Galileo Single Frequency Ionospheric Correction: Performances in Terms of Position

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Abstract

The ionospheric effect remains one of the main factors limiting GNSS accuracy. For GPS single frequency users, this contribution to the error budget is estimated thanks to the well-known Klobuchar algorithm. For Galileo, it will be mitigated by a global algorithm based on the NeQuick model. This algorithm relies on an optimisation procedure called ingestion. In this framework, an "effective ionisation level" Az plays the role of the solar activity information provided to the model in order to fit a specific dataset. For Galileo single frequency operation, daily Az values will be computed from slant Total Electron Content (sTEC) measurements performed within the ground segment and three coefficients will be broadcast to the users within the navigation message allowing them to run the model.

Although the performance specifications of these algorithms are respectively expressed in terms of delay and TEC, the actual users might find more interest in their impact on positioning. Hence we propose to investigate their performances in terms of positioning accuracy. To this extent we compare positions of Brussels permanent station in Belgium (mid-latitudes) calculated for the year 2002 (high solar activity level) with and without the ionospheric correction to the actual ones which are known at the sub-centimetre level. We obtain different conclusions for vertical and horizontal accuracies: on the one hand, the vertical errors decrease by 50 to 60% with the analysed ionospheric corrections; on the other hand, the horizontal errors decrease at most by 25%. We interpret these results using a fictitious symmetric satellite distribution highlighting the role of TEC gradients in residual errors. Hence we adopt an original point of view for futher investigation of potential alternative ionospheric corrections and we provide an interesting insight in the situation we could observe when Galileo reaches its Initial Operation Capability, during the next solar maximum[1].

1 Introduction

As long as Global Navigation Satellite Systems (GNSS) rely on signal radiopropagation through the atmosphere, their operation largely depends on the dynamics of the ionosphere (ARBESSER-RASTBURG & JAKOWSKI, 2007). This ionised part of the atmosphere modifies indeed the speed of navigation signals inducing delays among other effects. In turn these delays lengthen the satellite-to-receiver ranges from which single frequency code receivers compute their position.

Most of civilian GNSS receivers model the ionospheric delay to mitigate its effect on positioning. Processing single frequency measurements only, they cannot compensate for ionospheric errors taking advantage from the ionosphere dispersion causing differential effects between frequencies. They run an internal model fed with external information about the state of the ionosphere provided by the navigation system. Hence the Global Positioning System (GPS) broadcasts 8 coefficients suited for the ionospheric correction algorithm designed by KLOBUCHAR (1987). On the other hand, the future Galileo system will transmit 3 coefficients representing the spatial dependence of an "effective ionisation level" Az constituting the solar activity input of the NeQuick model (NAVA *et al.*, 2008). To this extent, the European system will measure slant Total Electron Content (slant TEC or sTEC) at each Galileo Sensor Station (GSS) and perform data ingestion, an optimisation procedure finding the best input for the model to fit a specific dataset.

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[1] Find material about this paper on `http://orbi.ulg.ac.be/handle/2268/88442`.

In the present study, we investigate the positioning accuracy reached with ionospheric corrections supplied by the Klobuchar and NeQuick models. For NeQuick, we consider the baseline version for Galileo referred to as NeQuick 1 and the latest version 2. We perform stand-alone point positioning from GPS single frequency code measurements. To apply the Klobuchar algorithm, we use the actual broadcast coefficients from GPS RINEX files. Regarding NeQuick, we simulate them for the In-Orbit Validation (IOV) phase of Galileo based on sTEC values computed from Global Ionospheric Maps (GIM) at 18 IGS stations (Bidaine & Warnant, 2011). First we characterise the corrections performances for a mid-latitude station (Brussels) at high solar activity level (year 2002). Then we interpret the results and identify different origins for the observed discrepancies.

2 Ionospheric corrections performances

To characterise the ionospheric corrections performances, we proceed in two steps. First we consider their ability to model sTEC, the primary parameter they are intended to provide for each satellite in view. Moreover this parameter – the equivalent ionospheric delay for the Klobuchar algorithm – is involved in dedicated system specifications. Second we focus on the positioning errors reduction they enable, heading to services accuracy evaluation.

2.1 sTEC

To analyse sTEC modelling, we compare modelled values to GPS-derived data calibrated by means of GIM. In particular, sTEC estimates from UPC maps were used to compute the ambiguities of the phase geometry-free combination (Orus *et al.*, 2007) and generate in turn reference sTEC measurements. From the differences between these measurements and corresponding modelled values, we calculate the relative Root Mean Square (RMS) errors at Brussels for the year 2002 taking into account the $43 - TECu$ mean measured sTEC for these conditions (cf. figure 1, left plot).

