The Galileo Single Frequency Ionospheric Correction Algorithm

B. Arbesser-Rastburg
Head, Wave Interaction & Propagation Section
ESA-ESTEC
bertram@tec-ee.esa.int

Contents

- The need for ionospheric correction
- The GPS Single Frequency algorithm
- The GALILEO Single Frequency Algorithm
- Algorithm validation
- Conclusions

The Need for Single Frequency (SF) Ionospheric Correction

- It is estimated that about 75% of all GPS receivers are Single Frequency receivers.
- Multi – frequency Galileo receivers will have a fall-back mode to single frequency operation (in case of interference)
- Single Frequency receivers require external information for correction of the variable ionospheric delay

Position Error Contributions

$$EPE = 2 \times HDOP \times UERE$$

EPE: Estimated Position Error (2D rms) [m]
HDOP: Horizontal Dilution Of Precision
UERE: User Equivalent Range Error [m]

$$UERE = \sqrt{(URE^2 + UEE^2)}$$

```
IN GPS (example):
Ephemeris error:          2.1 m
Sat Clock error:          2.1 m
Ionosphere error:         4.0 m
Troposphere error:        0.7 m
-----------------------------------
USER RANGE ERR (URE)

Multipath error:          1.4 m
Receiver error:           0.5 m
-----------------------------------
USER EQUIP ERR (UEE)
```

The biggest error for Single Frequency navigation receivers is the ionosphere error.

The GPS ICA Algorithm

$$\Delta t_1 = A_1 + A_2 \cos\,[2\pi\,(t-A_3)\,/A_4]$$

Where:

$A_1 = 5 \times 10^{-9}$ s

$A_2 = \alpha_1 + \alpha_2\ \varphi_{IP} + \alpha_3\,\varphi_{IP}^2 + \alpha_4\,\varphi_{IP}^3$

$A_3 = 14{:}00^{h}$ local time

$A_4 = \beta_1 + \beta_2\ \varphi_{IP} + \beta_3\,\varphi_{IP}^2 + \beta_4\,\varphi_{IP}^3$

