Analysis of Galileo NeQuick Ionospheric Model Based on the Station Position Error

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Abstract

The ionosphere, as a dispersion medium for electromagnetic waves in the L-band, affects the calculated GNSS position. One of the ways to remove the influence of the ionosphere on position computation is computation based on dual-frequency observation. In the case of single-frequency measurements the ionospheric error compensation method is the correction calculated from the ionospheric model. For navigation measurements, the model transmitted by GNSS satellites is adopted. Galileo satellites broadcast a NeQuick model adapted to navigational messages and called NeQuick-G. The Galileo performance analysis carried on in the Galileo Reference Centre - Member States (GRC-MS) project consist of analyses of various Key Performance Indicators. Two of them concern the error of horizontal and vertical position and were carried out for a single frequency (E1) and a combination of frequencies (E1E5a and E1E5b).

Analyses were performed for selected permanent GNSS stations attending the project and observing the Galileo signal. The stations are located at different latitudes and longitudes around the world.

The NeQuick-G model, for navigation purposes is broadcasted as parameters divided into 5 areas parallel to the geomagnetic equator. The results of the analyses presented in the article show the spatial heterogeneous of accuracy of the NeQuick-G model.

Keywords [1]

Galileo, Key Performance Indicators, NeQuick-G, ionospheric models

1. Introduction

The problem of precise positioning and ionosphere error mitigation is well known and described in many papers such as [1]–[3]. It is estimated that about 75% of all GPS (Global Positioning System) receivers in market are those single frequency [4]. When using a dual-frequency receiver for positioning, the precise position is calculated using the frequencies combination which removes the ionospheric time-delay. For a single-frequency receiver it is necessary to use the ionospheric model. Calculation in post-processing mode gives the possibility to use different and sometimes very complicated models, however, real-time position calculation requires the model that is simple and directly received by the device. For such transmission is used the navigation message in Global Navigation Satellite Systems (GNSS). The Galileo system, just like GPS, has an ionosphere model transmitted as a number of parameters broadcasted by satellites, which are used for ionospheric correction calculation [5], [6]. In the GPS system the Klobuchar model, described in [7] was applied. The Klobuchar model is defined as a single layer model. It is accepted that this model corrects the ionospheric time-delay RMS (Root Mean Square) in 50% or better. In the European GNSS system Galileo – the NeQuick model was applied, its algorithm is described in [8].

NeQuick is developed by the Aeronomy and Radiopropagation Laboratory (T/ICT4D Laboratory) of the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, Italy, and by the

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Institute for Geophysics, Astrophysics and Meteorology of the University of Graz, Austria. Based on the ionosonde parameters foE, foF1, foF2 and M(3000)F2, peaks of the ionosphere layers E, F1 and F2 are determined, they are the anchor points of the model. The output is the electron concentration anywhere in the ionosphere, and from this the Total Electron Content (TEC) along ground-to-satellite ray-path by means of numerical integration is also determined. The resulting values depend on solar activity (based on the monthly average number of sunspots R12 or 10.7 cm solar radio flux F10.7), as well as on the month and time of the day [9].

Space Research Centre of the Polish Academy of Sciences (SRC PAS) team is involved in the Galileo Reference Centre – Member States (GRC-MS) project granted by European GNSS Agency (GSA). One of the objectives of the work Package they are working in is the Key Performance Indicators analysis.

One of them was the analysis of horizontal and vertical position error. The results obtained in the research allow to present the NeQuick-G behaviour in various region of the Earth.

2. Data

For station position error analysis stations located around the world on various latitudes and longitudes were selected. The location of stations selected to analysis is presented in Figure 1, and their details – in Table 1.

The stations were selected so that they were located in 5 different areas for which the parameters of the NeQuick-G model are transmitted in the broadcast orbit. This allows the better analysis of the influence of the ionosphere model on the determined error of station coordinates. The stations equipped in various receivers were used for analysis. Regarding the Table 1 there are Trimble NetR9, Trimble Alloy, Septentrio POLARX5/TR and LEICA GR30. Data was collected at intervals of 30 seconds.

