

Article

Adjusting CCIR Maps to Improve Local Behaviour of Ionospheric Models

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Citation: Haralambous, H.; Leontiou, T.; Petrou, V.; Kumar Singh, A.; Charalambides, M.; Lithoxopoulos, N.; Agisilaou, A. Adjusting CCIR Maps to Improve Local Behaviour of Ionospheric Models. *Atmosphere* **2021**, *12*, 691. <https://doi.org/10.3390/atmos12060691>

Academic Editors: Ljiljana R. Cander and Bruno Zolesi

Received: 29 April 2021

Accepted: 26 May 2021

Published: 28 May 2021

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Abstract: The objective of this article is to present a concept for single-frequency Global Navigation Satellite System (GNSS) positioning local ionospheric mitigation over a certain area. This concept is based on input parameters driving the NeQuick-G algorithm (the ionospheric single-frequency GNSS correction algorithm adopted by Galileo GNSS system), estimated on a local as opposed to a global scale, from ionospheric characteristics measured by a digital ionosonde and a collocated dual-frequency Total Electron Content (TEC) monitor. This approach facilitates the local adjustment of Committee Consultative for Ionospheric Radiowave propagation (CCIR) files and the Az ionization level, which control the ionospheric electron density profile in NeQuick-G, therefore enabling better estimation of positioning errors under quiet geomagnetic conditions. This novel concept for local ionospheric positioning error mitigation may be adopted at any location where ionospheric characteristics foF2 and M(3000)F2 can be measured, as a means to enhance the accuracy of single-frequency positioning applications based on the NeQuick-G algorithm.

Keywords: ionosphere; GNSS; total electron content; Galileo; NeQuick model

1. Introduction

The performance of a GNSS system which provides three-dimensional position with global coverage is defined by the level of accuracy of the calculated position. There are different types of error that influence the positioning/navigation accuracy, such as satellite and receiver dependent (orbital, clock, antenna errors) and those induced by the propagation medium (ionospheric and tropospheric errors). Since the ionosphere constitutes the major error source in GNSS (and in extreme cases can degrade the positioning significantly, with errors exceeding 100 m), ionospheric modeling and prediction is crucial [1].

For post-processing applications, vertical TEC (VTEC) Global Ionospheric Maps (GIM) can be interpolated to calculate and subsequently remove the ionospheric delay. In the frames of real-time correction, the ionospheric effect may also be partially removed using certain complex techniques, such as dual-frequency receivers or suitable augmentation systems (Differential Global Positioning System -DGPS, Satellite Based Augmentation System -SBAS), although predicted GIM maps have also been used in the past for real-time correction [2–4].

Commercial single frequency stand-alone receivers are the cheapest and most widespread GNSS devices. They have the capability to estimate and partially correct

the error due to the ionosphere, through algorithms, which use parameters broadcasted in the navigation message [5,6]. These algorithms provide ionospheric delay estimation, from Slant Total Electron Content (STEC), defined as the electron concentration along the path between the receiver and the satellite, measured in Total Electron Content Units ($1 \text{ TECU} = 10^{16} \text{ el m}^{-2}$). STEC variability depends on many variables, including long- and short-term changes in solar ionizing flux, magnetic activity, season, time of day, user location, and observation azimuth. For the Global Positioning System (GPS), the Single Frequency Ionospheric Correction Algorithm is based on the Klobuchar model, which is a single-layer ionospheric model (treating the ionosphere as a condensed electron content layer located at 350 km) that employs eight broadcast coefficients from the navigation message to compute STEC based on a simple cosine function [5].

NeQuick is a semi-empirical climatological model that describes spatial and temporal variations of the ionospheric electron density at any location by using the peaks of the three main ionospheric regions (E, F1, and F2) as anchor points. STEC can be computed by integrating along the electron density path in each direction. The NeQuick model was adopted as the basis of the real-time ionospheric correction model algorithm (NeQuick-G) used for Galileo single-frequency positioning ionospheric correction [6]. Despite certain developments, that have been applied in the NeQuick formulation during its evolution [7], several recent studies have demonstrated that there is still room for further improvement [8,9].

A key input NeQuick-G parameter is the effective ionization parameter (Az), which represents the solar activity information ingested into the model. It is defined as a second order polynomial coefficients, broadcasted in the Galileo broadcast message to single-frequency users [6]. This is the main underlying extension over the original NeQuick specification which was formulated on the basis of R12, or the 10.7 cm solar radio flux, (F10.7). The coefficients of the polynomial are typically estimated daily from at least 20 permanent Galileo monitoring stations during the previous 24 h as a function of modified dip latitude (modip) to take the daily variation of the solar activity and the user's local geomagnetic conditions into account at the receiver location (Equation (1)). Comparative studies of the two empirical models demonstrate that slant ionospheric delay computed using NeQuick-G was considerably more accurate than slant delays computed from Klobuchar; therefore, it can achieve lower positioning error [10–15]. However, this superiority is achieved with the expense of a higher computational load, which is critical, for mass market devices [16]. In addition the NeQuick-G specification incorporates five Ionospheric Disturbance Flags which indicate the state of the ionosphere to alert users that the quality of ionospheric correction may not meet the performance specification in five different geographical regions specified in terms of their modip range [17].