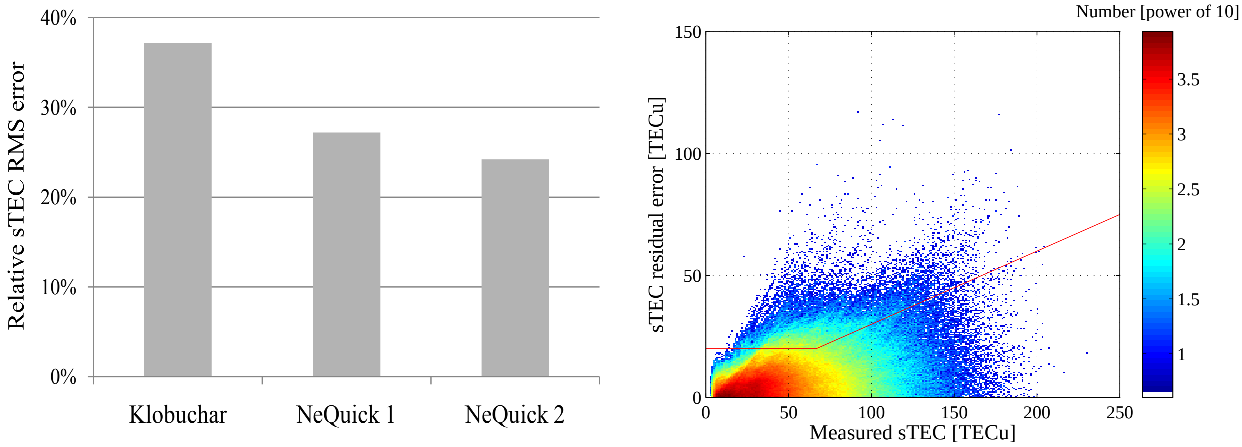

Figure 1: In the left plot, the decreasing relative sTEC RMS underlines the better performances of the NeQuick model in terms of sTEC by comparison with the Klobuchar model for Brussels in 2002. Focusing on NeQuick 1, 95% of its residual errors meet the Galileo algorithm specifications illustrated on the right plot (below the broken line).

According to sTEC statistics, NeQuick outperforms the Klobuchar model. Indeed the Klobuchar model underestimates sTEC by almost $5TECu$ and the standard deviation of its differences equals $15TECu$. NeQuick

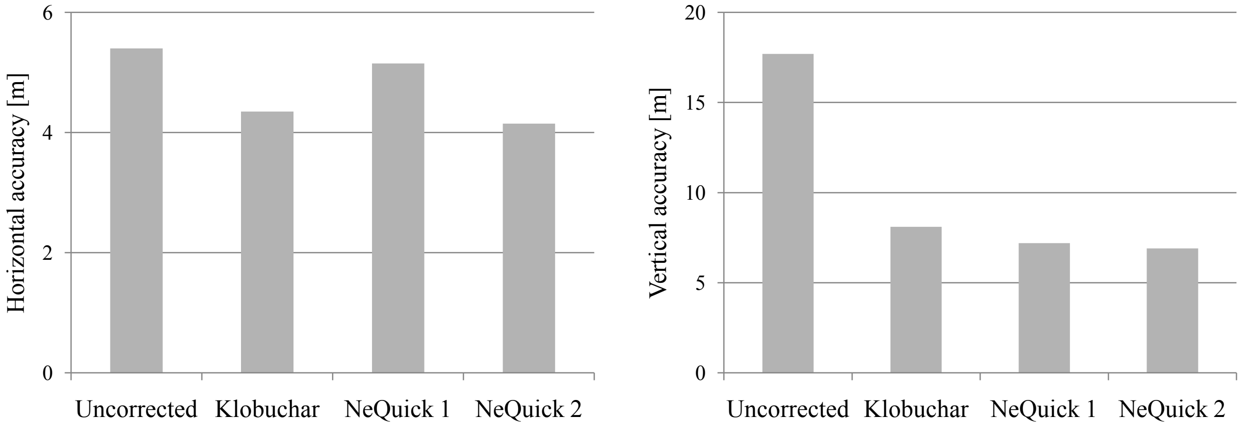

Figure 2: The ionospheric corrections improve more the vertical accuracy (right plot) than the horizontal one (left plot). These numbers correspond to the 95^{th} percentile of absolute horizontal and vertical positioning errors for Brussels in 2002.