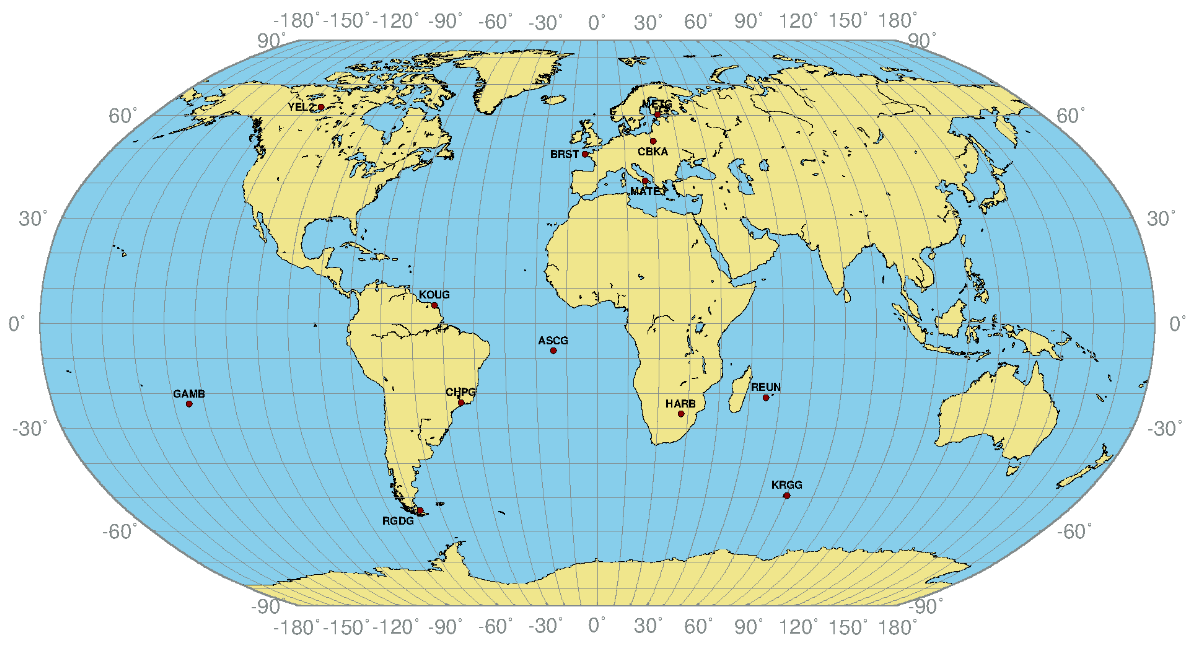

Figure 1: Location of stations selected for analysis

Table 1
Details of the selected stations

No	Station ID	MODIP region	Receiver type	Latitude (deg)	Longitude (deg)	Height (m)
1	ASCG	3	TRIMBLE NETR9	-7. 91628	-14. 33266	37.953
2	BRST	2	TRIMBLE ALLOY	48. 38050	-4.49660	65.500
3	CBKA	2	TRIMBLE NETR9	52.21473	21.06770	125.738
4	CHPG	4	TRIMBLE ALLOY	-22.68227	-45.00238	566.250
5	GAMB	3	TRIMBLE NETR9	-23.13035	-134.96482	80.660
6	HARB	3	SEPT POLARX5TR	-25.88696	27.70725	1558.078
7	KOUG	3	SEPT POLARX5TR	5. 09847	-52.63975	107.248
8	KRGG	4	TRIMBLE ALLOY	-49.35154	70.25551	72.967
9	MATE	2	LEICA GR30	40.64913	16.70446	535.600
10	METG	2	SEPT POLARX5	60.24197	24.38417	59.672
11	REUN	3	SEPT POLARX5	-21.20833	55.57167	1558.400
12	RGDG	4	TRIMBLE ALLOY	-53.78584	-67.75153	32.364
13	YEL2	1	SEPT POLARX5TR	62.48132	-114.48085	181.008

3. POSITION ERROR COMPUTATION

For the KPI10 defined as horizontal and vertical position accuracy calculated for each selected station the GALAT software was used. The GALAT was designed in SRC PAS for the purpose of Galileo signal analysis. The input data included the observation files in RINEX v.3 format, consolidated broadcast orbit files made by CNES and antenna phase centre variation files (IGS14.ATX) from IGS. The NeQuick-G model was implemented in the software based on the algorithm published in [5].

The computation of position accuracy was carried out as a Single Point Positioning (SPP) for E1b frequency and E1E5a, E1E5b combinations, according to the project requirements. The sampling interval for observations was set to 30 seconds and the elevation cut-off was 5°. The observations were weighted regarding the elevation using $\cos z$ function. The influence of troposphere was mitigated by a priori Saastamoinen model [10], [11] with applied Global Mapping Function (GMF) [12]. During the computation process the receiver coordinates and clock corrections were estimated in the epoch-wise mode. The estimation is prepared for observation meeting condition PDOP (Position Dilution of Precision) lower than 6.

4. RESULTS ANALYSIS

Analysing the Horizontal and Vertical Position Error (respectively: HPE and VPE) defined as a value corresponding to 95% of the observations, some regularities can be find. The considered stations were grouped according to the modified dip latitude (MODIP), which combines the geomagnetic dip I and the geographic latitude φ [13]:

$$MODIP = \arctan \frac{I}{\sqrt{\cos \varphi}}$$

MODIP is expressed in degrees, a table grid of MODIP values versus geographical location is provided together with the NeQuick-G model. In the area of the globe, five regions are defined on the basis of their MODIP (relating to the geomagnetic field, Table 2); they differ in the characteristics and intensity of ionospheric processes. [5].

Table 2
MODIP region ranges depending on geomagnetic latitude

region	range
1	60° < MODIP ≤ 90°
2	30° < MODIP ≤ 60°
3	-30° ≤ MODIP ≤ 30°
4	-60° ≤ MODIP < -30°
5	-90° ≤ MODIP < -60°

Selected stations are located in MODIP regions no. 1, 2, 3 and 4. Inside each of the MODIP regions results show certain similarity of behaviour. In this paper results for MODIP 2 and 3 are presented. In addition, a comparative analysis of the NeQuick-G model is performed in the context of the Total Electron Content (TEC) values.

4.1. HPE and VPE variability analysis in different MODIPs

For MODIP 2 HPE values are on the level of 1.5 m and VPE less than 3 m. The HPE and VPE values decrease as the number of satellites increase. For most stations HPE and VPE is lower for single-frequency computation with model. This suggests a very good fitting the NeQuick-G model to real conditions in the area of Europe. The following Figures 2-5 show the time series of HPE and VPE, covering the period from 4th quarter 2018 to 3rd quarter 2020, for the single-frequency (E1) results and the dual-frequency combination (E1E5b). The provided time series present results for the following days, these are values that cover 95% of all parameters observed over the day (at 30 s rate). The peaks visible in the graphs for both single- and dual-frequency results are caused by errors related to the system, the SIS (Signal in Space) status flag advising not to use the results has not been introduced in the broadcast orbit. When it comes to a bias in the first part of the considered period (systematically worse results until 11 February 2019), the decrease in positioning errors is due to the increase in the number of satellites available (four Galileo satellites began work in the operational mode). Table 3 below shows the mean HPE and VPE values for individual stations. The results presented therein indicate that the NeQuick-G model is very well suited in the case of the Europe area, and the greater mean values in the case of a dual-frequency combination result from greater observational noise.

Table 3
Mean HPE and VPE calculated for stations located in MODIP 2 for whole analysed period and for period from 2019-02-11 (22 operating Galileo satellites)

	4th quarter 2018 - 3rd quarter 2020				from February 11th 2019			
	mean HPE 95%		mean VPE 95%		mean HPE 95%		mean VPE 95%	
Station	E1b	E1E5b	E1b	E1E5b	E1b	E1E5b	E1b	E1E5b
BRST	1,351	1,524	2,097	2,477	1,272	1,450	2,037	2,369
CBKA	1,464	1,950	1,945	2,727	1,376	1,828	1,882	2,551
MATE	1,524	0,887	2,794	1,787	1,470	0,810	2,816	1,664
METG	1,320	1,513	1,933	2,107	1,255	1,369	1,820	1,922

