The Abdus Salam International Centre for Theoretical Physics
50th Anniversary 1964-2014

NeQuick model performance analysis for GNSS mass market receivers positioning

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PArthenope Navigation Group (PANG)

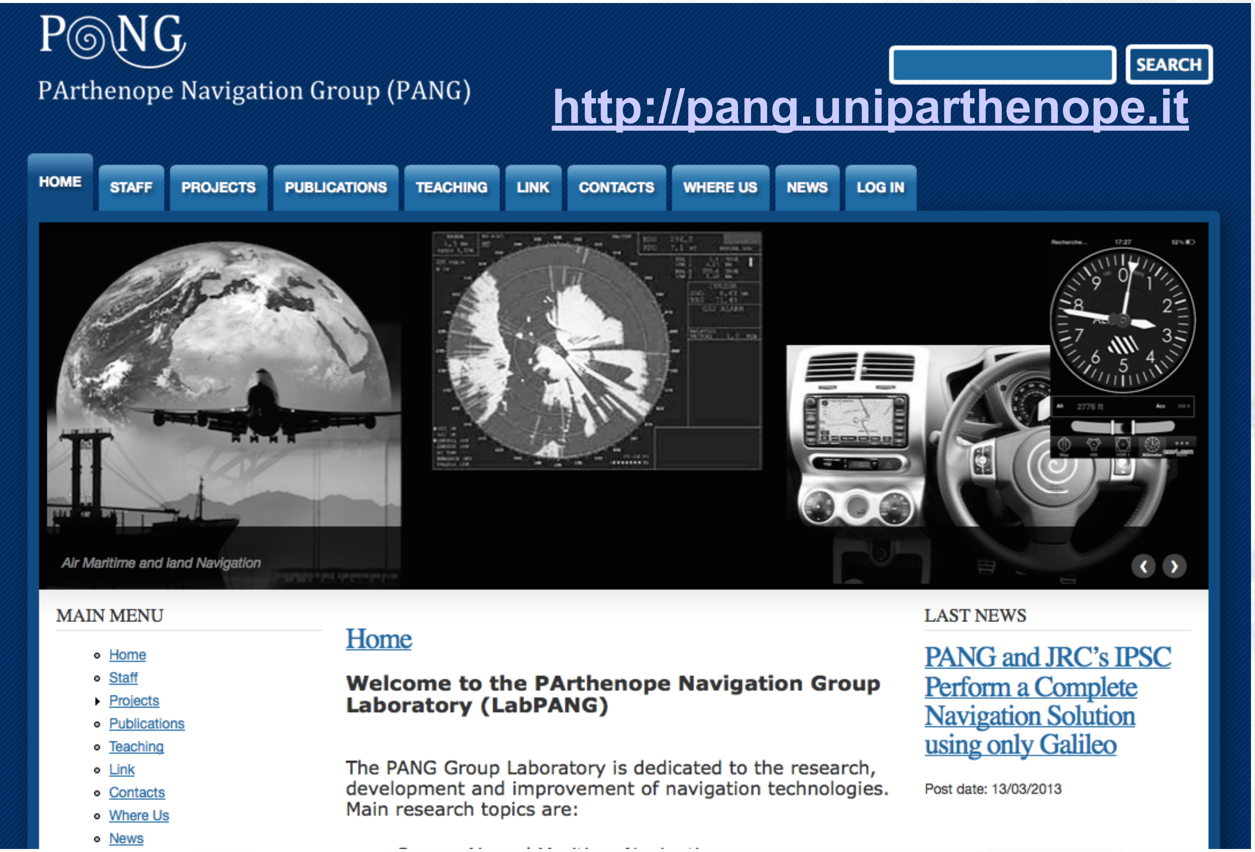
UNIVERSITA' DEGLI STUDI DI NAPOLI PARTHENOPE

PANG

Research Group composed by: Researcher, Post Doc, PhD Student, MSc

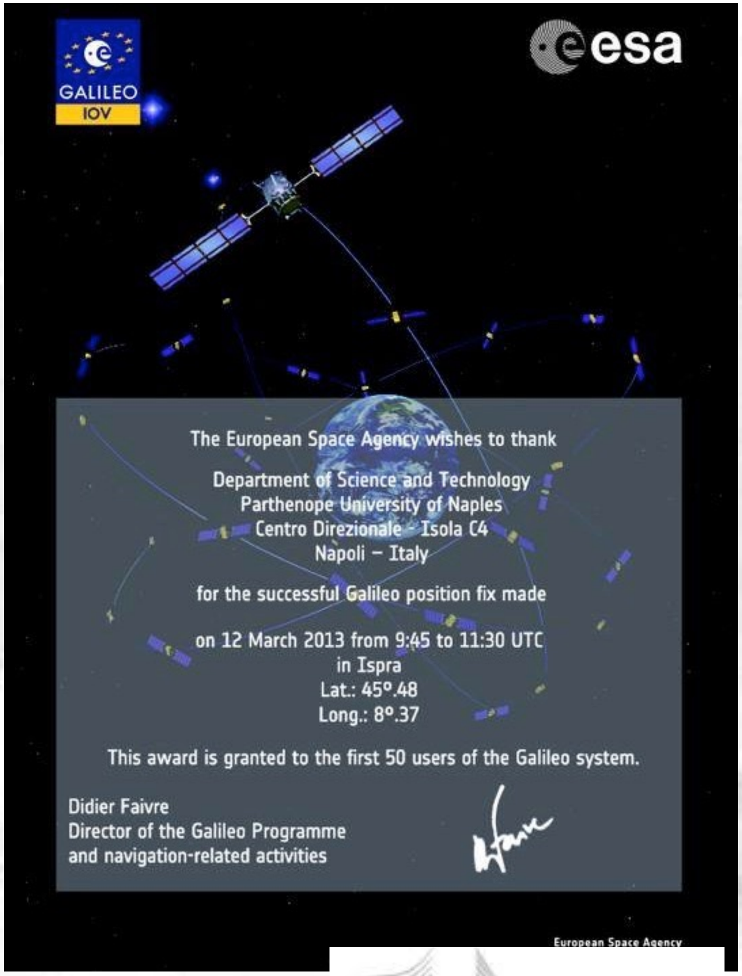
EDCN

PNRA



PANG

Galileo Fix certificate



NAVIGATION GROUP

European Commission
Joint Research Centre

Outline

- Objective
- GNSS Systems
- Ionosphere and GNSS
- PANG ionospheric activities
- Test and Results
- Conclusions

Objective

GNSS Devices:

- **Professional Receivers (Double Frequencies, High Accuracy & Costs)**

- **Mass Market Receivers:**
  - **single frequency receivers (~75% of all GPS devices), operating in single point positioning**
  - **mass market receivers**
  - **smart phone and tablet (~100*106 units per year)**
  - **in-car GNSS device (~10*106 units per year)**
  - **Ionospheric effects are the most important error sources for the segment of interest**