1 yields a bias four times smaller and a 24% reduced standard deviation. An additional 10% decrease brings NeQuick 2 standard deviation to $10TECu$, the same value than the RMS as NeQuick 2 mean difference vanishes.

Finally NeQuick complies with the Galileo algorithm specifications for the station and year of study. This algorithm has been designed to limit the residual error to 30% of the actual sTEC or $20TECu$, whichever is larger. In our simulation using NeQuick 1, 95% of the residual errors meet this criterium (cf. figure 1, right plot). This proportion is only slightly larger for NeQuick 2 (less than 1%). By comparison with NeQuick 1, it includes more large sTEC measurements (larger than $\frac{20TECu}{30\%} \simeq 66.7TECu$, associated to large residual errors) but less smaller sTEC measurements. Regarding the Klobuchar algorithm, its 37% RMS residual error fits the declared performance (50% RMS correction).

2.2 Positioning errors

Our second performance analysis consists in investigating differences between the actual position of Brussels IGS permanent station and the ones computed with and without each ionospheric correction. Hence we performed single-point single-epoch (SPSE) positioning characteristic of the operation of a typical mass-market single-frequency receiver: we use L1 C/A pseudorange measurements, broadcast orbits, clocks and hardware biases as well as the Saastamoinen tropospheric model with standard meteorological parameters and the Niell mapping function. As such this processing corresponds to a first "uncorrected" case and we obtain the three following ones applying additional pseudorange corrections accounting for the ionospheric delay using each model. We synthesise the results in terms of horizontal and vertical 95% accuracies (cf. figure 2) as these metrics are regularly used in services specifications (e.g. 4 and $8m$ for the Galileo Open Service).

We report improvements from each ionospheric correction with respect to the uncorrected case at different levels however for horizontal and vertical errors. The vertical error ($17.7m$) is significantly reduced thanks to the Klobuchar algorithm (-54%) and even more with successive NeQuick versions (-59% and -61%). On the other hand, the horizontal error ($5.4m$) decreases with the Klobuchar and NeQuick 2 models (-19% and -23%) but only slightly with NeQuick 1 (-5%). Consequently none of the corrections seem to comply with the Galileo Open Service specifications for horizontal positioning where they provide a sufficient vertical accuracy. However we need to put these statements into perspective. While we expect this mid-latitude station to exhibit average positioning errors, we also foresee larger values than for lower solar activity periods. Furthermore we should not attribute the obtained residual errors only to the ionosphere mismodelling. These errors are indeed largely influenced by the accuracy of the various products implemented (orbits, clocks, hardware biases and troposphere) as well as code noise and multipath which should be smaller for Galileo than for the GPS data exploited for this simulation.

3 Interpretation

Describing the impact of the ionosphere and its modelling on SPSE positioning is not straightforward. Therefore we analyse how the ionospheric delay translates into uncorrected coordinates in order to enable us to point out the weaknesses of Galileo ionospheric correction subsequently. We mainly discuss horizontal errors as, in previous section, we stated rather small horizontal correction levels despite the good sTEC performances.

3.1 Ionosphere influence on positioning

The distributions of horizontal and vertical uncorrected positioning errors underlying the 95% accuracies described in previous section inform us about systematic trends at northern mid-latitudes (cf. figure 3). We observe average drifts towards the north and up directions. Yet ionospheric delays lengthening the pseudoranges from every satellite would intuitively have lead to negative heights. We also notice a larger dispersion along the north axis than along the east one suggesting a larger role of the north error in horizontal errors.