$$Az = A_0 + A_1(\text{modip}) + A_2(\text{modip})^2. \quad (1)$$

The main principle behind the single-frequency GNSS positioning local ionospheric mitigation concept, described in this paper, is a more accurate representation of the state of the ionosphere on a local scale. This is primarily achieved through the long-term and short-term, adjusted CCIR files based on ionospheric characteristics recorded in Cyprus. The operational application of this concept facilitates the automatic collection and processing of ionospheric characteristics, that define the ionospheric electron density profile, therefore providing a direct indication of the extent of the positioning error which is attributed the ionosphere and which directly affect the trans-ionospheric propagation of GNSS satellite signals. This approach for ionospheric positioning error mitigation may be fully or partially adopted in other parts of the globe as a means to enhance the accuracy of single-frequency positioning devices in real-time operation or in post-processing techniques, such as Precise Point Positioning (PPP). It is important to note that, due to the specific geographical placement and coverage of Ranging & Integrity Monitoring Stations (RIMS) over the eastern Mediterranean region, Cyprus does not receive the level of accuracy, integrity, continuity, and availability that is provided, over most of the European region, by the

open-service of the corresponding European augmentation system EGNOS (European Geostationary Navigation Overlay Service) [4].

2. Methodology

Since the most significant contribution to STEC comes from the F layer, the key parameters to describe the electron density profile specification of NeQuick-G are foF2 and M(3000)F2, the critical frequency at the F2 layer and the propagation factor, respectively. These are calculated from CCIR maps that are based on the monthly median values of foF2 and M(3000)F2 from all available ionosondes (about 150 stations) during the years 1954 to 1958, corresponding to an approximate 10,000 station-months of data [18]. A numerical mapping technique developed by Jones and Gallet was used to capture the diurnal and geographic variations of foF2 and M(3000)F2 in the se CCIR maps [19]. They first used Fourier analysis in the universal time system for monthly median diurnal variation (one-hour time intervals) obtained by observations of each available ionosonde. The analysis of the data from each ionosonde station was carried out on a monthly basis. The least squares method was then used to estimate the Fourier coefficients of each month over each station. Then, in order to provide a worldwide description for each coefficient, the orthonormal and spherical forms of the Legendre functions were applied for the expansion of the geographical variation of each coefficient [20].

The CCIR maps for the foF2 parameter consist of 988 coefficients, and, for M(3000)F2, they consist of 441 coefficients for each month. CCIR provides two sets of coefficients for foF2 and M(3000)F2 characteristics, one for low and one for high solar activity ($R_{12} = 0$ to 100). The coefficients for intermediate levels of solar activity are determined by linear interpolation [6]. The complete CCIR maps of foF2 and M(3000)F2 for 12 months in a year consist of $(988 + 441) \times 2 \times 12 = 34,296$ coefficients.

These maps have been recently evaluated over Cyprus with a 2009–2013 dataset of (high-quality) manually scaled data encompassing periods of low (2009–2010) and high (2011–2013) solar activity periods. The results revealed systematic differences, with respect to CCIR maps, with daytime foF2 around equinoxes and solstices by as much as 1.00 MHz and nighttime foF2 as much as 1.17 MHz [21]. These differences are significant and correspond to high discrepancies of estimated NeQuick-G STEC to observed STEC over Cyprus. Similar conclusions came out of a comparative study over Cyprus with VTEC during periods of low (2008), and high (2001) solar activity for different seasons with corresponding predictions with the latest version of the NeQuick ingested with daily measured solar radio flux, (F10.7). According to that study, NeQuick underestimates VTEC during high solar activity, whereas it is particularly underestimated during summer and fall. The maximum difference between median VTEC and NeQuick VTEC was observed around midday, and the minimum was recorded around sunrise, as expected. It was also evident that NeQuick overestimated VTEC during low solar activity for all seasons. This overestimation was particularly noticeable during summer (June) [22]. Another recent study on the topside ionosphere over Cyprus indicated that NeQuick provides a superior representation than the a-Chapman function embedded in the Cyprus Digisonde Automatic Real-Time Ionogram Scaler with True height (ARTIST) software [9,23].

The mitigation approach described in this paper was designed to operate on two levels. The long-term level was premised on the adjustment of the existing global version of the CCIR maps to reflect long-term ionospheric conditions over Cyprus by exploiting a dataset of ionospheric characteristics recorded by a digital Digisonde (DPS-4D) during low and high solar activity periods. To augment this long-term approach with a short-term extension, TEC data provided by a GNSS reference station and ionospheric characteristics (foF2 and M(3000)F2), measured by a Digisonde, was also incorporated. These two approaches were tested, towards improved representation of the local ionosphere with respect to its median (long-term), as well as in its day-to-day variability, in order to examine the potential for significant improvement on the level of mitigation of the ionospheric positioning error, both in a climatological but also in a weather-like mode.

