An Assessment of the Galileo Single-Frequency Ionospheric Correction Model

QinetiQ

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Introduction

An independent assessment has been made of the ionospheric correction model proposed for single-frequency receivers of the ESA Galileo satellite navigation system. The model estimates the component of measured pseudorange caused by group retardation of the radio signal in the ionosphere - a value proportional to the Total Electron Content (TEC) along the path. TEC measurements from the International GPS Service (IGS) have been used to validate both the operational performance specification of the model and the budgetary estimates of ionospheric pseudorange.

The Galileo Ionospheric Model

Single-frequency Galileo receivers will determine TEC by line integration through the electron density model NeQuick. This model will be adjusted to global measurements of TEC by varying the solar flux parameter $F_{10.7}$. The $F_{10.7}$ value minimising the NeQuick model TEC errors over 24 hours is determined at each TEC Monitoring Station in the Galileo network. The latitude-dependence of optimum $F_{10.7}$ is determined by a polynomial fit, the coefficients of which are broadcast to users on the following day. User receivers execute NeQuick with the optimal $F_{10.7}$ found by evaluating the polynomial at the receiver latitude to estimate the TEC and hence correct for the ionospheric pseudorange component.

Validation Method

Galileo TEC Monitoring Stations have been simulated using 45 IGS stations. TEC has been recorded for all satellite elevations above 30°, for solstice and equinox months over a large part of the solar cycle (1997-2004). Differential Code Biases in the GPS pseudorange measurements have been removed using values published by the Centre for Orbit Determination in Europe (CODE). An independent set of 8 IGS stations was selected to represent the single-frequency User receivers and so test the accuracy of the model.

The Ionospheric Pseudorange Error Budget

The ionospheric pseudorange error budget is a product of three terms; the Obliquity Factor, the VTEC, and a model correction factor ΔC.

$$\sigma_{iono} \quad \frac{40.3}{f^2} \, VTEC.F(E).\Delta C$$

RMS pseudorange error

where

f = radio frequency (Hz)

VTEC = vertical TEC (el m^{-2})

ΔC = fractional residual error in the model prediction of TEC

$$F(E) = 1 + 16\cdot\left(0.53 - \frac{E}{180°}\right)^3$$

Obliquity factor

where E = satellite elevation (°)

Validation of the Obliquity Factor

The obliquity factor F(E) used in the error budget has been validated using slant TEC measurements from all User Stations. The data were categorised into 10° elevation bins and the 10, 50, 90 and 99 percentiles of the slant TEC are presented in Figure 1. The superposed dashed curves represent the analytical function VTECxF(E), where the value of VTEC has been chosen to match the curves at the percentile in the 80-90° bin.
Assuming the probability distribution of ionospheric conditions associated with each TEC measurement is independent of elevation, the curves should match perfectly, as is generally the case. The obliquity factor tends to overpredict TEC by up to 10% at lower elevations (below 25°).

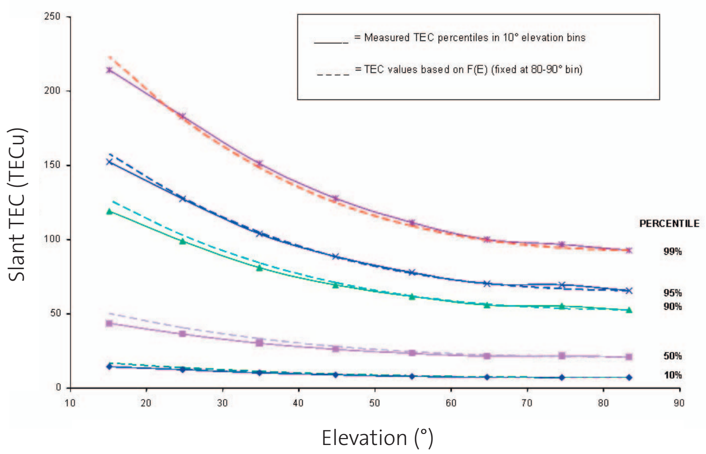

Figure 1: *Percentiles of slant TEC measurements (solid lines). Dashed lines indicate derived slant TEC = VTECxF(E).*