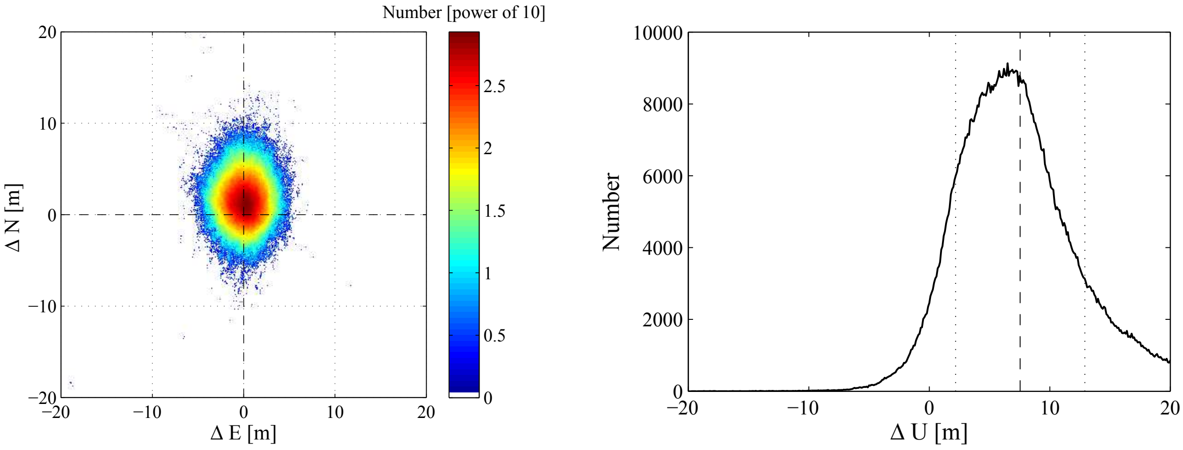

Figure 3: The horizontal (left plot) and vertical (right plot) uncorrected positioning errors distributions depict mean biases towards north and up directions at Brussels in 2002. On the right plot, the vertical dashed line correponds to the mean up error and the dotted lines to the 1-σ interval around the mean.

To explain these tendencies, we refer to the positioning mathematical problem. This problem aims at determining the three coordinate differences $\underline{\Delta r}$ from a priori approximations and an unknown bias Δb usually assimilated to the receiver clock error, all gathered in the vector $\underline{\Delta x}$. These unknowns relate to the differences $\underline{\Delta P}$ between the measured pseudoranges to the n satellites in view of the receiver and the corresponding values computed from the a priori coordinates. The corresponding system of equations usually overdetermined ($n \geq 4$) is characterised by the design matrix A containing the satellite unit vectors $\underline{u}^i$ $(i = 1$ to $n)$ and admits a solution in the least-squares sense (cf. equation 3).

$$\underline{\Delta P} = A\ \underline{\Delta x} + \underline{\nu} \tag{1}$$

$$\underline{\Delta P} = \begin{pmatrix} \Delta P^1 \\ \vdots \\ \Delta P^n \end{pmatrix}, A = \begin{pmatrix} -\underline{u}^1 & 1 \\ \vdots & \vdots \\ -\underline{u}^n & 1 \end{pmatrix}, \underline{\Delta x} = \begin{pmatrix} \Delta r \\ \Delta b \end{pmatrix} \tag{2}$$

$$\underline{\Delta x} = \left(A^T\ A\right)^{-1} A^T\ \underline{\Delta P} \tag{3}$$

We further build our intuition about the influence of the ionosphere on positioning on a particular case of the problem. Replacing first the observations ΔP^i by the ionospheric delays I^i provides us with positioning errors induced only by the ionosphere. To obtain analytical expressions binding the ionospheric delays to these errors, we would then need to develop the matrix $\left(A^T\ A\right)^{-1} A^T$. To this extent, MOHINO (2008) proposes to focus on a fictitious highly symmetrical satellite distribution. This distribution consists in one zenithal satellite and an even number of satellites at constant elevation η uniformly distributed in azimuth. The most simple example of such a distribution involves five satellites, one at the zenith and the others towards each cardinal direction.

This particular case yields simple formulas for horizontal errors (cf. equations 4 and 5). Indeed the north (resp. east) component depends only on the ionospheric delays – or corresponding TEC – along the north (resp. east) axis. Furthermore the horizontal errors relate not only on TEC but on its gradients.

$$\Delta N = \frac{1}{2\cos\eta}\left(I^S - I^N\right) \tag{4}$$

$$\Delta E = \frac{1}{2\cos\eta}\left(I^W - I^E\right) \tag{5}$$

Based on this reasoning, hourly means of horizontal errors and TEC gradients supply a useful interpretation of the observed error distribution (cf. figure 4). At mid-latitudes, these statistics disclose the effect of larger TEC values towards the equator with the largest gradients around local noon, leading to a north bias without proper correction. Following sun course, their profile along the east axis corresponds to a larger TEC towards east in the morning and west in the afternoon.

The vertical error formula reveals slightly more complicated but still explains the positive up drift. It consists in the difference between the common bias and the vertical delay and its concave daily mean profile remains positive all day long with a maximum at local noon. Its simulation involves the difference between low elevation mean TEC and vertical TEC.