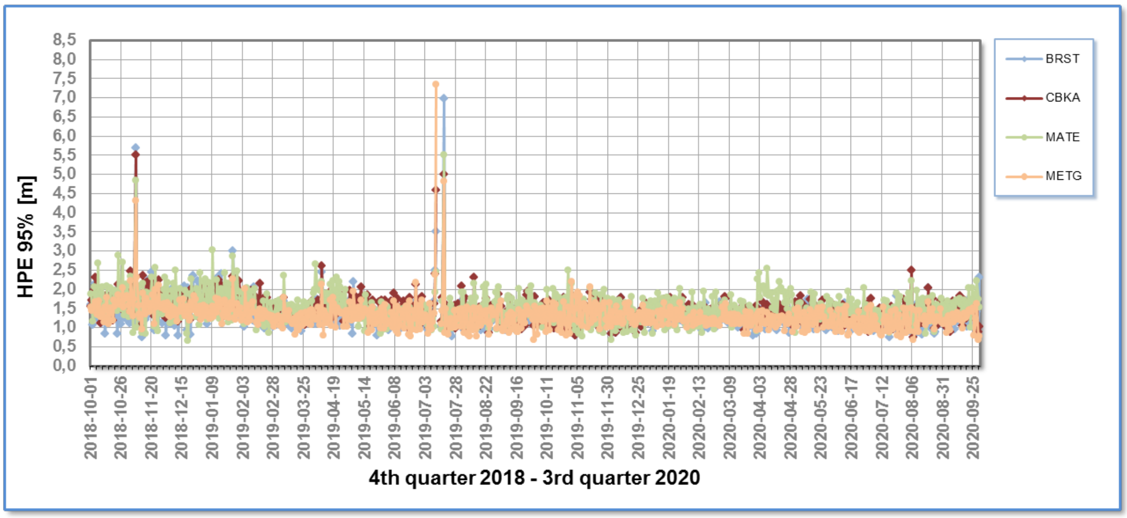

Figure 2: Horizontal Position Error – single-frequency: E1 (INAV) for stations located in MODIP 2

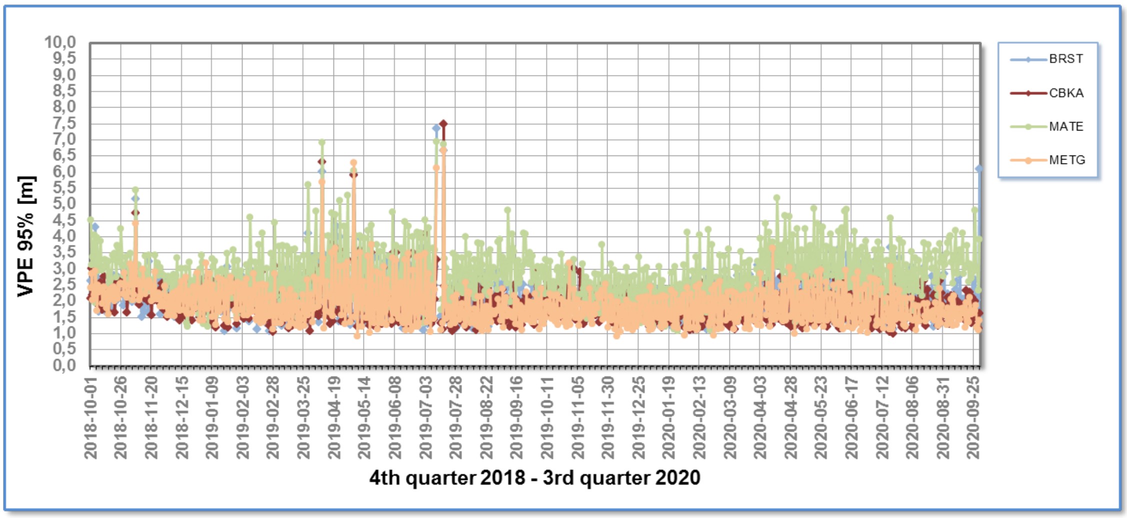

Figure 3: Vertical Position Error – single-frequency: E1 (INAV) for stations located in MODIP 2

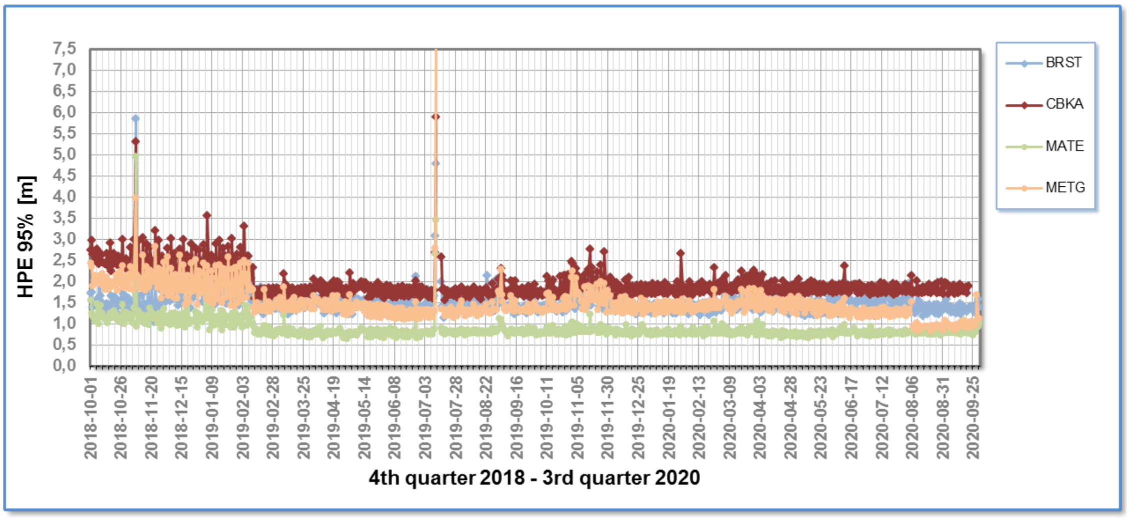

Figure 4: Horizontal Position Error – dual-frequency: E1E5b (INAV) for stations located in MODIP 2