3. Results and Discussion

Our idea for improving the long-term and short-term ionospheric representation over Cyprus is simple but applicable as the current specification of the NeQuick-G algorithm is not violated in any way by the replacement of the existing global CCIR files with local based files of the same structure. Although assessment studies to evaluate its performance on space applications have been attempted and suggestions to improve its computational efficiency have been proposed, in its current operational form, there has not been any attempt to address the algorithm improvement on a regional basis [24,25]. Based on our approach, the system modifies the coefficients and not the structure of the CCIR files, which is fully preserved. Efforts to improve the performance without violating the structure of CCIR files has been examined by past studies [26]. This concept is feasible as we are aiming towards an exclusively local improvement (over the area of Cyprus). Most of the coefficients of the CCIR files are set to zero apart from those limited ones that are manipulated to produce the CCIR files based on Cyprus Digisonde values. We have to underline that, when NeQuick-G is ran on a mobile device GNSS chip, it practically calculates the ionospheric error which is used in the positioning solution in real-time. The meaning of short-term, in conjunction with the simple concept we propose, refers to the calculation of CCIR files based on auto-scaled values from the previous day. Standard NeQuick-G algorithm (in the frames of Galileo) also operates in a short-term mode in a way, but only to calculate Az (ionization level) and not to update CCIR files (the standard global version of CCIR files is permanently embedded in the device).

3.1. Long-Term Improvement Based on Long-Term CCIR Files over Cyprus

To generate the long-term CCIR files over Cyprus (Cyprus CCIR), we used 2009 and 2014 high-quality foF2 and M(3000)F2 values, taking into account that these two years were representative low and high solar activity periods, respectively. This was possible through the manual scaling of ionograms from the Cyprus Digisonde at 15-min resolution. This resulted in a database of monthly median ionospheric characteristics which is representative of the long-term behavior of the local ionosphere. These files were developed to provide the first level of improvement as they can be used instead of the existing global (Standard CCIR) files. One CCIR file was generated for each month of the year with coefficients for low (2009) and high solar activity (2014) periods, by fitting appropriate polynomials in accordance to the CCIR formulation. According to this formulation, linear interpolation is applied to determine coefficients at an intermediate solar activity level. In Figures 1 and 2, the profiles of the monthly median measurements of foF2 (full and empty blue triangles) and M(3000)F2 (full and empty green triangles), as well as the corresponding predictions (red curve) calculated by using local Cyprus CCIR files. The Fourier terms used for these predictions are exactly the same as those used in the NeQuick-G algorithm (13 for foF2 and 9 for M(3000)F2). Figures 1 and 2 clearly demonstrate that the Fourier fitting with the same number of terms as in the standard NeQuick-G algorithm can represent adequately the median variation of foF2 and M(3000)F2 over Nicosia. The intention of the authors was to develop a simple concept based on the existing formulation of the NeQuick model and most importantly the NeQuick-G algorithm. According to this formulation, the CCIR coefficient files for both foF2 and M(3000)F2 are embedded in the specification for low and high solar activity levels. Any intermediate solar activity level set of coefficients has to be calculated as a linear interpolation between low and high solar activity level coefficients. According to the operation period of the Cyprus Digisonde, the most representative years to represent these critical solar activity levels were 2009 and 2014. Any attempt to involve more years in the calculation (although could provide a better model) would violate the specification of the CCIR files, which was beyond the scope of the long-term improvement proposed.

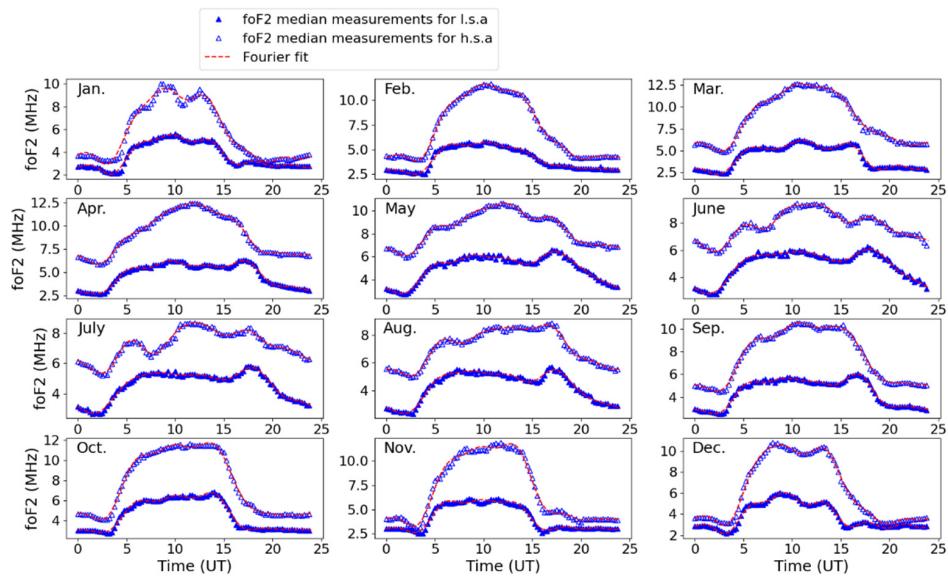


Figure 1. Long-term monthly median foF2 plots for low (2009) and high (2014) solar activity periods with corresponding local (Cyprus CCIR) polynomials (red line).