3.2 NeQuick correction discrepancies

Extending previous deductions to NeQuick 1 correction suggests an explanation for the small horizontal positioning improvement despite the rather efficient sTEC modelling. The horizontal errors distribution appears skewed towards south which influences the most the 95^{th} percentile (cf. figure 5). Considering the original north drift, this effect highlights a mean overcorrection from NeQuick 1 along the north axis. It ensues from a mean sTEC overestimation towards south and the absence of satellites in a portion of the north sector.

To identify the origin of NeQuick correction discrepancies, we go back through the three elements of the Galileo single frequency ionospheric correction algorithm (BIDAINE & WARNANT, 2011). The last element defines the broadcast coefficients in order to fit a parabola on the effective ionisation levels of each GSS (cf. figure 6). This feature has been introduced to cope with NeQuick observed mismodelling in the geomagnetic north-south direction. Nevertheless the receiver remains partially affected by this effect as, at mid-latitudes, the

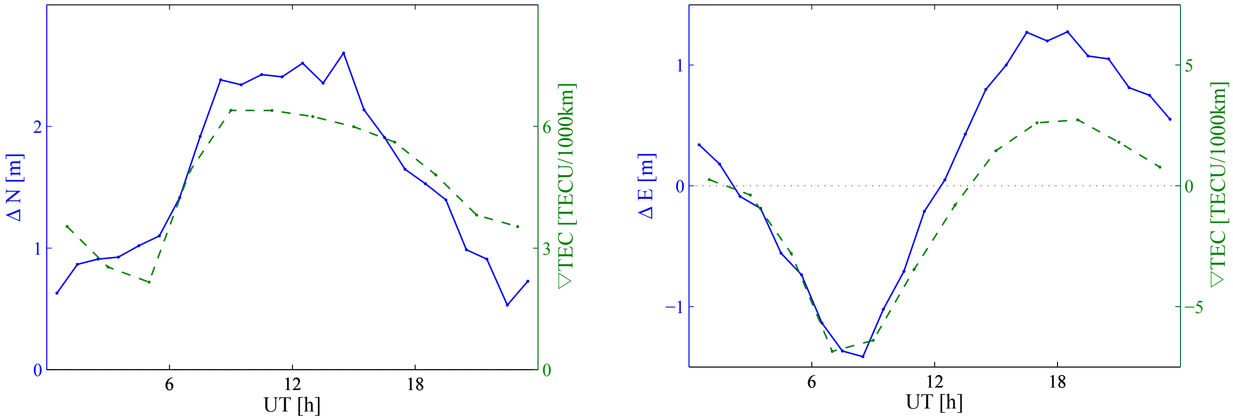

Figure 4: The north (ΔN on left plot) and east (ΔE on right plot) positioning errors (solid lines) relate to the north and east TEC gradients ∇TEC (dashed lines). These statistics proceed from the breakdown of the positioning errors dataset for Brussels in 2002 in 1-hour bins and the computation of TEC from 2-hour IGS GIM at ionospheric pierce points equidistant from the station towards each cardinal direction. A 30° elevation renders a mean DOP value similar to the actual one and defines ionospheric pierce points in a $450-km$ high thin shell at about $666km$ from the station.

computed effective ionisation level, larger than for lower latitudes, produces excessive sTEC values on average towards the equator. The previous element, sTEC data ingestion at each GSS, depends on the ingested data characteristics. The main concern about sTEC measurements lies in the biases estimation procedure which causes significant differences from one technique to the other (BIDAINE & WARNANT, 2009). Finally the first element consists in the NeQuick model itself and its intrinsic electron density profile formulation. This formulation has been improved mainly for the topside part from one version of NeQuick to the other and accounts for most of the positioning accuracies decrease.

4 Conclusion and perspectives

Galileo single frequency receivers will mitigate the ionospheric delay running the NeQuick model. For this purpose, the Ground Mission Segment will provide them with three daily-updated broadcast coefficients related to the effective ionisation level initialising the model. This procedure, usually assessed in terms of sTEC, aims at attenuating the influence of the ionosphere on point positioning performances.

In the present paper, we simulate the Galileo correction for Brussels (mid-latitudes) and the year 2002 (high solar activity) and we compare it to its hypothetic counterpart built on the second version of NeQuick as well as to the Klobuchar model implemented in the GPS. We obtain 27-24% sTEC RMS residual errors for successive NeQuick versions, 37% for the Klobuchar algorithm and a 95% level compliance of both NeQuick models with the Galileo algorithm specifications (residual error smaller than 30% of the actual sTEC or $20TECu$, whichever is larger). Heading to positioning errors, we observe a significant vertical accuracy improvement from the ionospheric corrections (95^{th} percentiles between 7 and $8m$ vs $18m$ without correction) but comparable horizontal accuracies with and without correction (between 4 and $5m$ residual errors with a maximum for the uncorrected case).