Error Budget

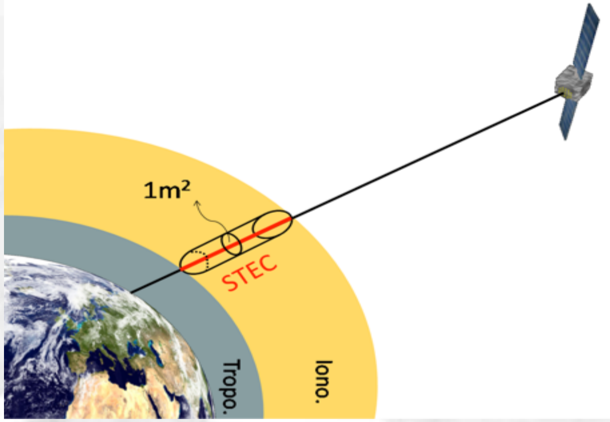
- **Single Point Positioning**
- **Single Frequency**
- **Open-sky**

Error Source	1 σ [m]
Satellite Clock	1.1
Ephemeris	0.8
Ionosphere	4.0
Troposphere	0.2
Multipath	0.2
Receiver Noise	0.1
UERE	**4.2**

Ionosphere and GNSS

Effects of Ionosphere on GPS (GNSS)

- code (pseudorange) delay
- range-rate (Doppler shift) error
- Faraday rotation
- angular refraction
- distortion of pulse waveforms
- scintillation



$$\Delta I = 40.3\frac{TEC}{f^2}$$

$$\rho = d + cdt_u + cdt_s + \Delta I + \Delta T + \varepsilon_\rho$$

$$\dot{\rho} = \dot{d} + c\dot{d}t_u + c\dot{d}t_s - \Delta \dot{I} + \Delta \dot{T} + \varepsilon_\rho$$

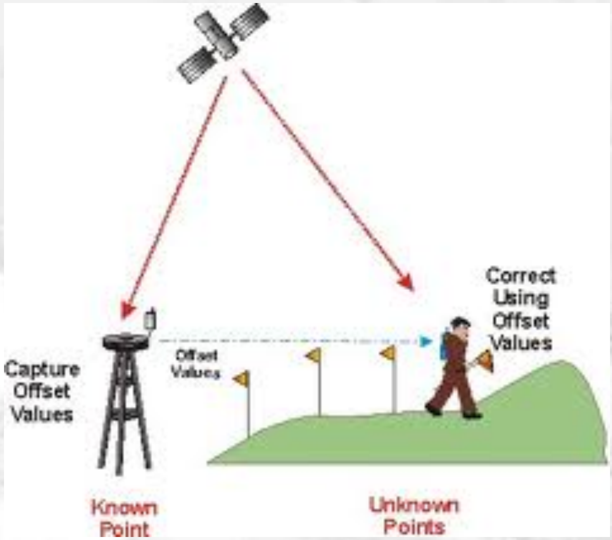
Ionosphere and GNSS

Strategies for the Iono-Effects Reduction

- multiple frequency combination: Iono-Free

$$\rho_{IF} = \frac{\rho_{L2} - \gamma \cdot \rho_{L1}}{1-\gamma} \cdot \gamma = \left(\frac{f_{L1}}{f_{L2}} \right)^2$$

- Differential GNSS Positioning: DGPS, SBAS



Ionospheric models: single frequency and single point positioning

~75% of all GPS receivers are Single Frequency

Ionospheric Models

- Klobuchar
  - adopted by GPS
  - single layer model
  - 50% or better RMS correction of the ionospheric time-delay

- NeQuick
  - 3-D model
  - 75% or better RMS correction of the ionospheric time-delay

- belongs to DGR profilers (1990 Di Giovanni & Radicella)

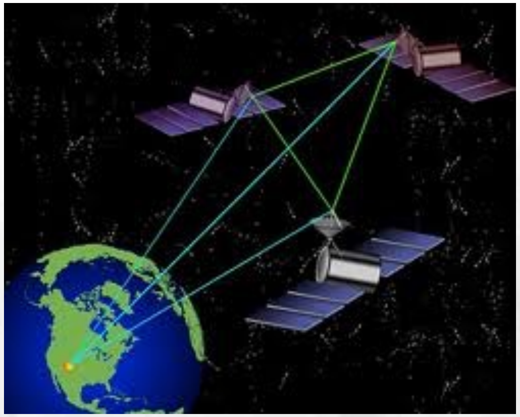
- NeQuick 1
  - Developed by ITUR

- NeQuick Galileo version (NeQuickG)
  - Developed by ESA

Klobuchar Model

Model Input

- Receiver coordinates (latitude, longitude, altitude)
- satellite elevation and azimuth
- Measurement epoch (Universal Time)



4 coefficients for A
4 coefficients for P

GPS Navigation Message

```
     2.10           N: GPS NAV DATA                   RINEX VERSION
teqc  2009Oct19      CORS-ADM Account    20100326 23:45:04UTCPGM
Solaris 5.10|UltraSparc IIIi|cc SC5.8|=+|*Sparc              COMMENT
      2              NAVIGATION DATA                          COMMENT
RINGO/GLOBAL         NATIONAL GEODETIC SURVEY                 COMMENT
    1.1176D-08  7.4506D-09 -5.9605D-08 -5.9605D-08        ION ALPHA
    9.0112D+04  0.0000D+00 -1.9661D+05 -6.5536D+04        ION BETA
```

NeQuick Model

Inputs and auxiliary files

- receiver location (latitude, longitude, altitude)
- satellite location
- month
- Universal Time (UT)
- Effective ionization parameters [a_0 a_1 a_2]
- MODIP (Modified DIP latitude) grid
- ITU-R (or CCIR) maps

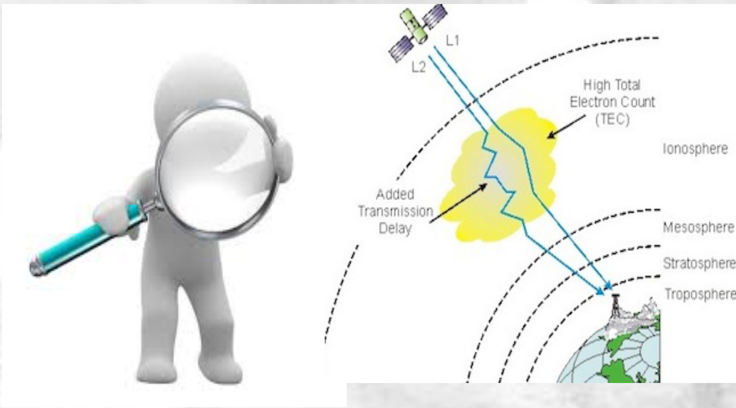
- MODIP grid allows the estimation of μ at a defined location;
- μ + [a_0 a_1 a_2] (Galileo Navigation Message) are used to compute the Effective Ionization level (Az)

