factors should be taken into particular consideration within GNSS data processing. In contrast to these dominant factors, the influences of the ambiguity resolution approach and neutrospheric prediction modelling on the standard deviation of the SSNP are marginal, less than 0.5 cm.

Additionally, an improved observation weighting model based on signal-to-noise power ratio (SNR) measurements was briefly described. This approach is independent from the functional model given in LANGLEY (1997) and is based on normalised SNR-weighting related to the specific antenna-receiver combination. In contrast to the standard elevation-dependent weighting model provided by the BS5 this advanced weighting model is directly related to signal quality measures and enables a frequency-related weighting of each observation. Using a minimum elevation cut-off angle of 3°, an improvement of nearly 25% in the standard deviation of the estimated SSNP can be achieved by means of the SNR-based weighting model.

Future work will concentrate on the contribution of meteorological data to neutrospheric modelling and will focus on the validation of the SNR-based weighting model using different data sets considering data quality, observation period and GNSS equipment.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support by DAAD (German Academic Exchange Service) in the framework of the project *PROBRAL: Precise positioning and height determination by means of GPS: Modelling of errors and* *transformation into physical heights*. Additionally, we would like to thank the department 31 of the state survey office of Baden-Württemberg for providing GNSS data and absolute antenna calibration values.

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(Recebido em fevereiro de 2007)