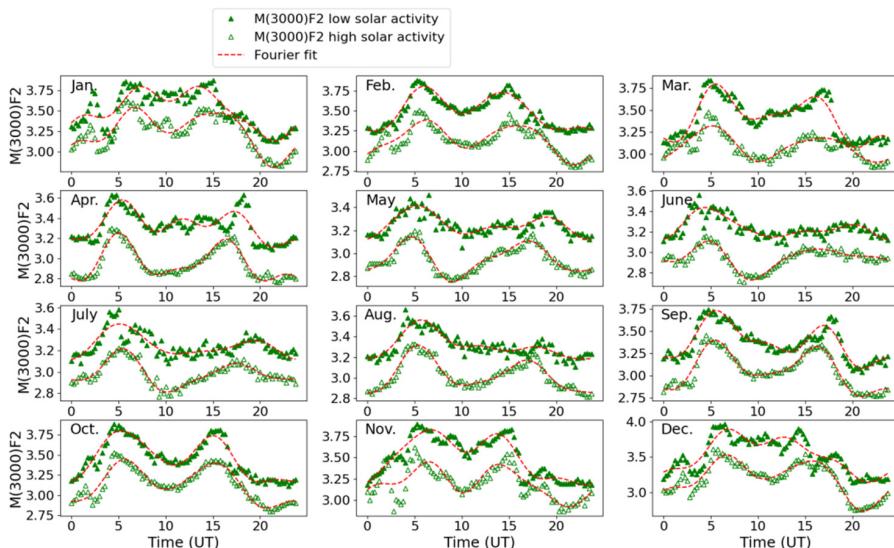


Figure 2. Same as Figure 1, but for M(3000)F2.

To examine if this approach could potentially provide improvement over the Standard CCIR files, we calculated the percentage difference between VTEC extracted from Eceiver Independent EXchange format (RINEX) data from NICO International Geosynthetics Society (IGS) station and VTEC by running NeQuick-G, using Az parameters broadcasted by Galileo, for each particular day for a full year in 2018. We then plotted the results for the relative difference (with respect to estimated VTEC) values achieved with Standard CCIR files and these (long-term) Cyprus CCIR files from the polynomials given in Figures 1 and 2. The results are depicted in Figure 3 and demonstrate the potential of using the Cyprus CCIR files which exhibit less relative difference compared to the Standard CCIR files. According to Figure 3, the improvement seems to be more evident during daytime where the discrepancy between NeQuick-G and measured VTEC over Cyprus seems to be higher. Figure 3 represents results that were produced during the first phase of a funded project where the median long-term CCIR files were estimated. Data from 2018 was intentionally selected as we had a full year dataset of RINEX files (without any gaps) to estimate VTEC

that we could exploit to demonstrate the applicability of the concept for a year outside the interval 2009–2014.

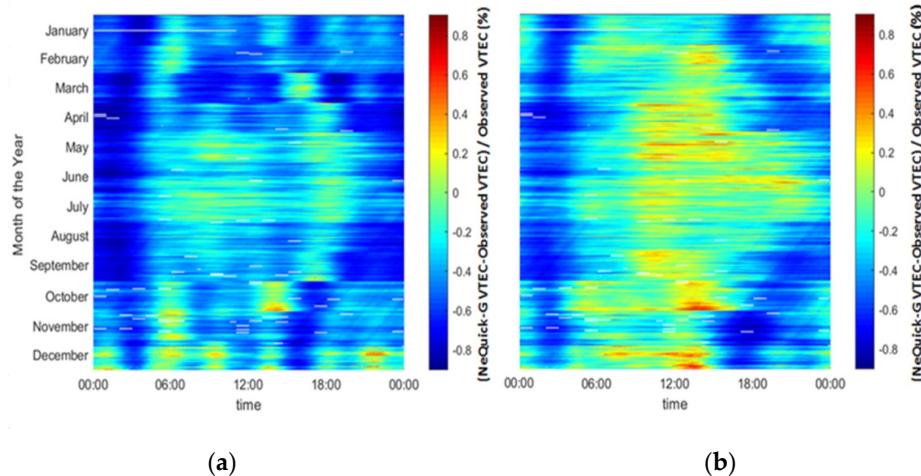


Figure 3. Comparison of relative difference (NeQuick-G VTEC-Observed TEC) / Observed TEC (%) between measured VTEC data over Cyprus and corresponding estimations using NeQuick-G with (a) Cyprus (long-term) CCIR files and (b) Standard CCIR files.