PANG Ionospheric Activities

2011/12: NeQuick 1 performance analysis (position and measurement domain); Az parameters computation

2013: NeQuick G* performance evaluation (positon domain) Az parameters computation

2014: NeQuick G* validity period, Az parameters from Galileo navigation message

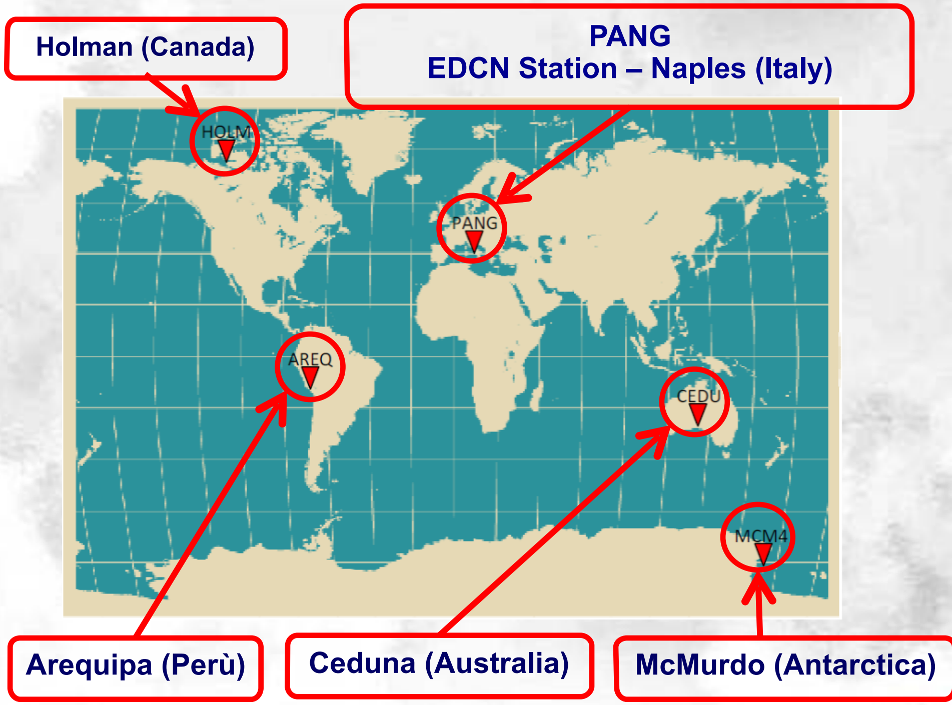


The software used for part of the work here presented in this paper have been provided by the European Space Agency. The views presented represent solely the opinion of the authors and should be considered as research results not strictly related to Galileo or EGNOS Project design

Test and Results – 2011

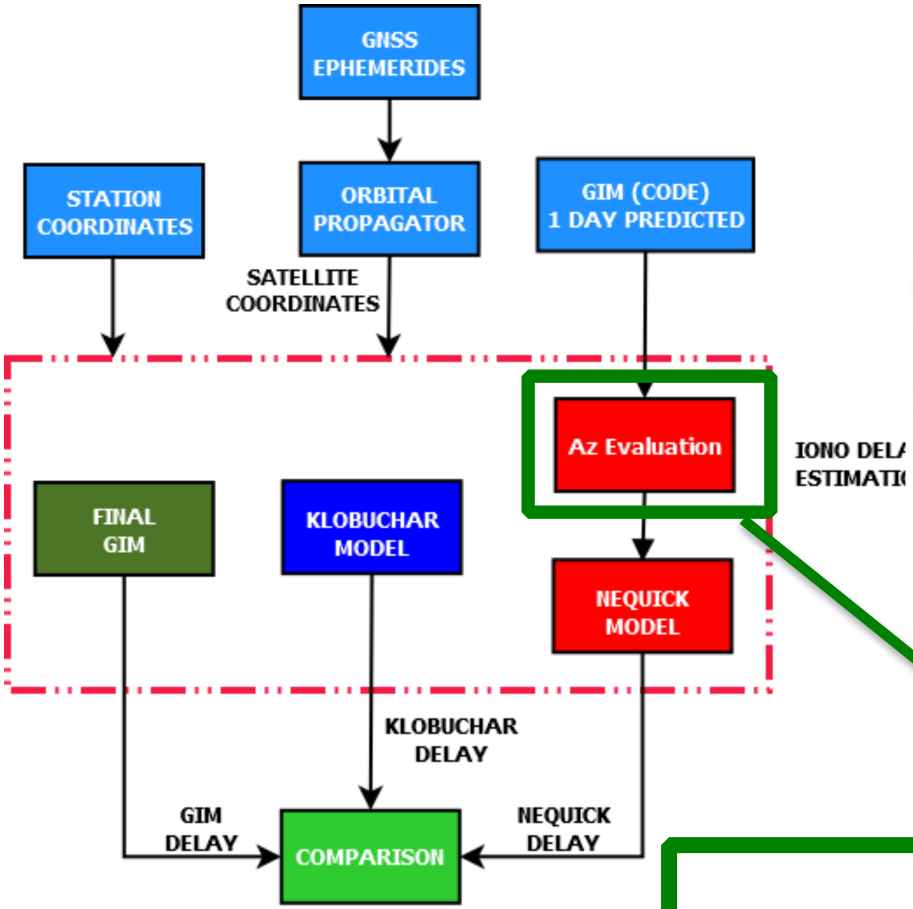
- **Models analyzed: NeQuick 1 (Az computation) vs Klobuchar vs GIM**
- **Goals: measurement analysis**
- **Data used: several days in the years 2008-2010 featured by different geomagnetic activities and from five stations**

Geomagnetic Activity	Ap index	DOY/ YEAR
Light	0	257/2008
	0	316/2009
	1	016/2010
	1	344/2010
Medium	18	032/2008
	16	194/2008
	16	175/2009
	26	296/2010
High	36	087/2008
	34	285/2008
	55	095/2010
	36	122/2010
	49	216/2010