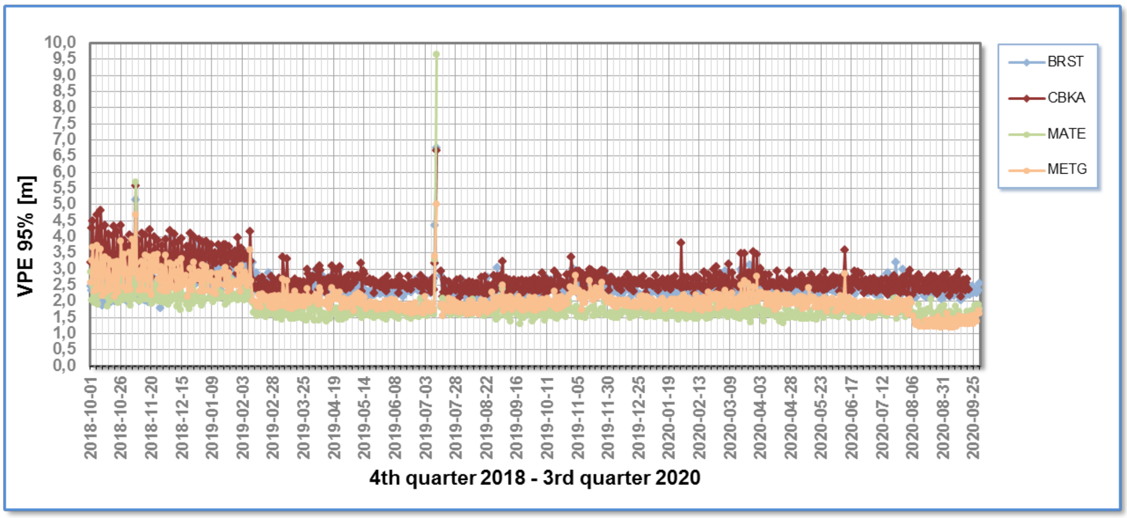

Figure 5: Vertical Position Error – dual-frequency: E1E5b (INAV) for stations located in MODIP 2

For MODIP 3 HPE and VPE values for single-frequency computations are greater than for MODIP 2 area. They are also greater than for dual-frequency results. The HPE and VPE values are decreasing when the number of satellites is increasing. Similarly to the MODIP 2 results presented above, the Figures 6-9 below illustrate the time series of HPE and VPE for the same time range and the same frequencies, while the mean values of these parameters are shown in Table 4.

The station KOUG is the special case. We observe the higher values for HPE than for VPE. Because they are strongly better for dual-frequency results this suggest that in vicinity of station KOUG the NeQuick-G model is not well fitted to real local ionospheric conditions. It is also seen in seasonal variability of HPE values.

Table 4

Mean HPE and VPE calculated for stations located in MODIP 3 for whole analysed period and for period from 2019-02-11 (22 operating Galileo satellites)

	4th quarter 2018 - 3rd quarter 2020				from February 11th 2019			
	mean HPE 95%		mean VPE 95%		mean HPE 95%		mean VPE 95%	
Station	E1b	E1E5b	E1b	E1E5b	E1b	E1E5b	E1b	E1E5b
ASCG	1,816	1,394	3,603	2,969	1,809	1,325	3,473	2,737
GAMB	2,261	1,452	3,551	2,848	2,030	1,355	3,194	2,691
HARB	1,481	0,962	2,614	1,855	1,412	0,894	2,507	1,764
KOUG	3,239	1,032	2,950	2,150	3,315	0,966	2,816	2,023
REUN	1,501	1,604	2,874	3,249	1,444	1,441	2,812	2,977

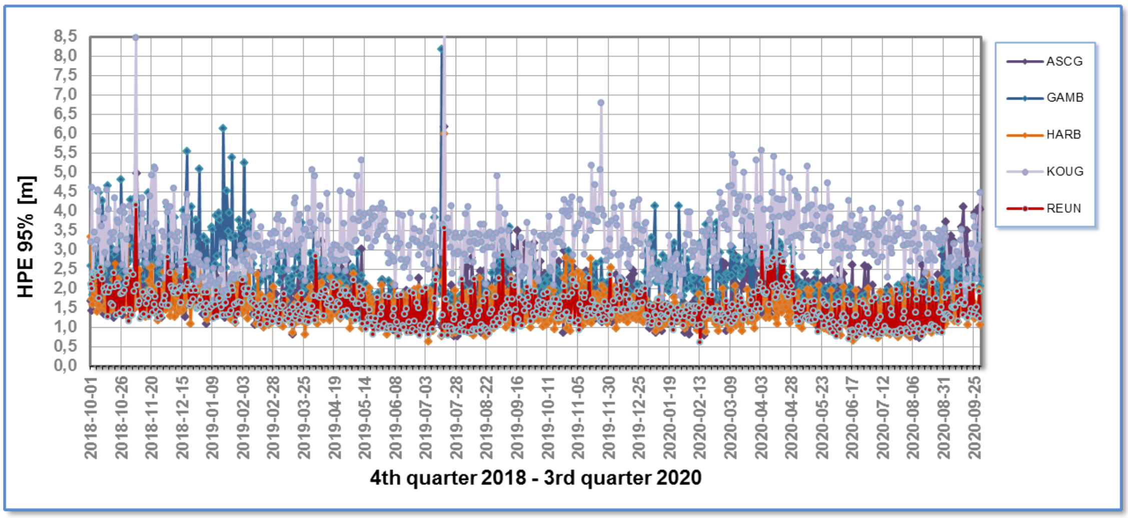

Figure 6: Horizontal Position Error – single-frequency: E1 (INAV) for stations located in MODIP 3