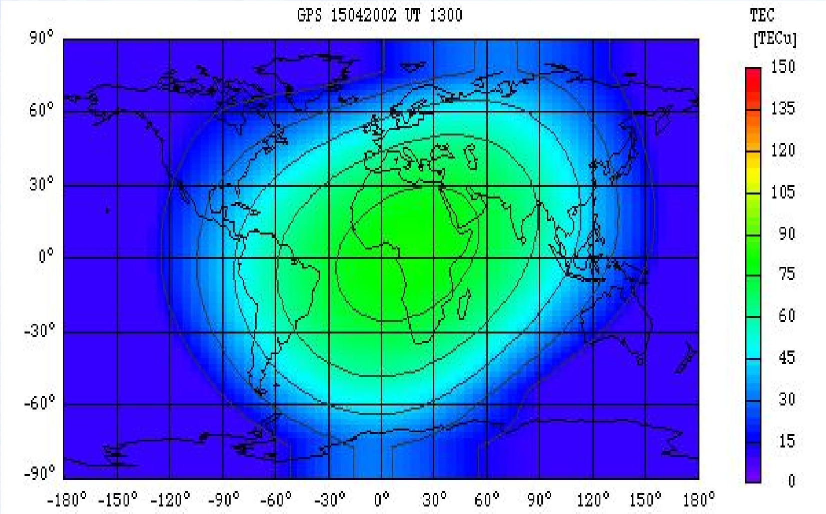
all α_i and β_i are transmitted

$t = t_{UT} + \lambda_{IP} / 15$

t_{UT} is UTC, IP is Iono Point

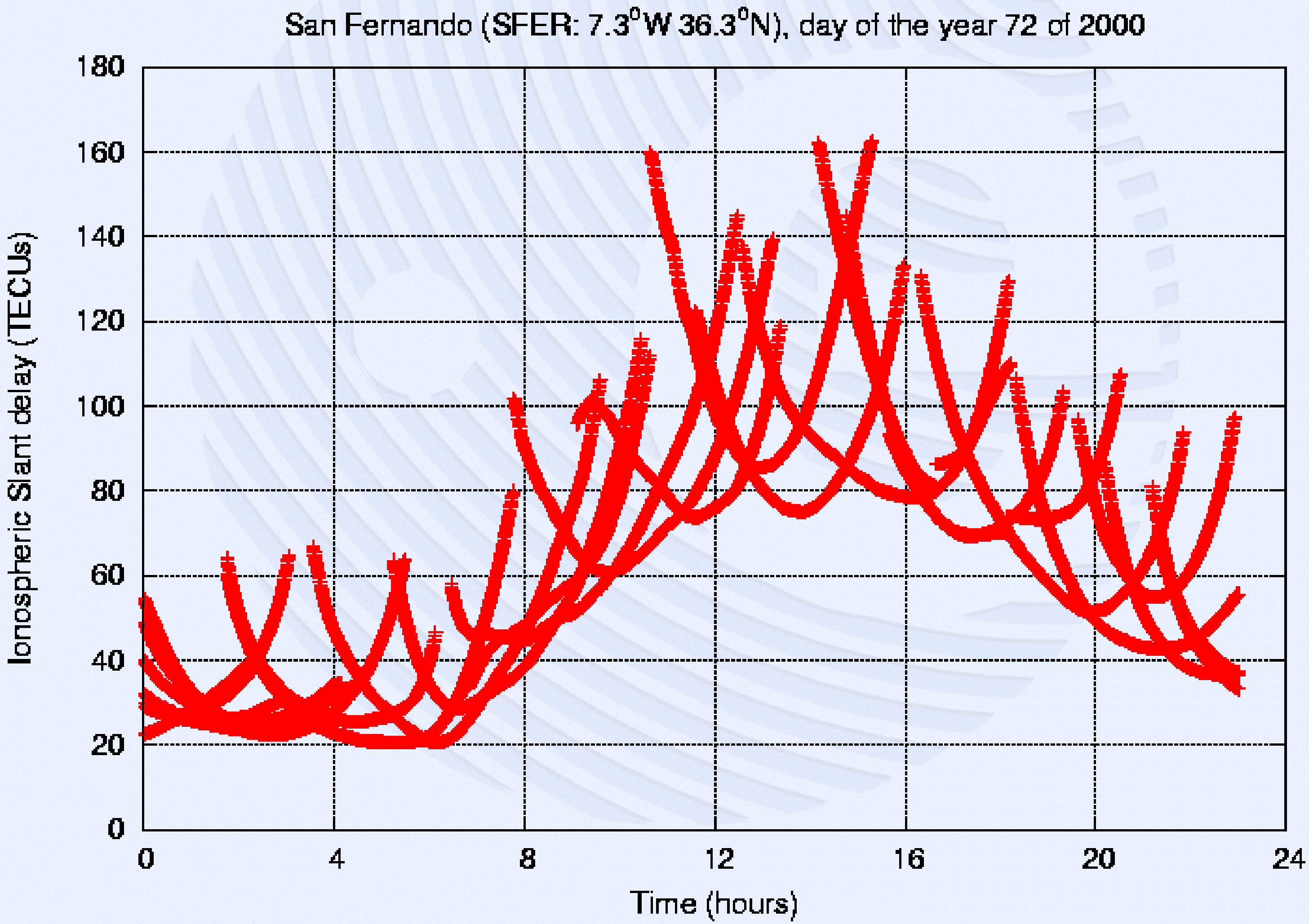
λ_{IP} is longitude of IP

φ_{IP} is the spherical distance of IP from geomagnetic pole



See: **Klobuchar, J.A.,** (1996) "Ionospheric Effects on GPS", in Parkinson, Spilker (ed), "Global Positioning System Theory and Applications, pp.513-514.

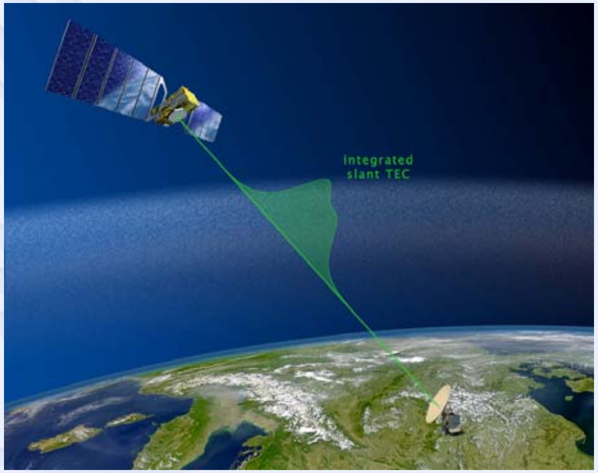
Slant TEC



San Fernando (SFER: 7.3°W 36.3°N), day of the year 72 of 2000
Ionospheric Slant delay (TECUs)
180
160
140
120
100
80
60
40
20
0
0
4
8
12
16
20
24
Time (hours)

Galileo Iono Pseudorange Error

$$\sigma_{iono} = \frac{40.3}{f^2} \cdot VTEC \cdot F(\varepsilon) \cdot \Delta M$$



Where

f : carrier frequency [Hz]

$VTEC$: vertical TEC [el /m^2]

ΔM: fractional error of model TEC

$F(\varepsilon)$: obliquity factor

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

Where

ε = elevation angle [deg]

$STEC = VTEC \times F(\varepsilon)$

Specification:

The residual error is not to exceed 20 TECu or 30 % (whichever is larger)

$STEC \geq$ **66.7** $\Rightarrow \Delta M$ **= 0.3**

$STEC <$ **66.7** $\Rightarrow \sigma_{iono}$ **= 20** $f^2/40.3$

(TUSREQ Definition)