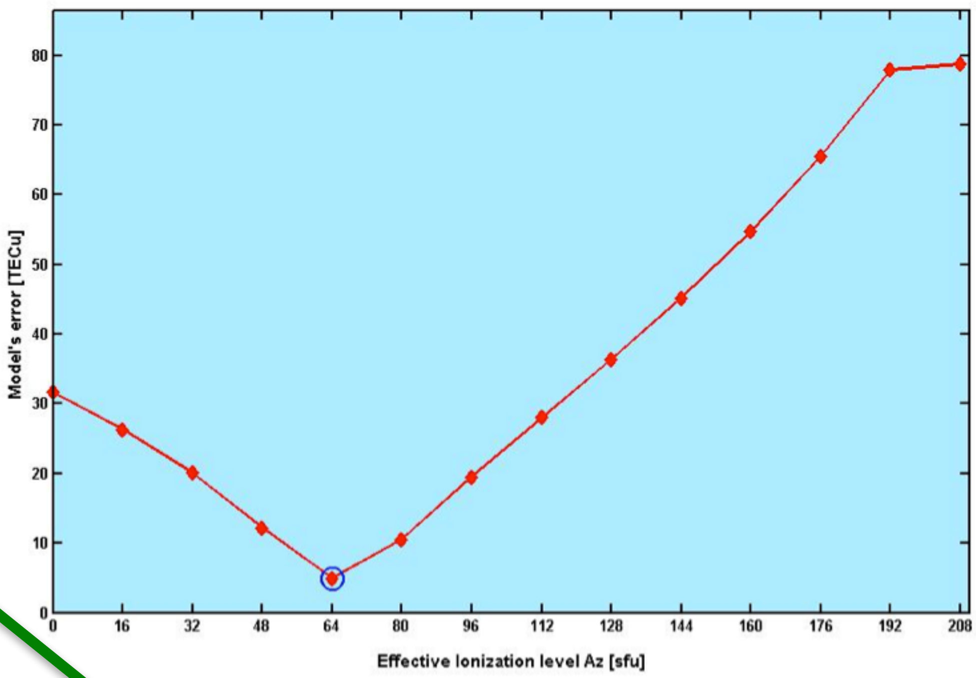


**Angrisano, A., Gaglione, S., Gioia, C., Massaro, M., Robustelli, U. (2013).”Assessment of NeQuick ionospheric model for Galileo single-frequency users”. Acta Geophysica, 61 (6), pp. 1457-1476.*

Test and Results – 2011 studies



Brent Method



$$Az = \arg\min \sum_{i=1}^{n} \left| VTEC_{\text{Reference}} - VTEC_{\text{NeQuick}}(Az) \right|_i^2$$

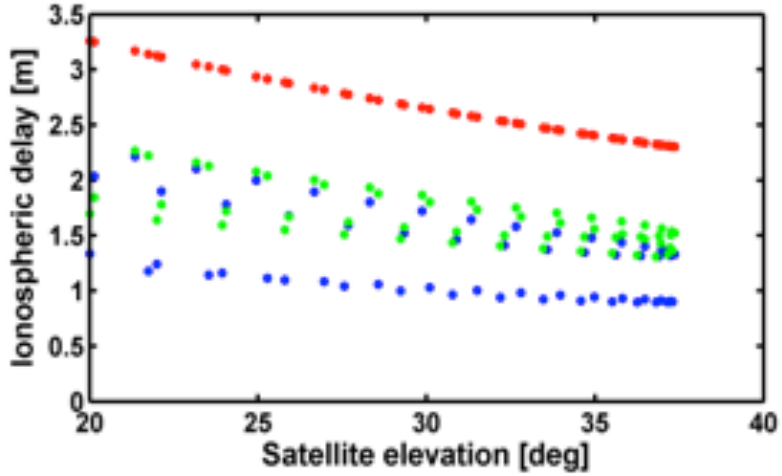
**Memarzadeh, Y. (2009), Ionospheric modeling for precise GNSS applications, PhD thesis, Delft University of Technology*