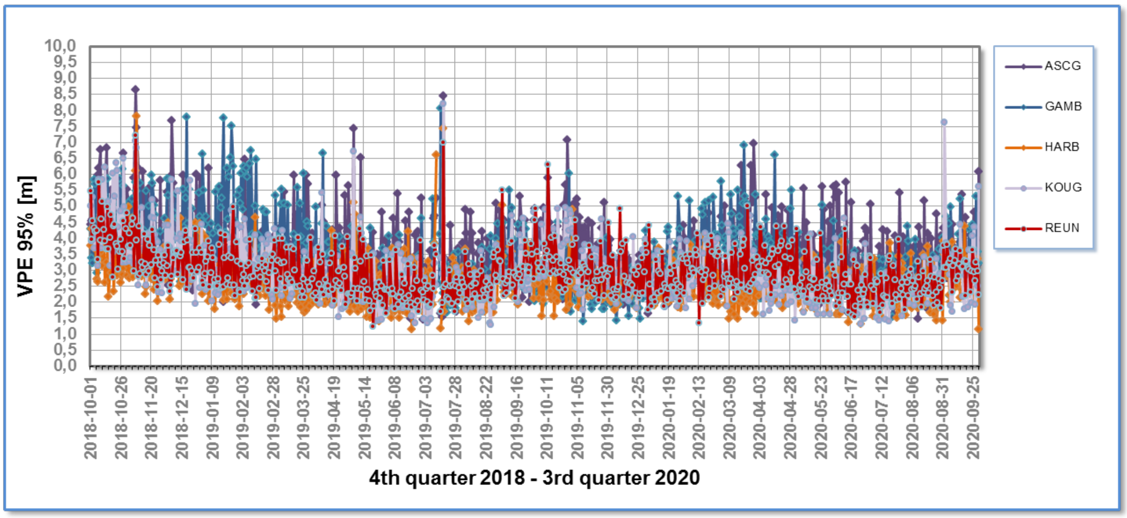

Figure 7: Vertical Position Error – single-frequency: E1 (INAV) for stations located in MODIP 3

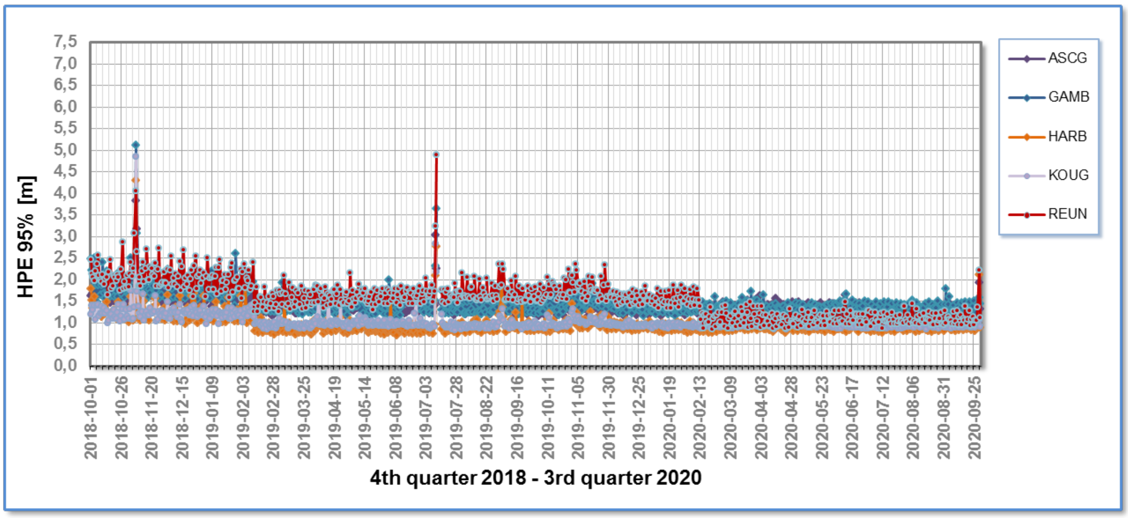

Figure 8: Horizontal Position Error – dual-frequency: E1E5b (INAV) for stations located in MODIP 3

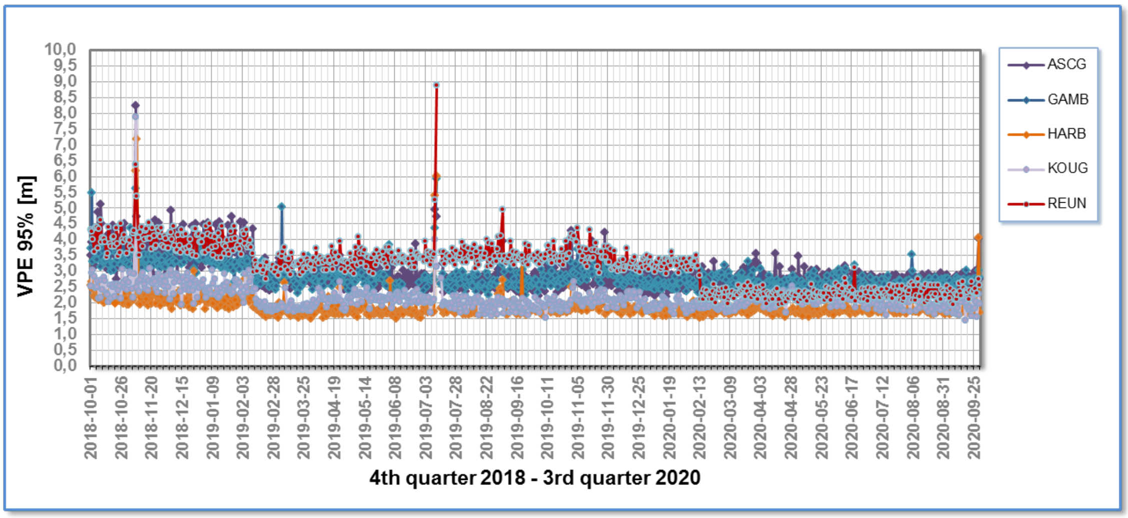

Figure 9: Vertical Position Error – dual-frequency: E1E5b (INAV) for stations located in MODIP 3

4.2. Comparison of the NeQuick-G model in various conditions and locations

One of the considered aspects is the evaluation of the NeQuick-G model results against the model provided by International GNSS Service (IGS) in the IONEX files, the solution by Astronomical Institute of the University of Bern (AIUB) was used. TEC values for the following locations were compared: near the equator (KOUG – Kourou, French Guiana) and in the central Europe (CBKA – Warsaw, Poland).

In the first stage, statistical parameters for the following hours of the day were considered, independently for each month. Based on the results for 2019, it was decided to perform the analysis for the month of July, when the ionosphere was relatively quiet and the differences in TEC values were low. Similarly, as an example of a month with higher ionosphere activity and high variability of the TEC parameter throughout the day (and in the level of discrepancy between models, as well), the month of October was chosen. The following Figures 10 and 11 show the average values of the TEC coefficient during the day, in July and October 2019, respectively, for both considered stations, as well as for both models and the differences between them.