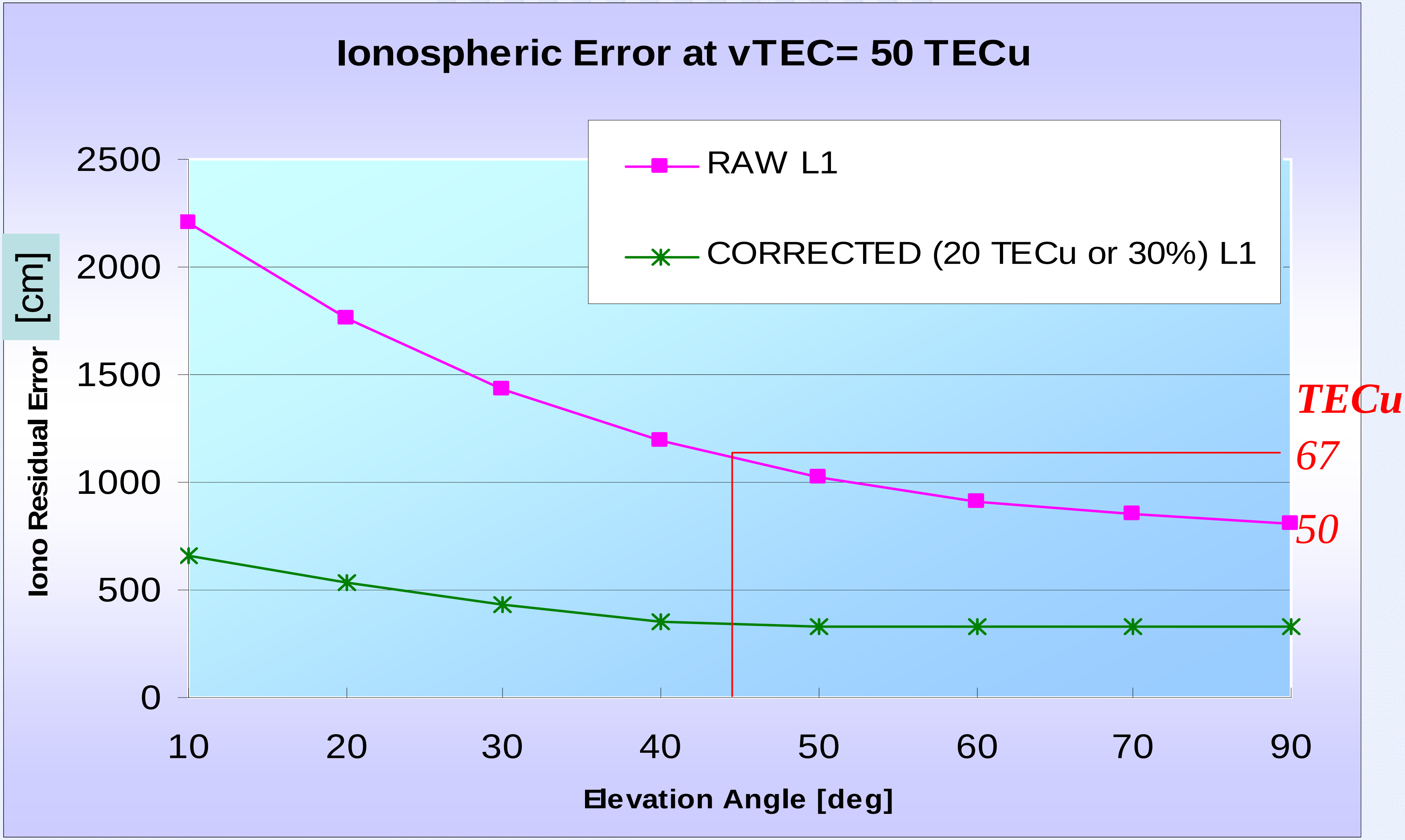
SF Algorithm - Specified Performance (1)

Nominal Iono: VTEC=50, Max Iono: VTEC=120

vTEC	UNCORRECTED (RAW)			CORRECTED (20 TECu or 30%)		
50		**L1**	E5a		**L1**	E5a
Elev [deg]	**sTEC [TECu]**	**Delay [cm]**	**Delay [cm]**	**sTECcorr [TECu]**	**Delay [cm]**	**Delay [cm]**
10	135.4	2199	3944	40.6	**660**	1183
20	108.8	1767	3168	32.6	**530**	950
30	88.4	1435	2573	26.5	**430**	772
40	73.3	1191	2135	22.0	**357**	641
50	62.8	1020	1830	20.0	**325**	582
60	56.1	911	1633	20.0	**325**	582
70	52.2	848	1521	20.0	**325**	582
90	50.0	812	1457	20.0	**325**	582

L1=1575.42 E5a= 1176.45 MHz

SF Algorithm - Specified Performance (2)



Galileo Single Frequency Iono algorithm

SENSOR STATION

Observe slant TEC in Sensor Stations for 24 hours

Optimise effective ionisation parameter for NeQuick to match observations

SATELLITE

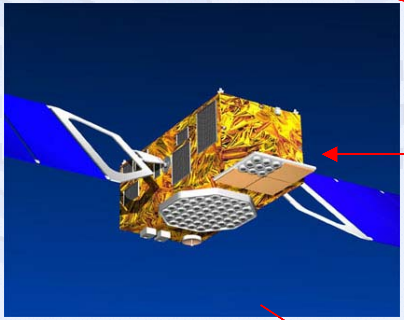
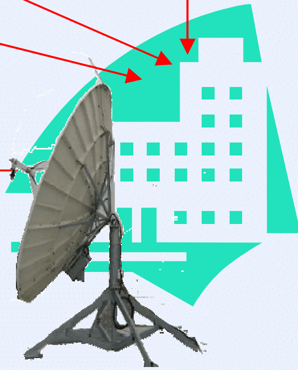
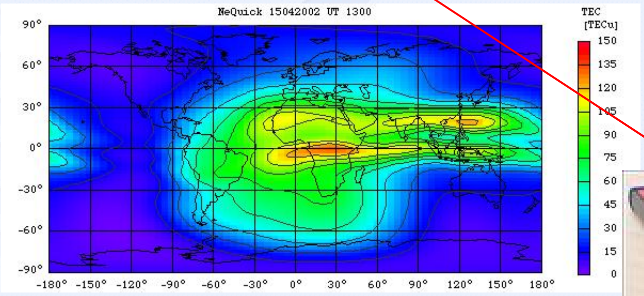
Transmit effective ionisation parameter in Navigation message