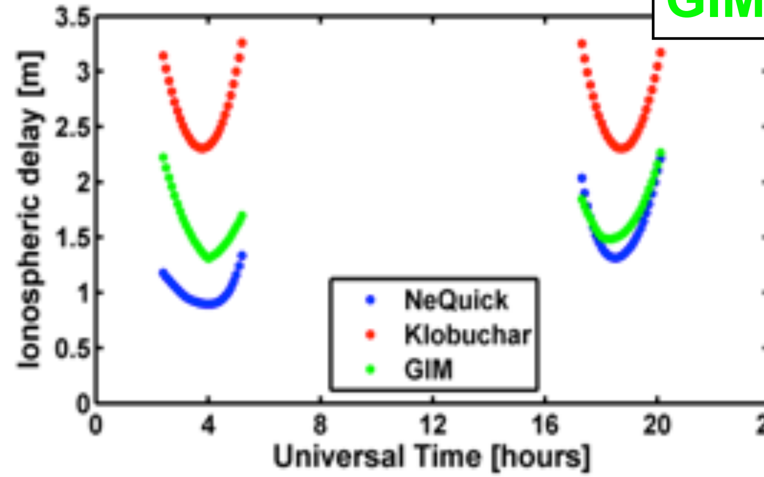
Test and Results – 2011-2012

PANG Station
GPS - SAT12

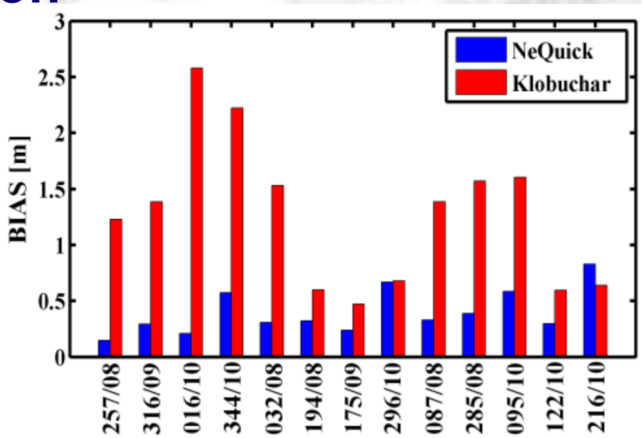
Measurement Domain

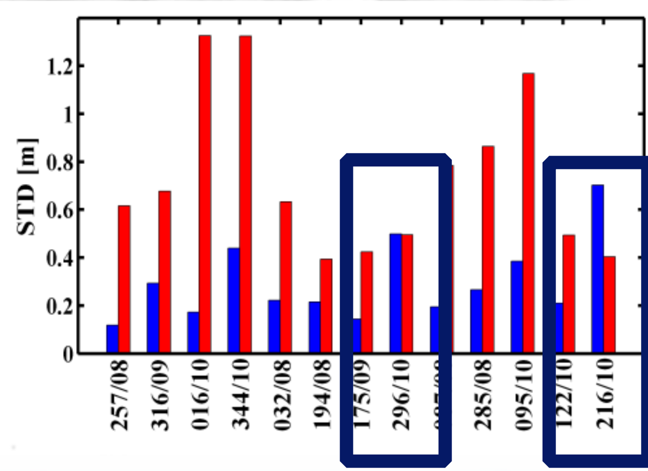
NeQuick 1
Klobuchar
GIM





HOLM Station

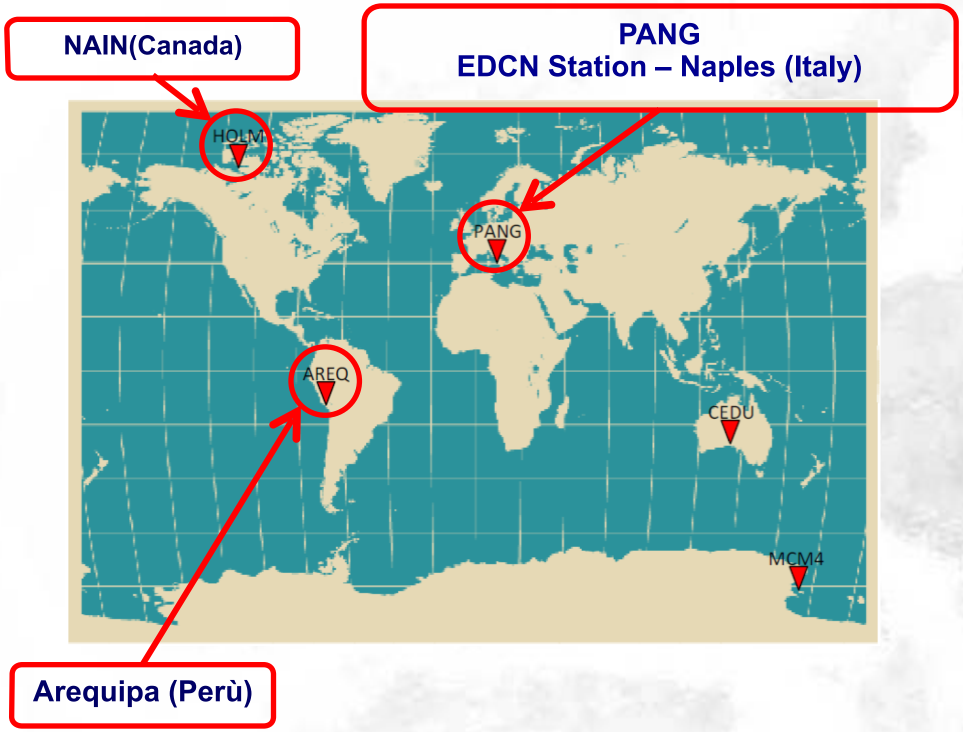


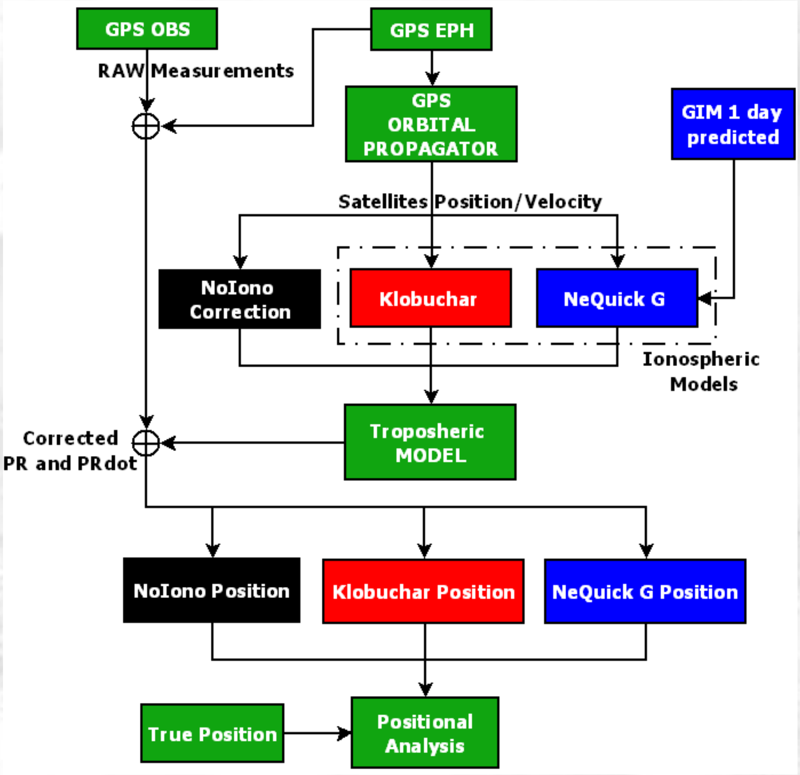


Klobuchar
NeQuick 1

Test and Results – 2013

- **Models analyzed NeQuick G (Az computation) vs Klobuchar vs No-Iono**
- **Goal: Position Analysis**
- **Data used: 3 days on May 2012 from 3 different stations**

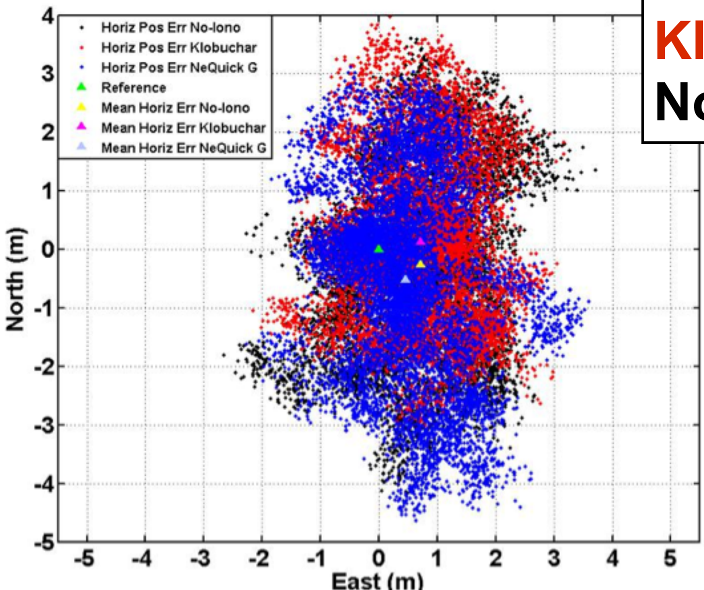




**Angrisano, A., Gaglione, S., Gioia, C., Massaro, M., Troisi, S. (2013). "Benefit of the NeQuick Galileo version in GNSS single-point positioning". International Journal of Navigation and Observation*