3.2. Short-Term Service Level Based on Short-Term CCIR Files Over Cyprus

In the frames of the short-term service, we used a dual-frequency GNSS reference station collocated with the Cyprus Digisonde. This was exploited in order to extract STEC values and optimize the calculation of Az ionization level which minimizes the discrepancy calculated by the NeQuick-G model in order to be used for the next day (in the same way Galileo NeQuick-G is used) to drive the model on a local level. To generate the short-term CCIR files over Cyprus, we used automatically scaled foF2 and M(3000)F2 values. For this task, we needed to address the fact that some ionograms are impossible to scale by ARTIST. This is a common situation over Cyprus during summer months as the occurrence of strong sporadic E (Es) increases significantly. As a result, a lot of ionograms become impossible to scale because of the fact that the F region cannot be illuminated by Digisonde signals that are completely blocked by strong (blanketing) Es layers. This can last for extended periods of time, as shown by a series of ionograms over Nicosia in 30 June 2014 in Figure 4.

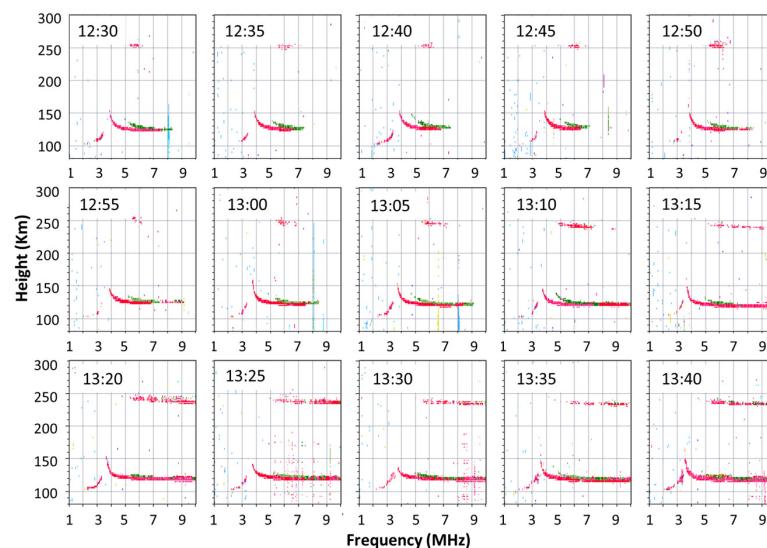


Figure 4. Series of consecutive ionograms with strong (blanketing) Es over Nicosia station.

In order to overcome the effect of possible gaps of auto-scaled ionospheric characteristics in the context of real-time application of the mitigation approach, we adopted a χ^2 minimization approach to estimate the coefficients for the short-term Cyprus CCIR files, as opposed to the Discrete Fourier transform approach [27]. The problem of having continuous absent autoscaled values of ionospheric characteristics in the construction of CCIR files is reflected in Figure 5 below.

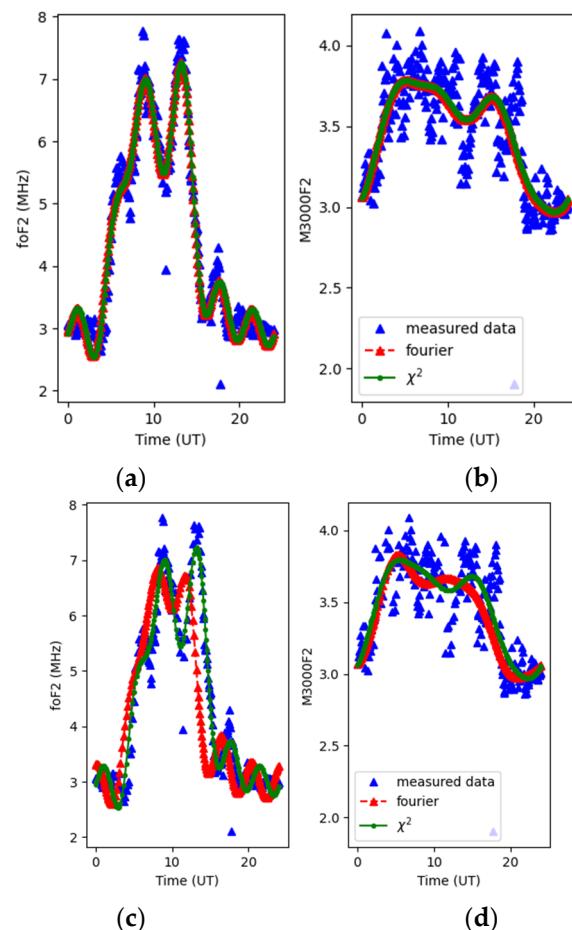


Figure 5. CCIR polynomials estimated using χ^2 minimization (green) and Discrete Fourier transform (red) from auto-scaled values of $foF2$ and $M(3000)F2$ for the case of no data gaps (**a,b**) and after removing the equivalent of 3 h of data (**c,d**).

In Figure 5a,b, the actual $foF2$ and $M(3000)F2$ values extracted from the auto-scaling algorithm are compared with the CCIR polynomials generated in the absence of any continuous missing values using both Discrete Fourier transform (red) and χ^2 minimization (green). Clearly, the two approaches are in perfect agreement. The same process was repeated after removing the equivalent of 3 h of data, and the results are given in Figure 5c,d. Evidently, χ^2 minimization retains the original form, while the applicability of the Discrete Fourier transform begins to deteriorate.