$$Az = a_0 + a_1 \cdot \mu + a_2 \cdot \mu^2$$

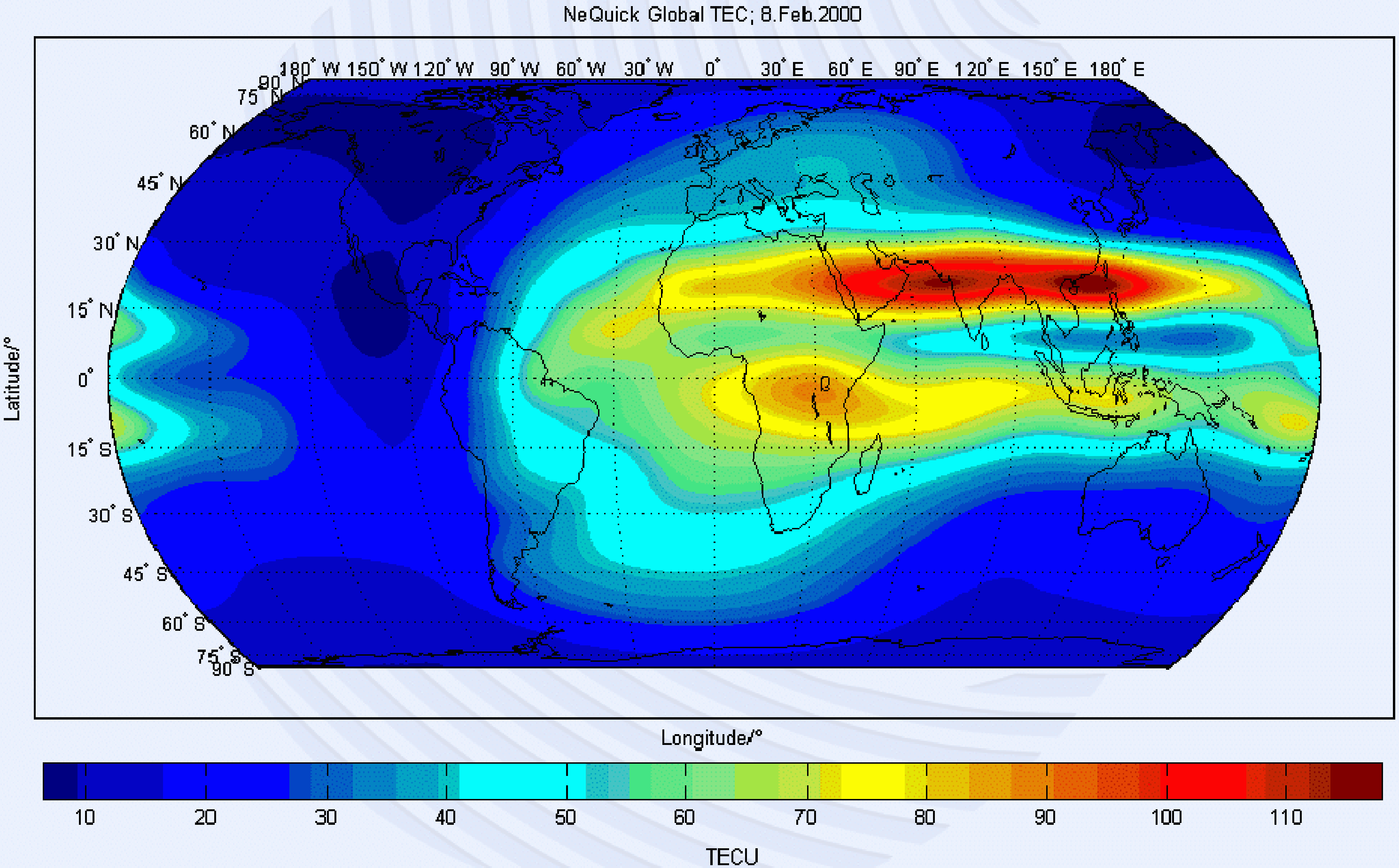
USER RECEIVER

Calculate slant TEC using NeQuick with broadcast ionisation parameter. Correct for Ionospheric delay at frequency in question.



Example of Global TEC Map



NeQuick-derived map of vTEC for 2000-02-08

Source: DLR, GSTB-V1 Report

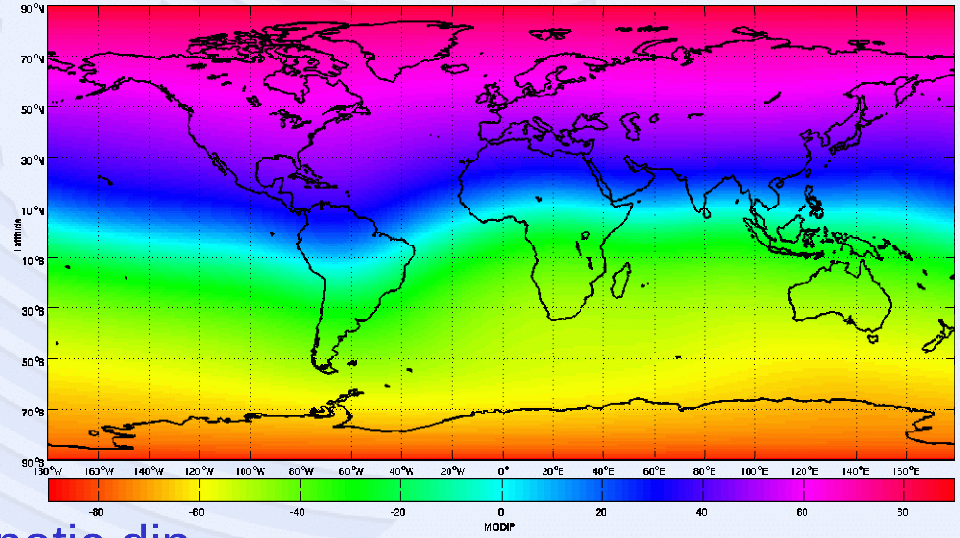
GALILEO Single Frequency Message (1)

EFFECTIVE IONISATION LEVEL

The effective Ionization level *Az* replaces solar flux in the NeQuick model. Three coefficients determine the Effective Ionisation Level, *Az:*

$$Az = a_{io} + a_{i1} \cdot \mu + a_{i2} \cdot \mu^2$$

Where μ = modified dip latitude or "MODIP"