Comparing the differences in the values of NeQuick-G and AIUB solutions, it can be noticed that for stations in Europe they reach the ceiling of 20 TECU only during the period of disturbed ionosphere, while near the equator they differ by only a slightly smaller value even during the quiet season. Meanwhile, in the more active October, for station in Kourou the amplitude of differences between the models, in particular around 13-14 LT (Local Time), are close to 30 TECU on some days. It is also worth paying attention to the following tendency, especially noticeable for the presented October 2019: while the TEC parameter value for the Warsaw station in the case of the NeQuick-G model is consistently higher than the AIUB result, for the Kourou station it is the other way round – the result of the NeQuick-G model turns out to be underestimated compared to the AIUB model. Moreover, taking into account the local time, it can be noticed that for KOUG station the difference in mean values is positive during the daytime (TEC values for AIUB model are higher than for NeQuick-G model), however, after sunset there is a sharp decrease in this parameter and the difference takes a negative sign.

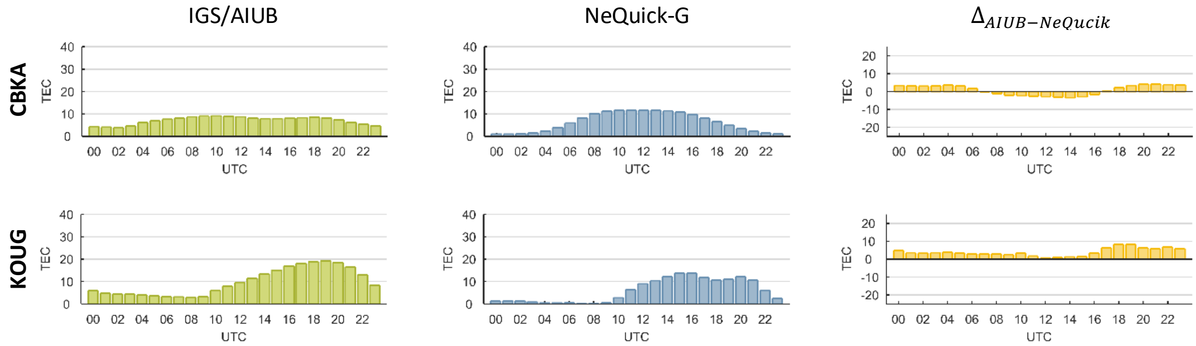

Figure 10: Mean TEC parameter for consecutive hours during the day – July 2019

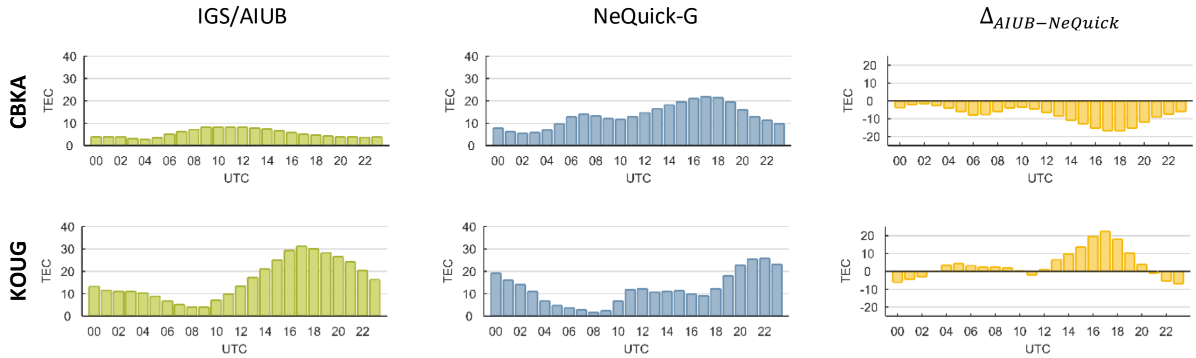

Figure 11: Mean TEC parameter for consecutive hours during the day – October 2019

The results obtained in the discussed stage of the research allowed to indicate the time of day when the ionosphere is characterized by the lowest and the highest activity (approximately). A common hour for the whole year was consistently used, the presented examples of results refer to the same concerned months - July and October 2019. As the hour with the lowest TEC values 4 LT was assumed (2 UTC and 7 UTC for stations CBKA and KOUG, respectively), while as the period of the highest TEC values – 14 LT was chosen (12 UTC and 17 UTC for stations CBKA and KOUG, respectively).

For both selected hours, the course of the TEC differences between NeQuick-G and AIUB models was visualized. The charts below present this parameter for the combination of both months and both models, wherein Figure 12 shows the results for 4 LT and Figure 13 - for 14 LT. The difference between the results for day- and night-time is clear, especially in the case of KOUG station. At night, the TEC differences do not exceed a few TECU for both months concerned. Otherwise it is during the daytime: in July the differences are greater and amount to 12 TECU, and in October they are at the level of 15 to almost 30 TECU. Moving on to CBKA station, the diversity is slightly smaller. A greater dynamics of the time series for the daytime period is also noticeable.

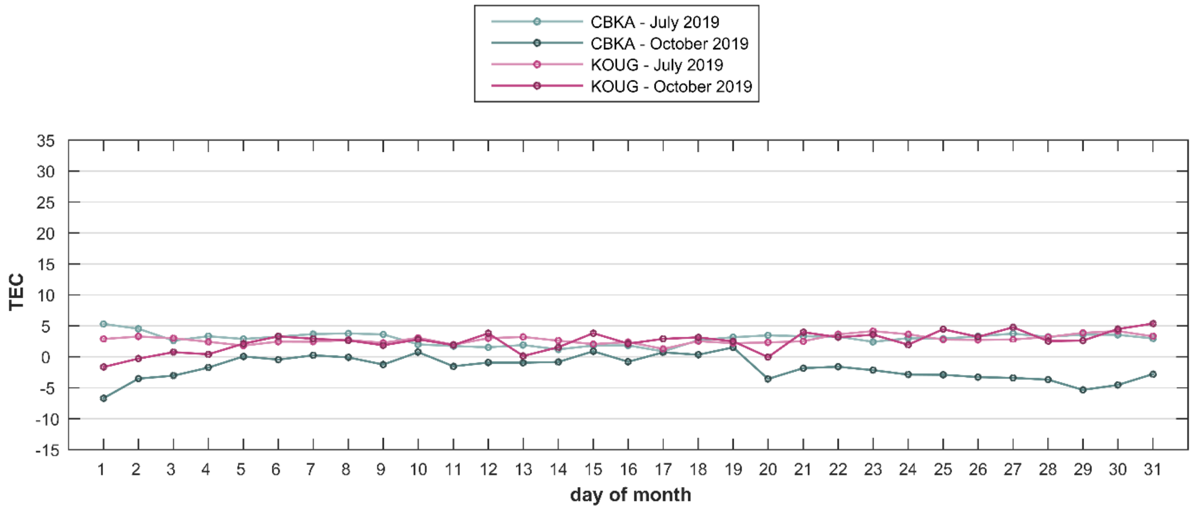

Figure 12: TEC parameter differences for the time with the lowest TEC values during the day (CBKA – 2 UTC, KOUG – 7 UTC)