The next step is to estimate the optimal value of A_0 for which we minimize the error between measured and NeQuick-G estimated values VTEC values over Cyprus for a complete day using an appropriate calibration algorithm [3]. Since, under the proposed concept, we are only dealing with a single location, there is no need to optimize all three coefficients (A_0, A_1, A_2) of Az , as given in Equation (1), but only for A_0 , since we do not need to consider modip variations. This will be the value that will be used to run the NeQuick-G algorithm for the next day.

Figure 6 demonstrates the Root Mean Squared Error (RMSE) between measured and NeQuick-G modeled VTEC values for a certain day as a function of A_0 . By varying A_0 , we can select an appropriate A_0 value that minimizes RMSE and which will be used to drive NeQuick-G for the next day. Different NeQuick-G daily VTEC profiles for different A_0 values are also shown in Figure 7. We can visually identify that the profile corresponding to the selected optimal value of $A_0 = 118$ coincides to a significant extent to the measured VTEC profile, indicated by the thick black line.

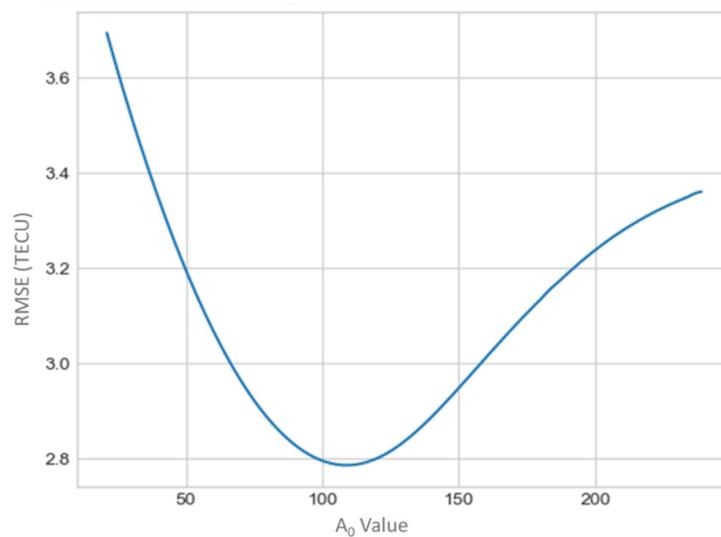


Figure 6. Minimization of RMSE (at $A_0 = 118$) to be used for the next day.

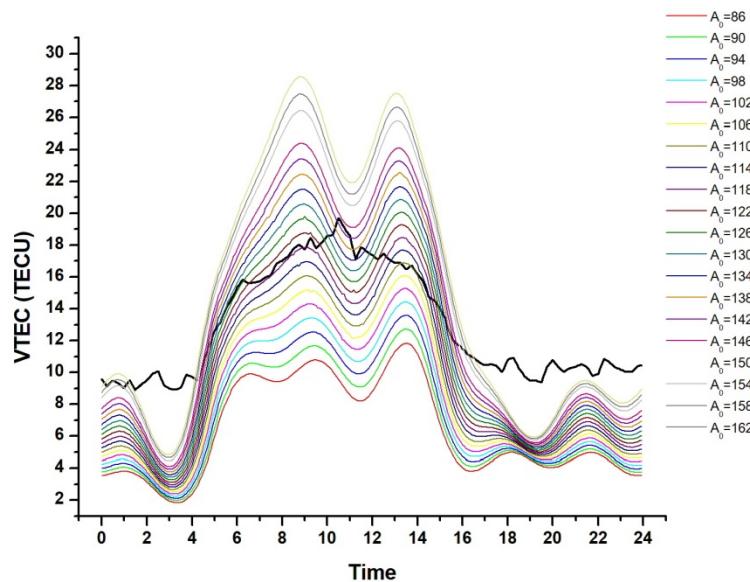


Figure 7. Actual VTEC profile over Cyprus (thick black line) and NeQuick-G VTEC profiles for different A_0 values.

The assumption that two consecutive days will exhibit similar ionospheric behavior (under quiet geomagnetic conditions) is the underlying requirement for the application of the proposed concept which is of course the basis on which the Galileo NeQuick-G algorithm currently operates. So, for our case, Equation (1) will reduce to $Az = A_0$. The assumption is violated of course under disturbed geomagnetic conditions, during which Galileo broadcasts warning information in the navigation message, through Ionospheric Disturbance Flags. These indicate the disturbed state of the ionosphere to alert users that

the quality of ionospheric correction may not meet the performance specification in each of the five different geographical regions specified in terms of their modip range. A synoptic diagram illustrating the Short-term improvement service is given in Figure 8.