MODIP Map

$$\tan \mu = \frac{I}{\sqrt{\cos \phi}}$$

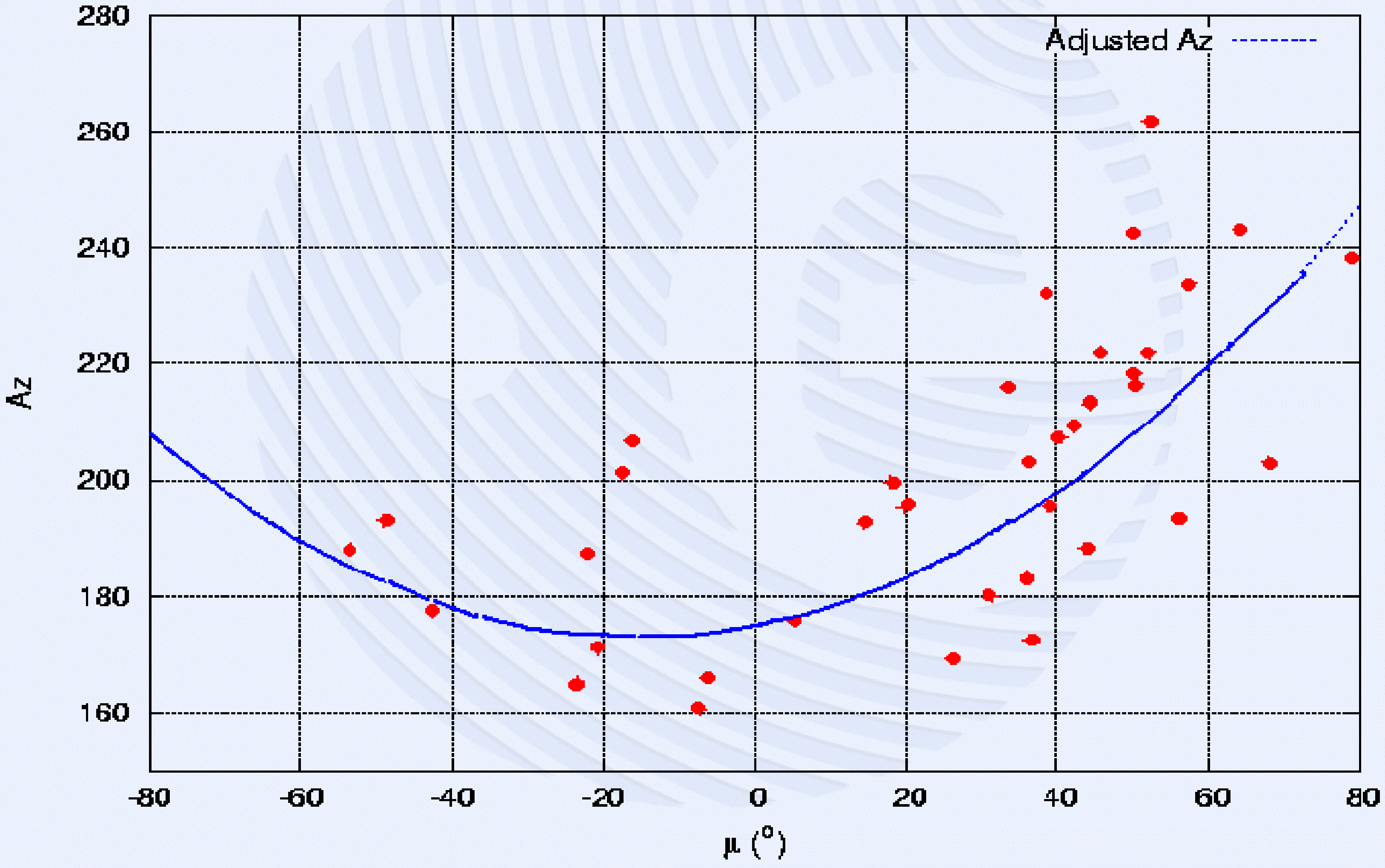
where:

I = true magnetic dip

ϕ = geographic latitude.

The coefficients will be updated at least **every 24 hours**.

Example for $Az = f(\mu)$

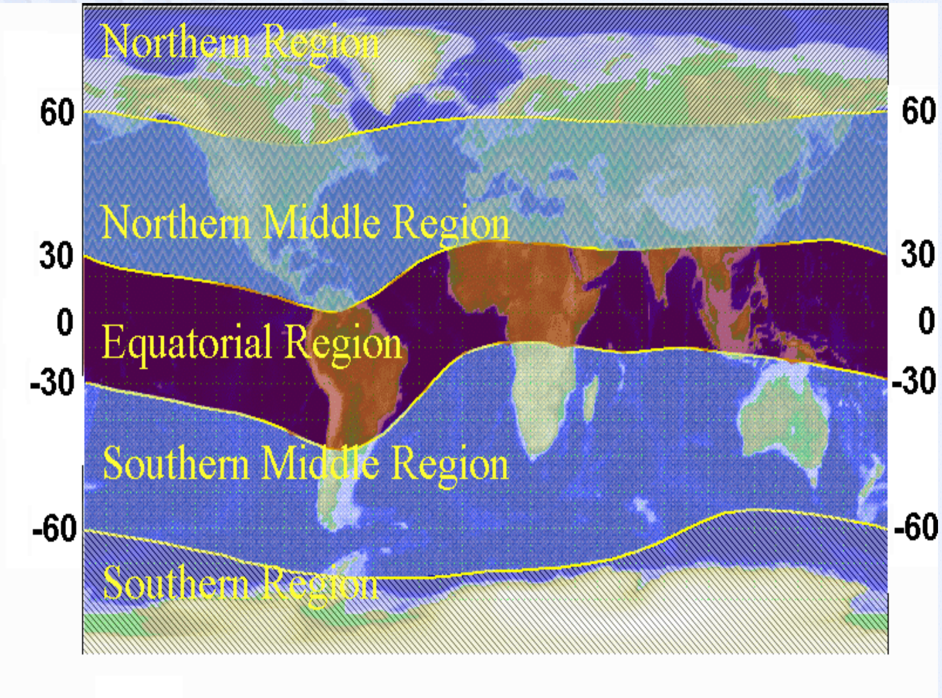


GALILEO Single Frequency Message (2)