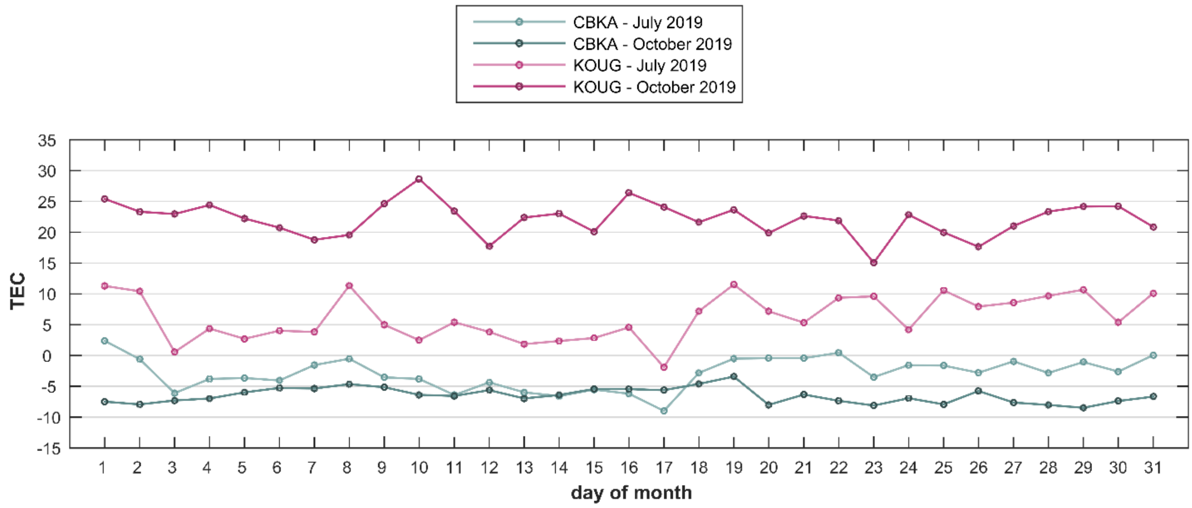

Figure 13: TEC parameter differences for the time with the highest TEC values during the day (CBKA – 12 UTC, KOUG – 17 UTC)

4.3. HPE and VPE variability considering various computation approach

For 2019 HPE and VPE were calculated for example station from MODIP 2 and MODIP 3. As the example of station located in MODIP 2 CBKA station was selected, while for MODIP 3 – KOUG station. Various calculation methods were considered: dual-frequency combination (E1E5a and E1E5b), single-frequency E1b with various ionospheric models (NeQuick-G, Klobuchar and IGS obtained in IONEX format). Results are presented below (Figures 14-17).

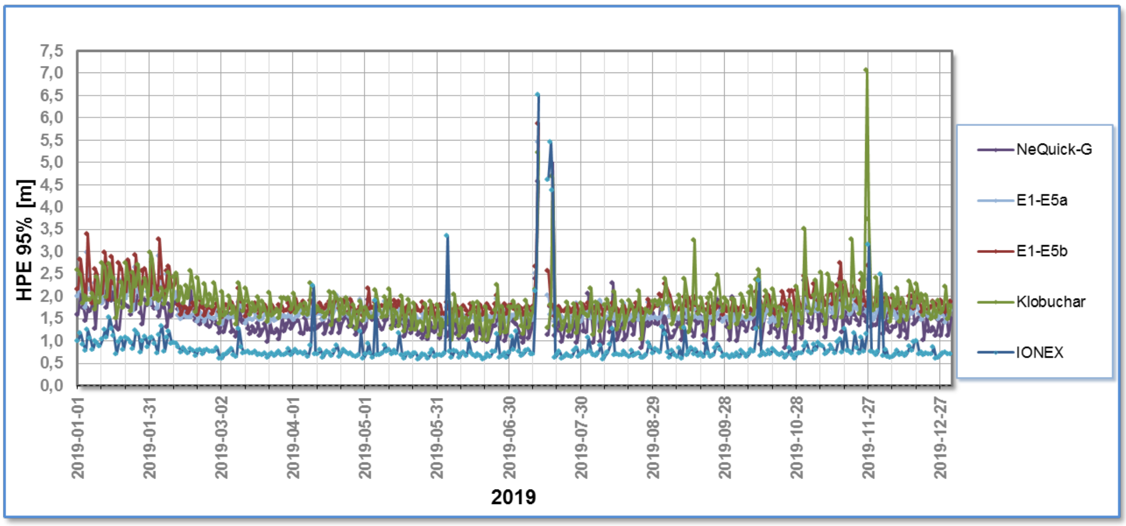

Figure 14: Horizontal Position Error using various calculation approaches, station: CBKA (MODIP 2)