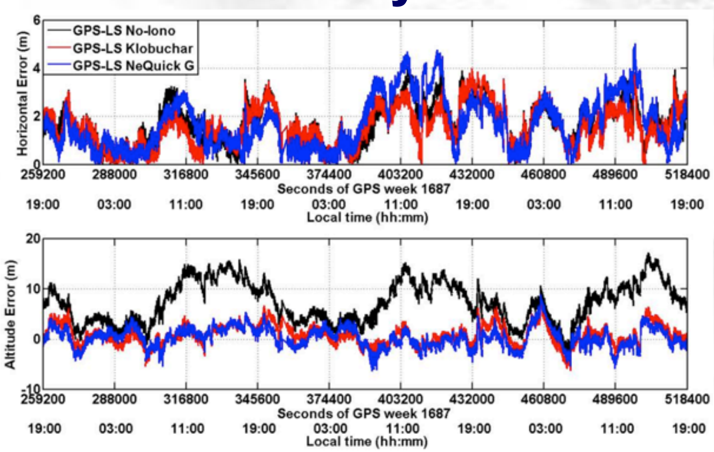
Test and Results – 2013

Horizontal Scatter



NeQuick G
Klobuchar
No-Iono

Error Analysis

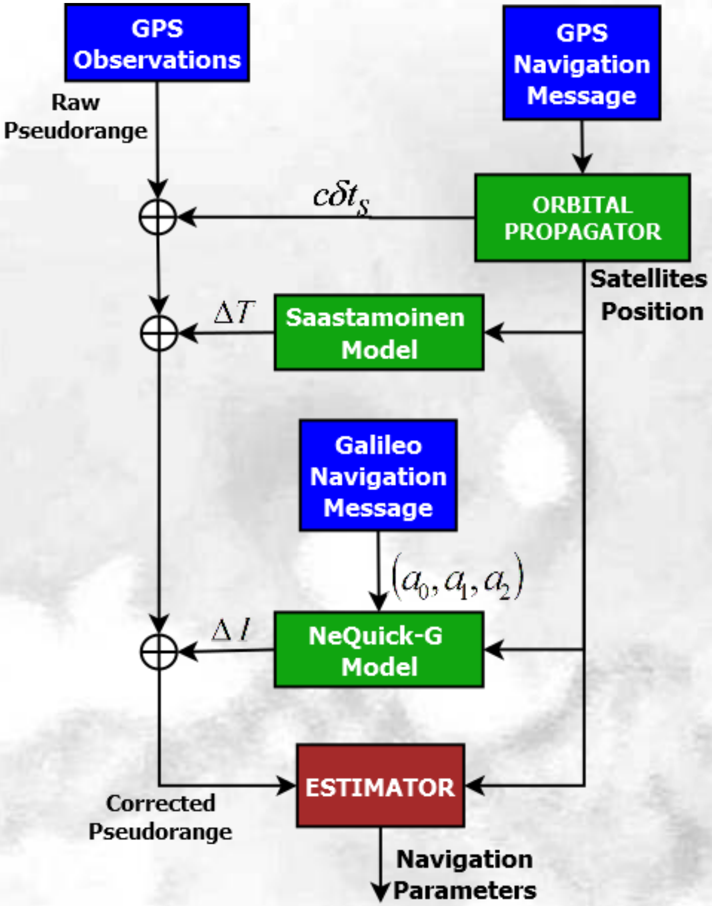


Position Domain Analysis

Ionospheric Model	Station	Up RMS [m]	Hor RMS [m]	Up Max Error [m]	Hor Max Error [m]
Klobuchar	NAIN	1,958	1,548	10,597	7,861
	PANG	2,436	2,053	11.542	6.731
	AREG	2.176	1.763	7.982	3.985
	Overall	2.193	1.793	11.542	7.861
NeQuick G	NAIN	2.057	1.510	11.234	8.305
	PANG	2.834	1.477	10.081	5.926
	AREG	2.065	1.974	8.869	5.035
	Overall	2.335	1.672	11.234	8.305

Test and Results – 2014

- **Models analyzed: NeQuick G (Galileo Navigation Message) vs NeQuick G validity period**
- **Performance and computational analysis**
- **Static (24 hours, 3rd March 2014)**
- **Kinematic test**
- **Target to mass market receivers**

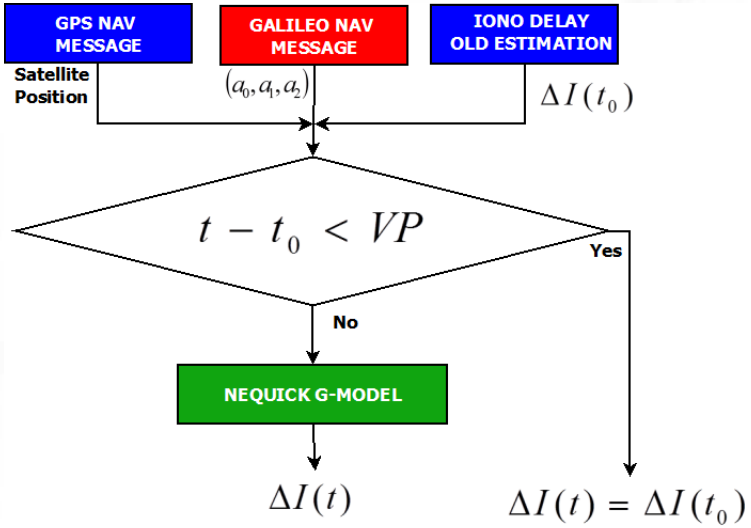


Angrisano, A.; Gaglione, S.; Gioia, C.; Troisi, S., "Validity period of NeQuick (Galileo version) corrections: Trade-off between accuracy and computational load," Localization and GNSS (ICL-GNSS), 2014 International Conference on , vol., no., pp.1,6, 24-26 June 2014 doi: 10.1109/ICL-GNSS.2014.6934183

Validity Period of NeQuick Corrections

What is the Validity Period (VP) of NeQuick Corrections?

- Scheme for the NeQuick iono-correction update:
  - t current epoch;
  - t_0 last update epoch



- VP is progressively increased in order to Identify a trade-off between position performance and computational load
- Position performance: RMS/maximum horizontal/vertical errors
- Computational load: number of NeQuick calls and time spent to process a defined data set n

$$n_r = \sum_{i=1}^{k} n_i$$

where:

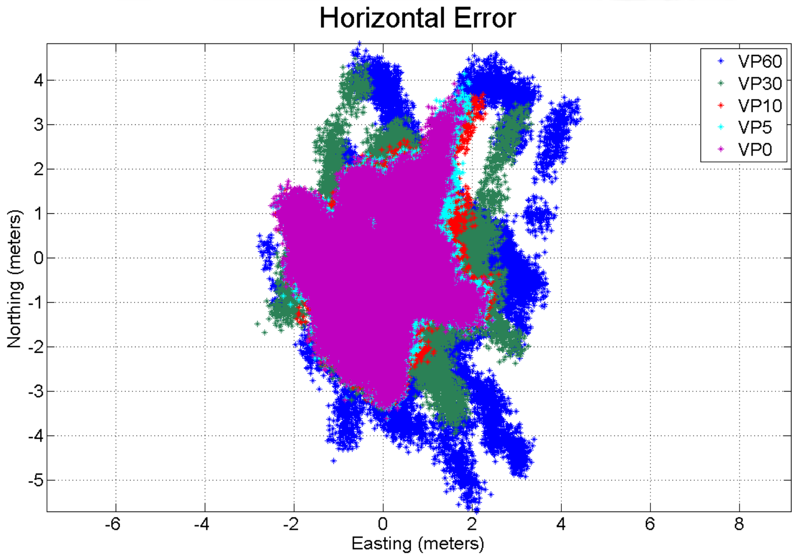
n_r number of NeQuick Model calls

k number of test epochs

n_i number of visible satellites (no propagation)