IONOSPHERIC DISTURBANCE FLAGS

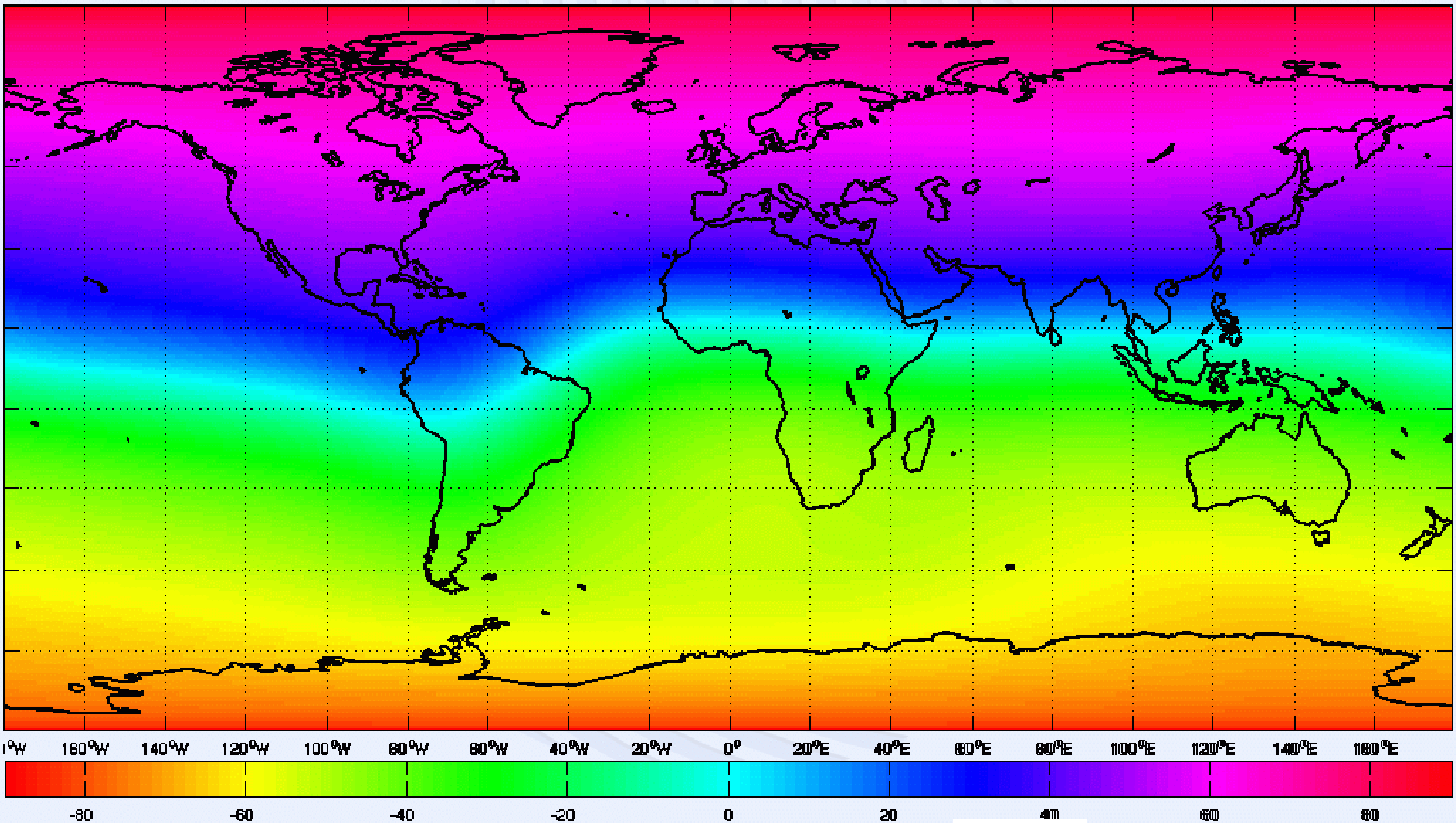
The “Ionospheric Disturbance Flag” alerts the user of a Galileo Receiver in S/F mode to the fact that the ionospheric correction coming from the Galileo broadcast message **might not meet the specified performance**.

The disturbance flags for the five predefined regions will be transmitted continuously and updated with the update rate of the Navigation Message (**every 100 minutes**).



The 5 Regions defined for the Disturbance Flags (in degrees MODIP)
-90 to -60, -60 to -30, -30 to 30, 30-60, 60-90

Variability of Mag Field



2005

Galileo SF Receiver inputs

From the Navigation message:

- The *Az* coefficients a_{i0}, a_{i1} and $a_{i2.}$
- The Ionospheric Disturbance Flag
- The actual time (UT and month of the year)
- Satellite position
- Receiver estimated position (before ionospheric correction).