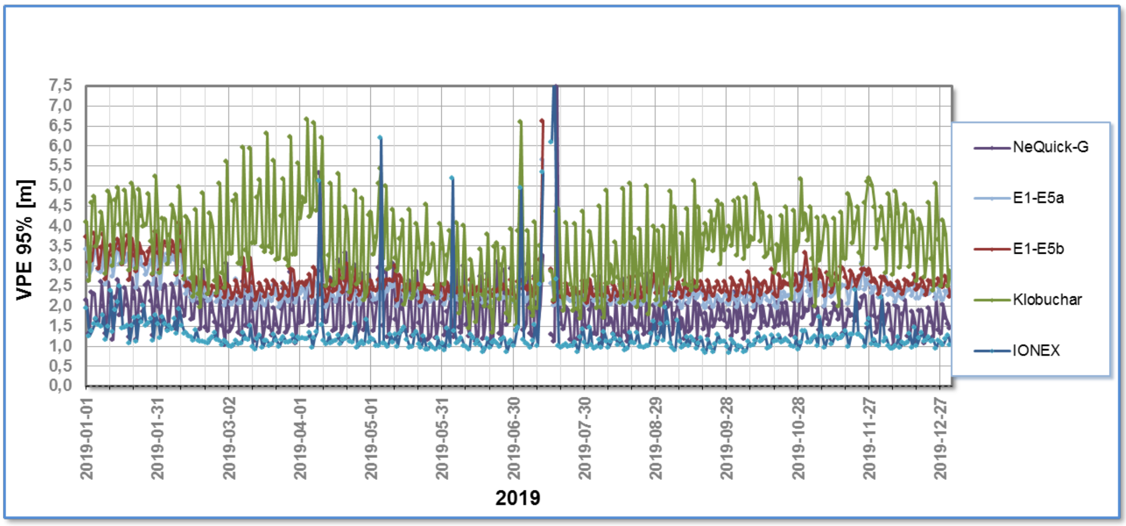

Figure 15: Vertical Position Error using various calculation approaches, station: CBKA (MODIP 2)

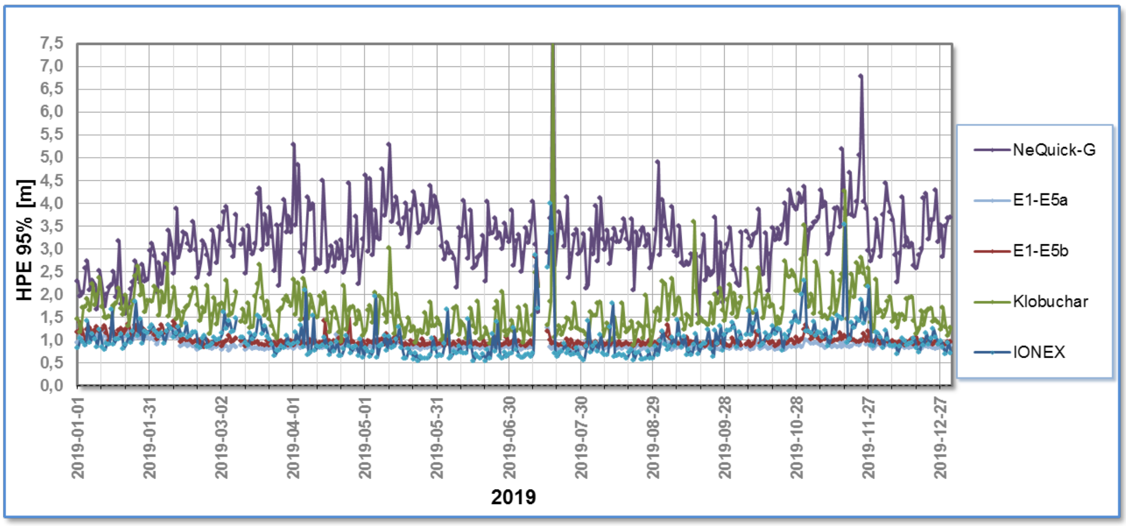

Figure 16: Horizontal Position Error using various calculation approaches, station: KOUG (MODIP 3)

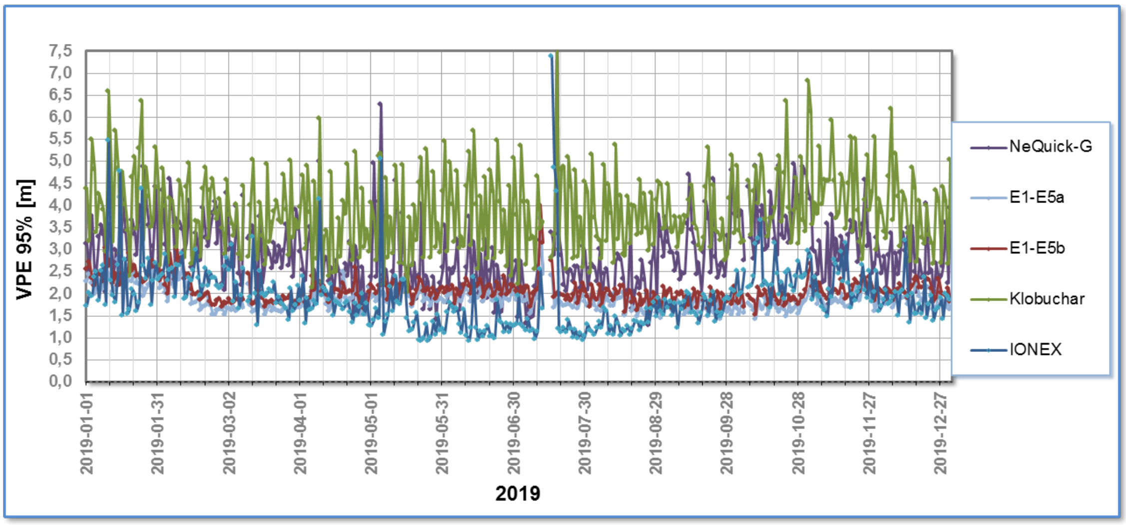

Figure 17: Vertical Position Error using various calculation approaches, station: KOUG (MODIP 3)

For CBKA station it can be noticed, that:

- best results are obtained for computations on single frequency with IGS model both for HPE and VPE,
- for VPE, the highest error relates to single-frequency calculated using the Klobuchar model.

In the case of KOUG station:

- similarly to results from CBKA station, best results are obtained for computations on single frequency with IGS model both for HPE and VPE; however the dual-frequency results are very similar and only slightly worse,
- for HPE the results for single-frequency computation with NeQuick-G model are significantly worse than for other methods.

5. Conclusions

The analysis of the first results show that NeQuick-G model performance is heterogeneous. There are areas where the model is very well adapted to the real ionospheric conditions (MODIP 2 in the Europe), but it is also seen that in the equatorial region the areas of reduced accuracy of reflecting real conditions could be found. This is especially important in the vicinity of the KOUG station (northern part of South America) where the NeQuick-G model causes increased errors in determining the horizontal position.

It is planned to extend the current investigation to different MODIP and areas in the world.

6. Acknowledgements

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