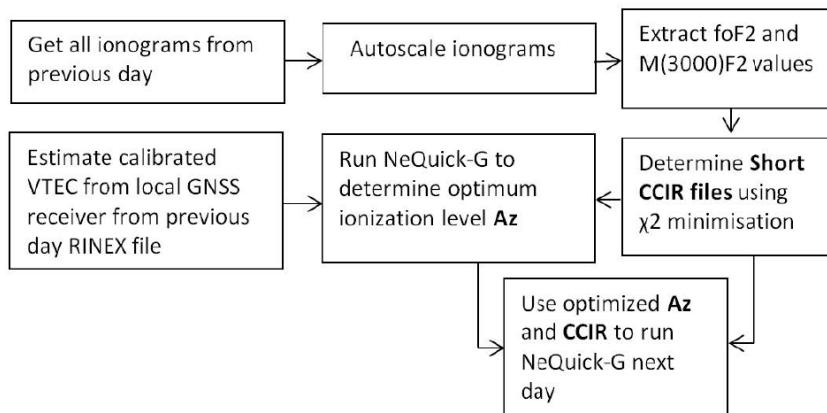


Figure 8. Diagram illustrating the Short-term improvement service.

The proposed concept has been developed into an operational system and is currently undergoing a testing phase. Since the purpose of this paper is primarily to introduce the concept, we have not yet run an analysis based on previous years. This is something we intend to do in the near future. Figure 9 depicts examples of the system output for 4 consecutive days 1–4 April 2021 during quiet geomagnetic conditions (Daily Geomagnetic Planetary Index $Ap = 7, 5, 4, 2$, respectively). The measurements are VTEC values over Nicosia, and the green plots represent the actual NeQuick-G output over Cyprus with Galileo broadcasted Az coefficients as input using the standard global CCIR files. The orange plots correspond to NeQuick-G output with the short-term calculation of CCIR files over Cyprus, using the auto-scaled values from the Cyprus Digisonde. The red plots correspond to the NeQuick-G output obtained using the same long-term CCIR files which have been calculated over Cyprus to get the results shown in Figures 1 and 2 for the month of April, but driven by the Galileo broadcasted Az coefficients for the day in question to serve as a benchmark. We have to underline that what we present here is an ideal scenario as the calculated short-term CCIR files correspond to Digisonde auto-scaled characteristics for that particular day. The Galileo broadcasted Az coefficients, although applied for the day in question, have been calculated based on data from the day before as in the normal operational mode of the Galileo Ionospheric Correction Algorithm.

We can observe that the short CCIR approach performs really well for 2–4 April 2021. For the 1st of April, it overshoots around 10 UT. It is also evident that the short-term Cyprus CCIR option is better than the long-term Cyprus CCIR option which does not follow the measurements' diurnal profile (especially for 2–4 April 2021). This is also reflected in the Root Mean Squared Error (RMSE) values provided in Table 1. It seems that combining Galileo broadcasted Az coefficients (that have been calculated on the basis of global TEC values), with locally generated albeit long-term CCIR files, is not the best option. We can also observe the fact that the global and long-term diurnal profiles that are based on fixed CCIR files (standard and locally generated, respectively) retain their basic diurnal profile as expected, for a certain month. The strength of the proposed concept is evident in the possibility to adjust the diurnal profile of TEC based on the actual ionospheric behavior that could considerably change on a day to day basis. We observe that, for all days, during this 4-day interval in question, all the options considered underestimate the measurements during night-time. The possibility to adjust Az for daytime and night-time sections of the profile would enable a better adjustment of the NeQuick-G output to the measurements. This is something we are going to explore in the near future.