From the receiver firmware:

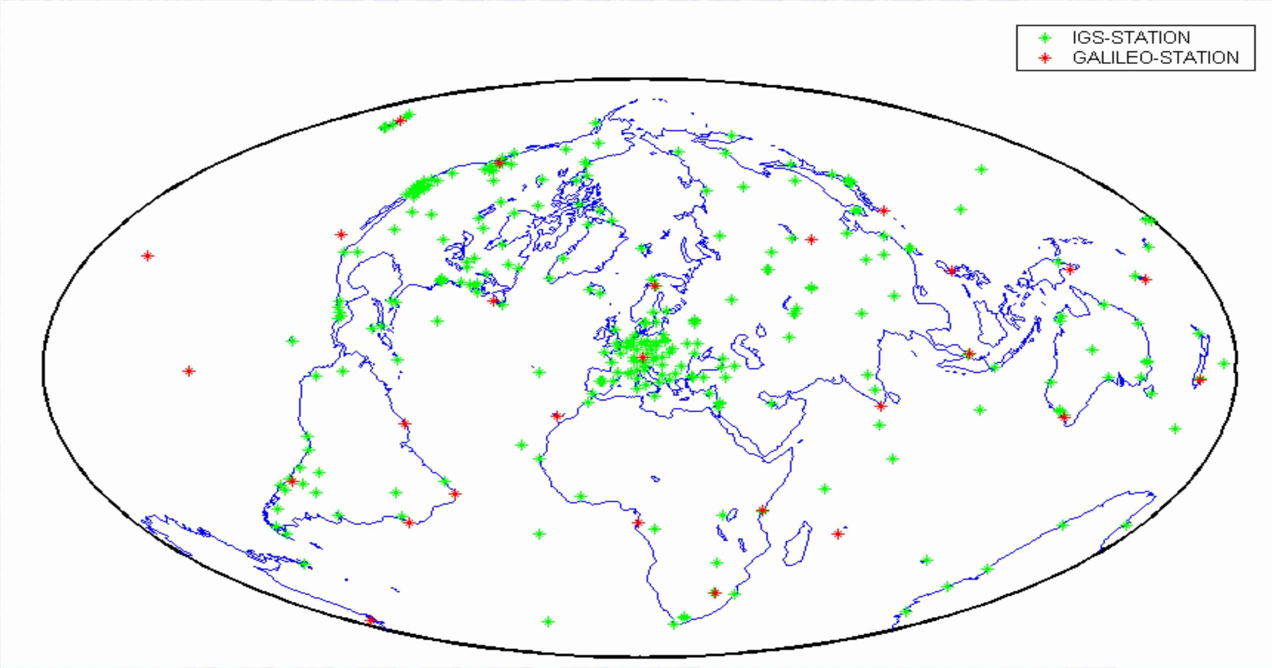
- The DIPLATS matrix, stored in an ASCII file. The DIPLATS matrix should be updated every 5 years (to take account of the natural variation of the Earth's magnetic field). This update shall be considered in the design of the Galileo receivers (MODIP table flash-able in firmware).
- The ITU-R maps for FoF2 and M3000 (F2) files, stored in 12 ASCII files, one for each calendar month.

Galileo S/F receiver algorithm

These steps are performed by single frequency receivers:

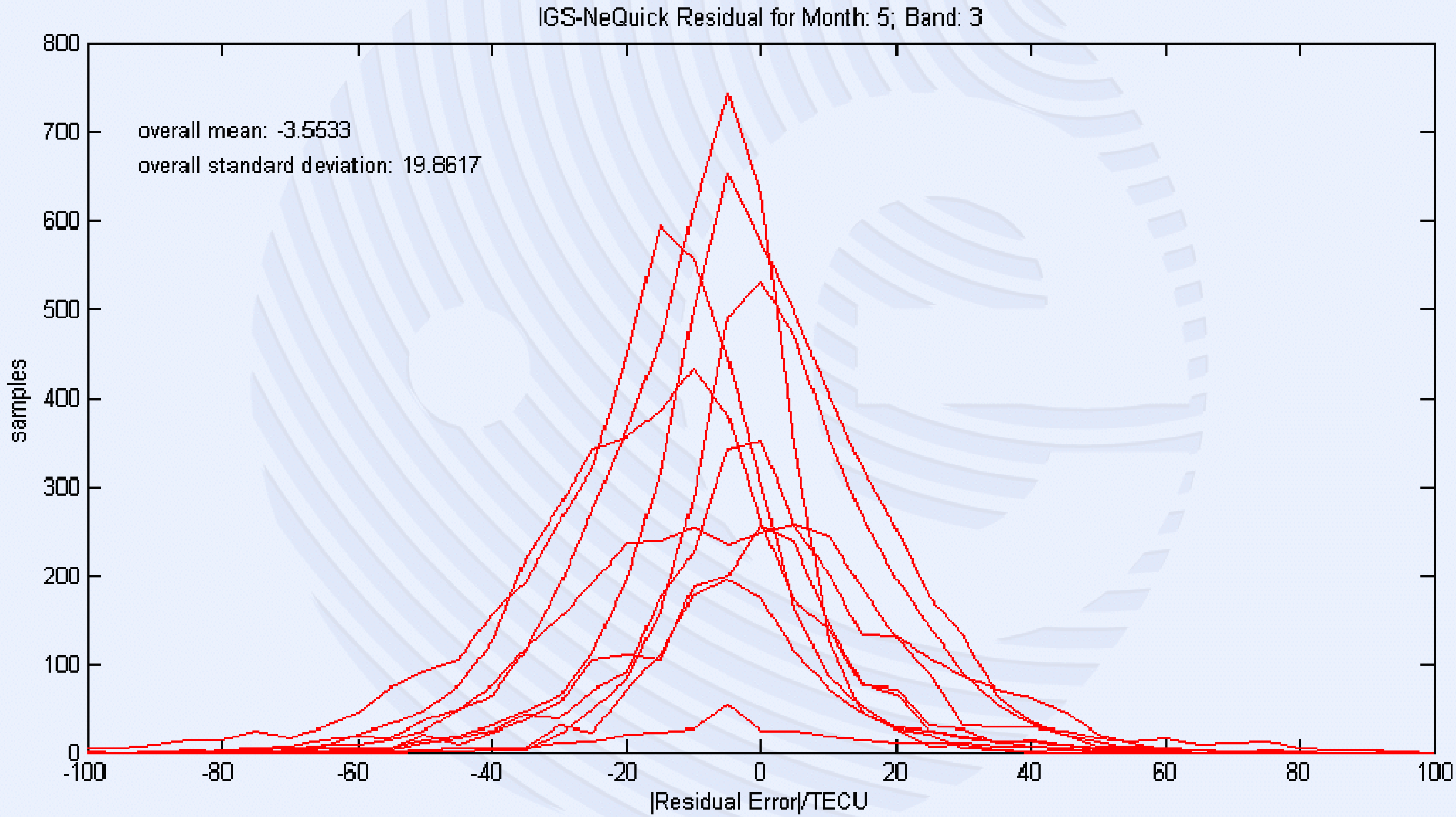
- *Az* is evaluated using a_0, a_1, a_2 (from nav message) and *MODIP* calculated from the data inside the DIPLATS matrix from the NeQuick model (which depends on estimated receiver position).
- Electron density is calculated for a point along the satellite to receiver path, using the NeQuick model with *Az* in place of *F10.7*.
- Steps 1 and 2 are repeated for many discrete points along the satellite receiver path. The number and spacing of the points will depend on the height and they will be a trade-off between integration error and computational time and power.
- All electron density values along the ray are integrated in order to obtain Slant TEC.
- Slant TEC is converted to slant delay for correcting pseudo-ranges. $\Delta s = 40.3 \times 10^{16}\ TEC / f^{2}$ (m)