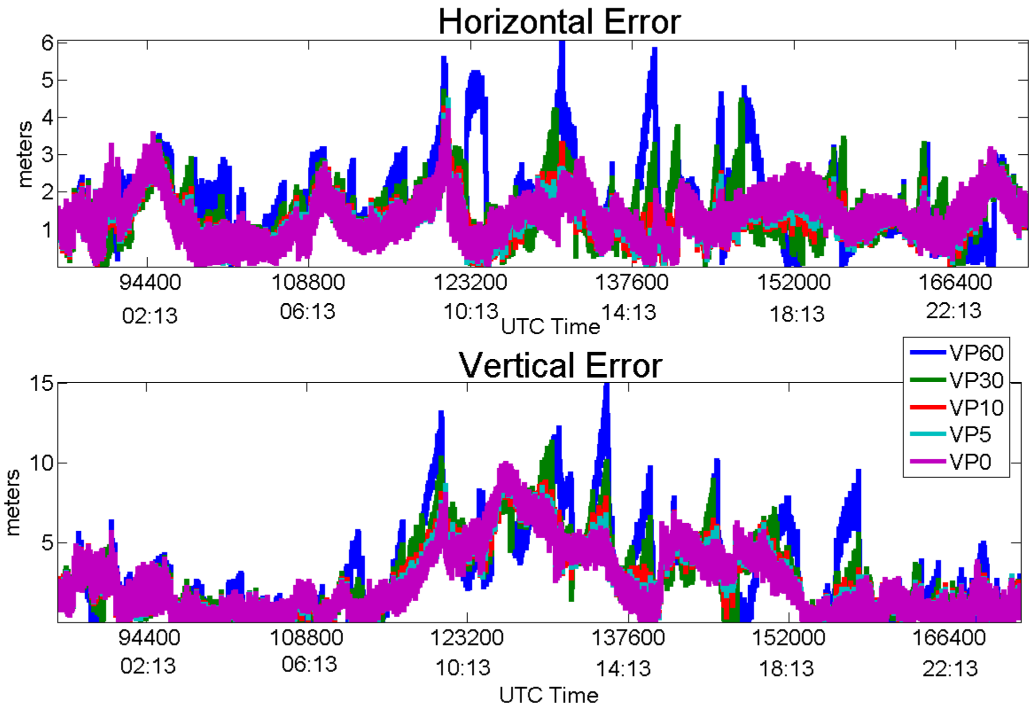
Static Session

- $VP = k\,minutes$ is indicated as VPk
- Considered VPs: $VP0, VP5, VP10, VP30, VP60$



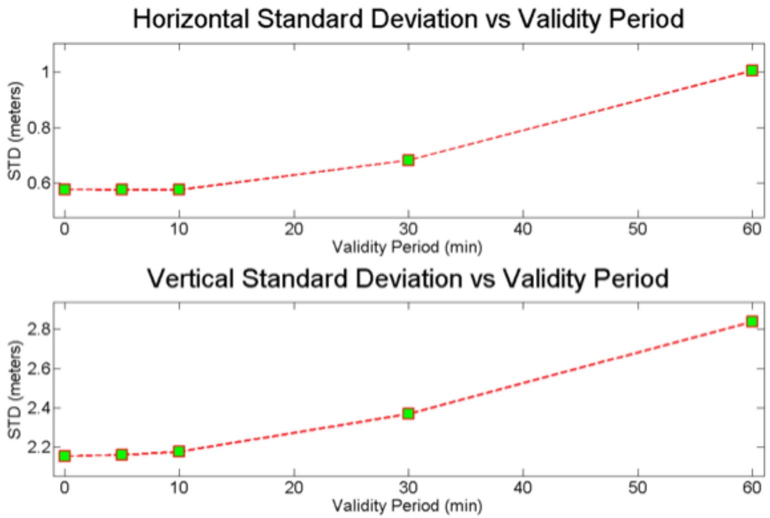
Horizontal Scatter

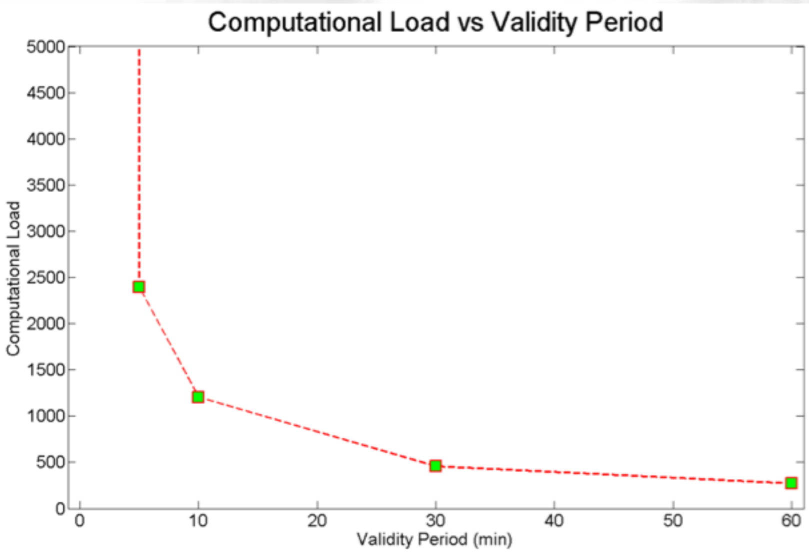
Error Analysis



Test and Results – 2014

Error STD vs VP





VP (min)	H RMS (m)	U RMS (m)	H Max Error (m)	U Max Error (m)	Run Time* (min)	Nr of NeQuick calls
0	*1.45*	*3.26*	*4.24*	*10.12*	*750*	*709087*
5	*1.43*	*3.29*	*4.52*	*9.96*	*12.4*	*2396*
10	*1.42*	*3.32*	*4.52*	*10.11*	*11.2*	*1206*
30	*1.56*	*3.59*	*4.75*	*11.44*	*10.5*	*455*
60	*1.98*	*4.22*	*6.07*	*15.08*	*10.4*	*269*

***** time spent by the workstation (3 cores processor @ 3.20 GHz) to process the whole data***

Test and Results – 2014

Kinematic Session

- **March 2014 Naples suburb area**
- **ublox LEA-6T receiver**

- **Considered VPs: *VP0, VP5, VP10, VP15***

Validity Period (min)	H RMS (m)	U RMS (m)	Run Time (min)	Nr of NeQuick calls
0	*3.61*	*5.08*	*10.33*	*11370*
5	*3.82*	*5.29*	*<1*	*163*
10	*4.03*	*5.51*	*<1*	*147*
15	*4.01*	*5.52*	*<1*	*127*