We put these results into perspective forming our intuition on a particular case of the positioning mathematical problem and distinguishing the potential effect of the different elements of the Galileo algorithm. Consider-

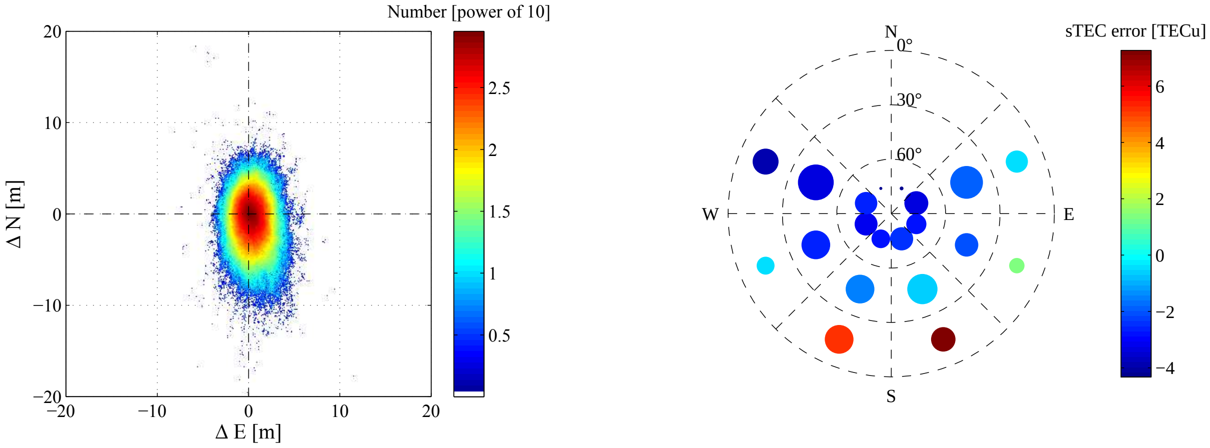

Figure 5: At Brussels in 2002, NeQuick 1 correction induces an horizontal mean error towards south (left plot) consistent with a sTEC mean overestimation in this direction (right plot). The sTEC errors correspond to means for $30°$ elevation and $45°$ azimuth bins and the dots size to the number of values in each bin.

ing a fictitious highly symmetrical satellite distribution, we depict the influence of TEC gradients on horizontal positioning errors, emphasising the role of the north component. Finally we attribute the apparent overcorrection of NeQuick 1 along the north axis to the effective ionisation level spatial dependence, the sTEC measurement technique and the intrinsic electron density profile mismodelling.

Benefiting from this background, we will further address single frequency users needs for an efficient ionospheric correction. We will envisage possible alternatives to the current definition of the Galileo algorithm, among which regional procedures. Moreover we will develop a real-time service in the framework of the project "Space Weather And Navigation Systems" (SWANS) of the University of Liège and the Royal Meteorological Institute of Belgium. As two Galileo receivers have been bought in this context, this service will be available for the In-Orbit Validation phase of Galileo.

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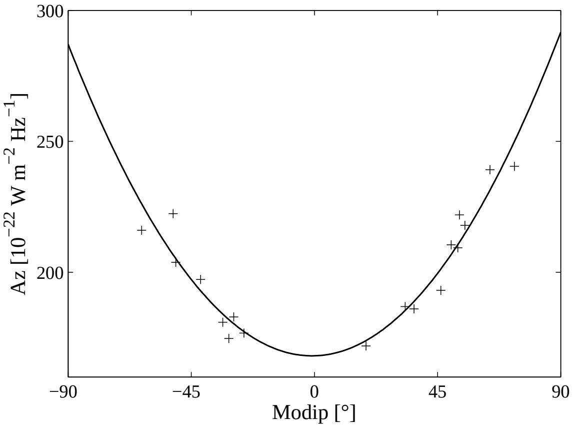

Figure 6: In 2002, the mean modified dip-latitude (modip) parabolic interpolation (solid line) of mean effective ionisation levels Az at Galileo Sensor Stations (+ markers) leads to decreasing Az values towards the equator.

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