Algorithm Validation using IGS



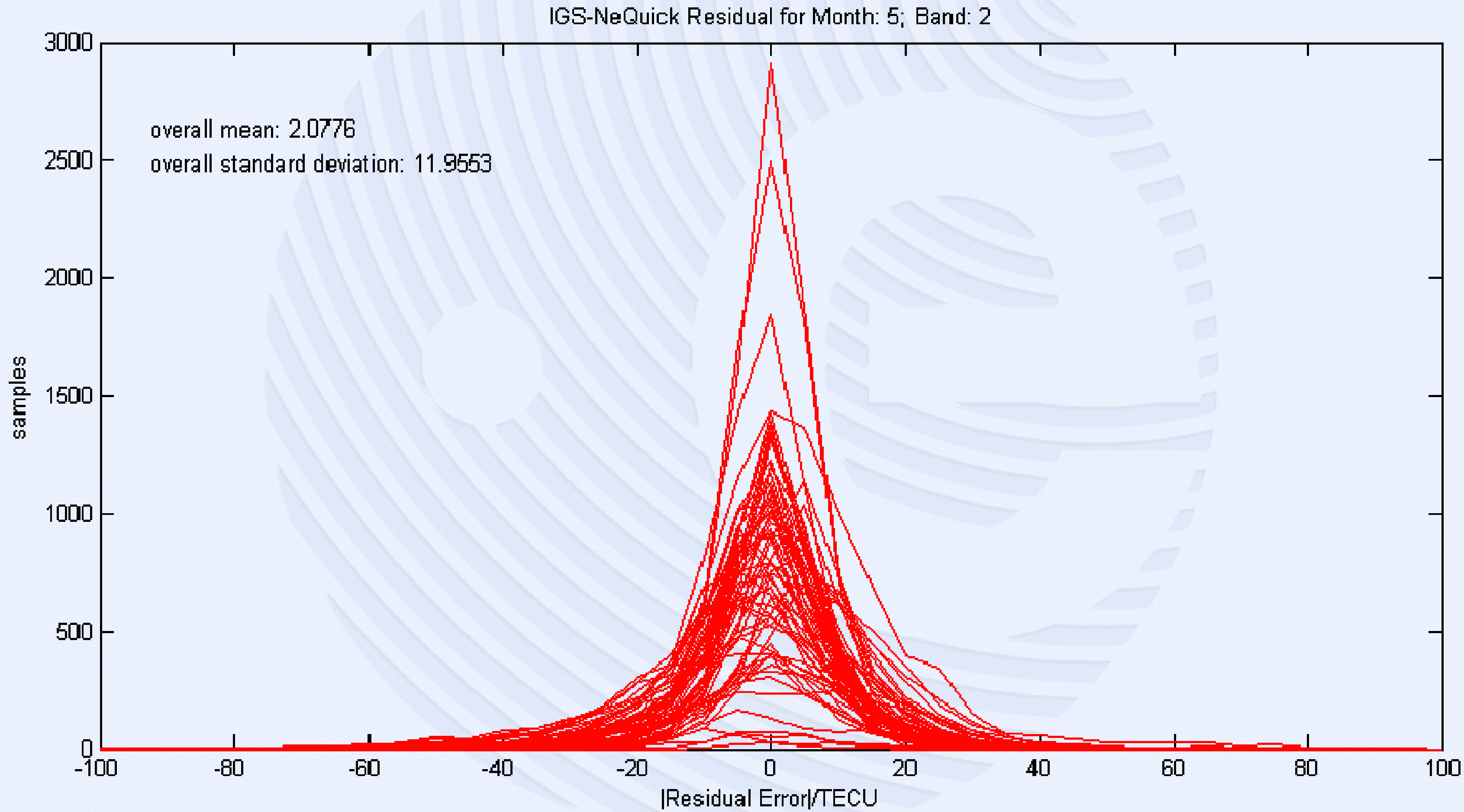
Some IGS stations were used as reference stations to create the broadcast message, the others were used as "test stations were the SF-algo prediction was compared to the actual slant TEC

Algorithm Validation Results



May 2000, Equatorial Region (Band 3)

Algorithm Validation Results



May 2000, Northern Medium Region (Band 2)

Conclusions

- The Correction for Single Frequency receivers is important, even for multi frequency receivers
- The Galileo SF algorithm is based on a 3D Ionospheric Model (rather than the thin-shell approach of GPS)
- First analyses of the Galileo SF algorithm have shown satisfactory performance

Thank

You!