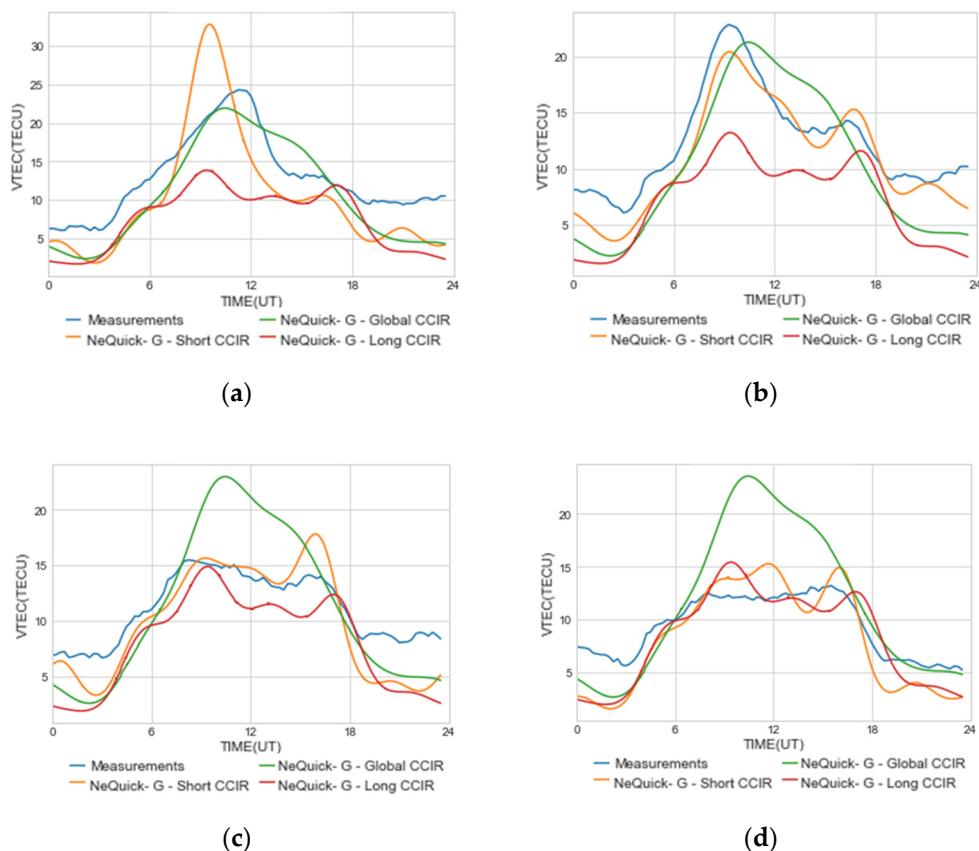


Figure 9. Output of the system under the testing phase with Cyprus Short (orange), Cyprus Long (red), and Global (green) CCIR options for (a) 1 April 2021, (b) 2 April 2021, (c) 3 April 2021, and (d) 4 April 2021.

Table 1. RMSE values in TECU for each day in the interval 1–4 April 2021.

Date	RMSE (Short-Term CCIR)	RMSE (Long-Term CCIR)	RMSE (Global CCIR)
1 April 2021	4.9	6.2	3.45
2 April 2021	2.0	5.7	3.8
3 April 2021	2.6	3.4	4.2
4 April 2021	2.5	2.3	5.1

4. Concluding Remarks

The main objective of this study was to explore techniques to improve and optimize the Galileo single frequency users' positioning algorithm in a context of assisted GNSS driven by a local and, therefore, more accurate ionospheric representation. Demonstration of the tangible benefit of this concept provides the basis for the development of relevant applications relevant to navigation and positioning in the near future. The systematic operation of the ionospheric mitigation service is based on the priority for the deployment of a service for the systematic provision of ionospheric corrections through the development of new value-added products useful for large number and navigation systems users, like those that are currently based on single-frequency positioning devices, which is the vast majority of users.

The prospect for the adoption of the underlying concept proposed through this study, is stimulated by the increasing network accessibility and rapid market penetration of smartphones and tablets with significant processing power and even capable of calculating raw carrier and phase measurements [28]. Our short-term improvement proposal goes one

step further by exploiting updated information on the state of the local ionosphere in the form of ingested ionospheric characteristics exploiting available ionospheric monitoring infrastructure such ionosondes and dual-frequency GNSS receivers. The techniques that were considered in the frames of this study are, therefore, expected to have an impact on a vast array of devices that, due to limited cost specifications, rely on the Galileo single-frequency positioning scheme.

There are various additional avenues that could be explored in an effort to extend the main elements of the proposed idea even further by investigating additional adaptations of the existing NeQuick-G algorithm. Therefore, the application of this idea in the local context will form the starting point for a more extended solution. These idea could be applicable to a significant part of Europe due to the significant number and satisfactory coverage by ionosondes over the region. For example, using the proposed novel idea, we could introduce augmented and more geographically-extended solutions (similar to the EGNOS framework for SBAS-enabled devices) driven by the network of European ionosondes and GNSS reference stations tailored for 3G-4G-5G GNSS devices without SBAS functionality. Thus, building on this concept we can propose a system of a significantly higher scale and of subsequently greater exploitation possibilities in commercialization terms. In the near future, we plan conduct an investigation in order to quantify the actual degree of mitigation of positioning errors that can be achieved based on the application of our proposed concept.

Author Contributions: Conceptualization, H.H. and A.A.; methodology, H.H. and T.L.; software, V.P., T.L., and M.C.; validation, V.P., H.H., and A.K.S.; formal analysis, H.H. and T.L.; investigation, H.H., T.L., and A.K.S.; data curation, N.L.; writing—original draft preparation, H.H.; writing—review and editing, H.H. and M.C.; visualization, V.P. and A.K.S.; supervision, A.A. and H.H.; project administration, A.A. and H.H.; funding acquisition, A.A. and H.H.; All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the project “Service for Improving Galileo operation over Cyprus” (SERVING)-ENTERPRISES/0916/0159 which is co-funded by the Republic of Cyprus and the European Regional Development Fund (through the ‘RESEARCH IN ENTERPRISES’ RESTART 2016–2020 Program for Research, Technological Development and Innovation).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The NeQuick electron density model was developed by the Abdus Salam International Center of Theoretical Physics in Trieste, Italy, and the University of Graz in Austria. The adaptation of NeQuick for the Galileo single-frequency ionospheric correction algorithm (NeQuick G) was undertaken by ESA.

Conflicts of Interest: The authors declare no conflict of interest.

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