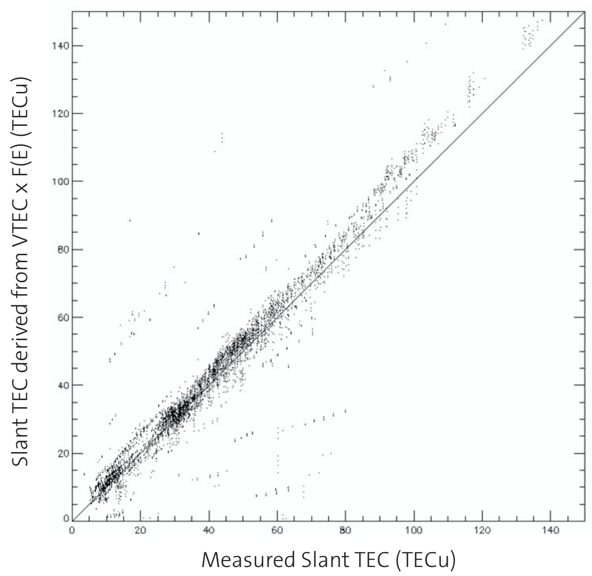

Figure 2: *Slant TEC derived from vertical (>80°) TEC measured at BRUS (Brussels, Belgium; 50.8°N, 4.4°E) multiplied by the obliquity factor plotted against slant TEC measured at GOPE (Ondrejov, Czech Republic; 49.9°N, 14.8°E (745km East of BRUS). Years 2000-2004. Paths cross in the ionosphere at 350km altitude within 200km horizontal distance. The graph shows a reasonably good fit although there are more points above the line of equality than below. This is particularly apparent at higher levels of TEC.*

Validation of the Model Correction Factor

For all VTEC ranges above 20TECu, the model RMS correction factor ΔC (top curve of Figure 3) remains roughly constant in the range 19-30% (cf. budget value of 30%). The mean error (model bias) (lower line of Figure 3, shown with +/- 1 standard deviation error bars) becomes increasingly negative at high values of VTEC (>100 TECu).

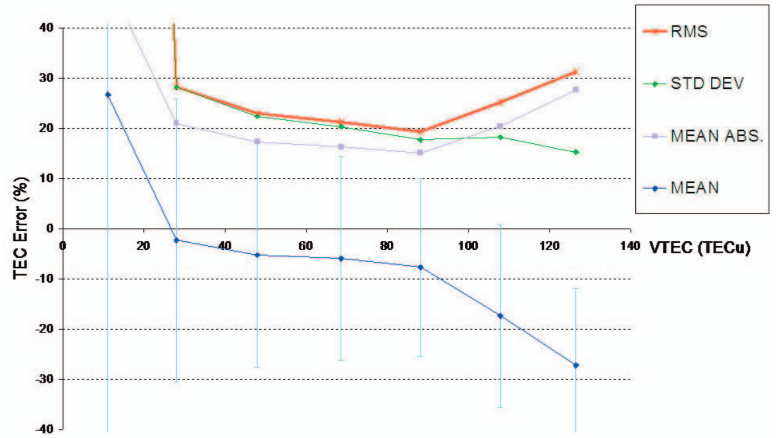

Figure 3: *Mean, mean absolute, standard deviation and RMS percentage error (ΔC) in the TEC as a function of equivalent vertical TEC. Abscissas represent the mean VTEC in each bin of width 20 TECu. Years 2000-2004 (5 million measurements). Non-storm periods only.*

Conclusions

- The model corrects to within 30% (RMS error) for any choice of VTEC above 40TECu. This is true regardless of whether an ionospheric Disturbance Flag is present.
- The obliquity factor is accurate at most elevations, though its use may yield values up to 10% too high at low elevations (<25°).
- There is a tendency of the model to under-predict TEC at high TEC values by up to 25% above VTECs of about 100 TECu, but by less than 10% below VTECs of 100 TECu.
- Overall, the model predicts TEC to within 51% for 95% of measurements (excluding data for which the TEC error is >30% and <20TECu).
- In choosing a VTEC value for budgeting, 120 TECu represents a high percentile (99.6%) and 50 TECu is the 88.2 percentile. It is noted that an excessively high VTEC value will adversely affect the accuracies obtainable in the 'Position, Velocity, Time' error budget.
- The Disturbance Flag may be set for up to 65% of the day (on average) at low latitudes and near solar maximum (i.e. where the general level of TEC in the ionosphere is high).
- The model RMS error during 'Disturbance Flagged' periods is not substantially different to the performance at other times, with RMS errors remaining below 30% for VTEC above 40 TECu. This procedure is now under revision.
- The minimum number of TEC Monitoring Stations used for updating the model may be reduced from 20 to 10 with very little change in the standard error of the optimum $F_{10.7}$ polynomial fit. The error increases sharply for less than 10 Monitoring Stations.
- RMS TEC errors do not increase appreciably over the 24-hour period between coefficient updates, and tests of 6-hourly updates (using 6-hour samples for generating optimum-$F_{10.7}$ coefficients) show that the RMS error actually increases by up to 4% compared with 24-hour updates.

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