Conclusions

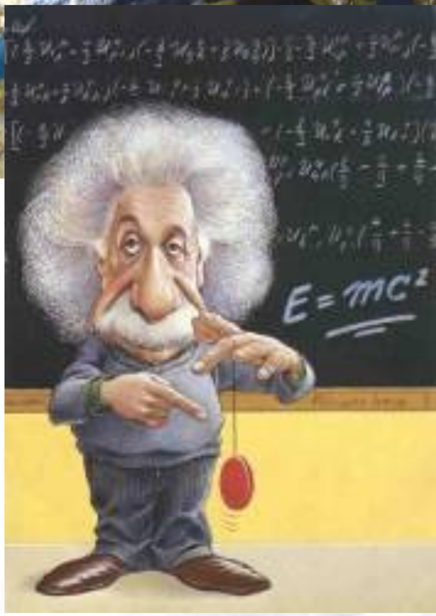
- **Overview on PANG activities on NeQuick Models;**

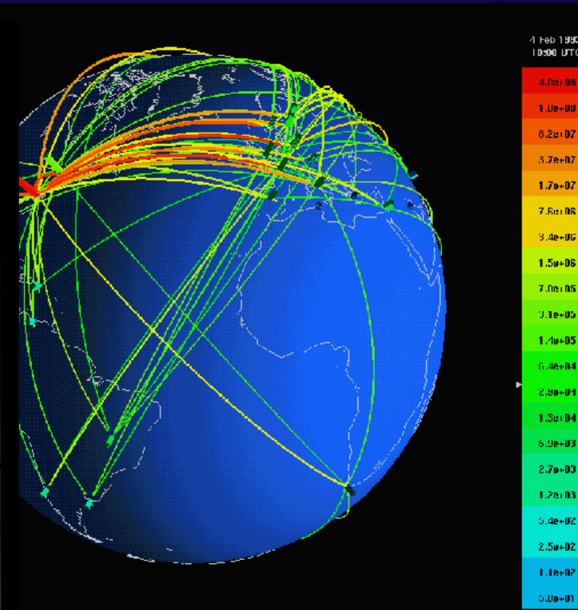
- **From the performance analysis in measurement Domain (2011): NeQuick 1 model more close to GIM with respect to Klobuchar; except for one day of medium activity (296/10) and one of heavy condition (216/10);**

- **From the performance analysis in Position Domain (2013 -14): The NeQuick G model has better results for Horizontal RMS and for Vertical and Horizontal Maximum Error (in middle latitude).**

- **NeQuick VP was proposed (2014):**

  - **VP=10 minutes: trade-off between position accuracy and computational load**





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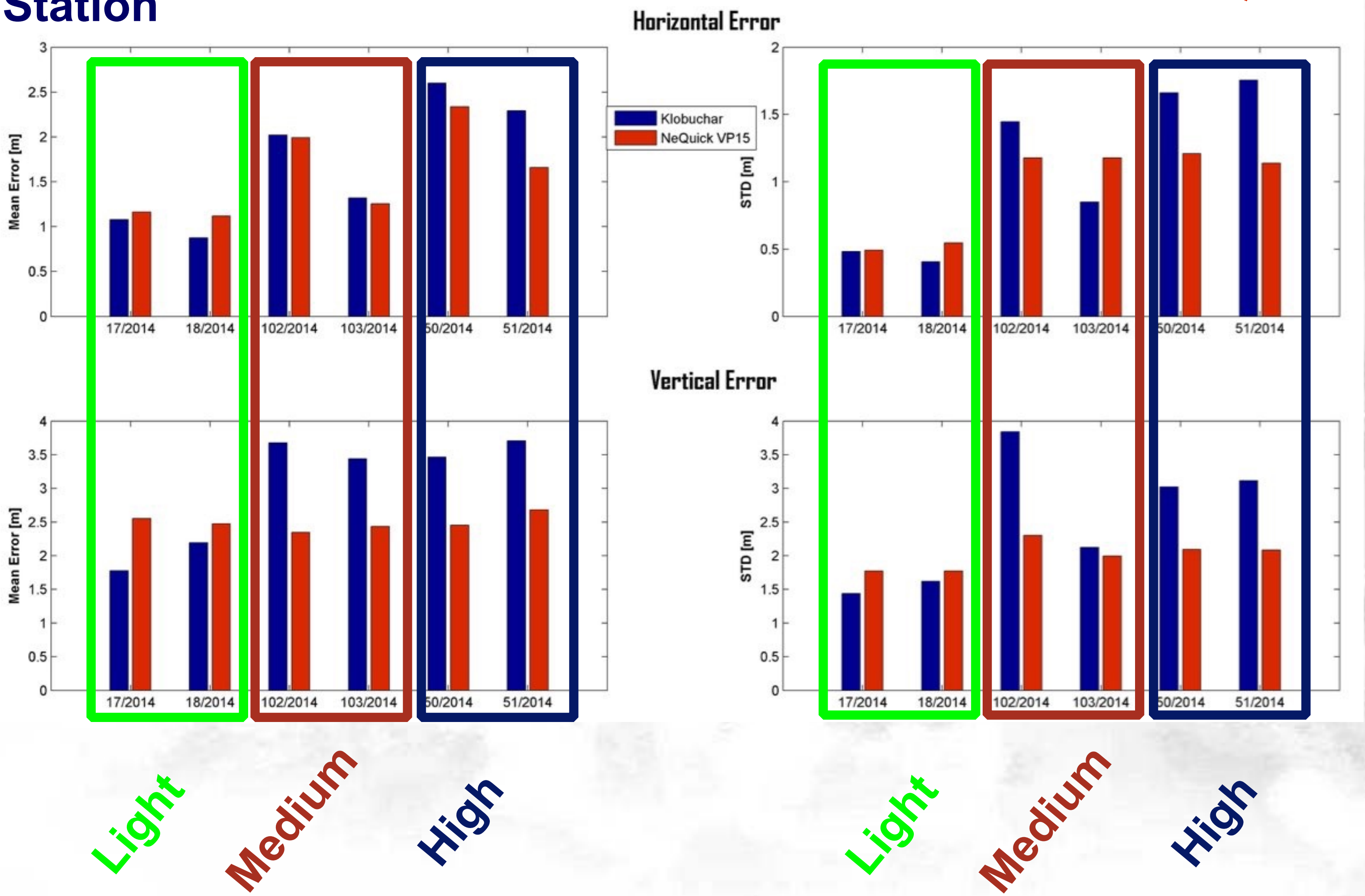
Thanks for the attention

Geomagnetic Activity Influence

AREG Station

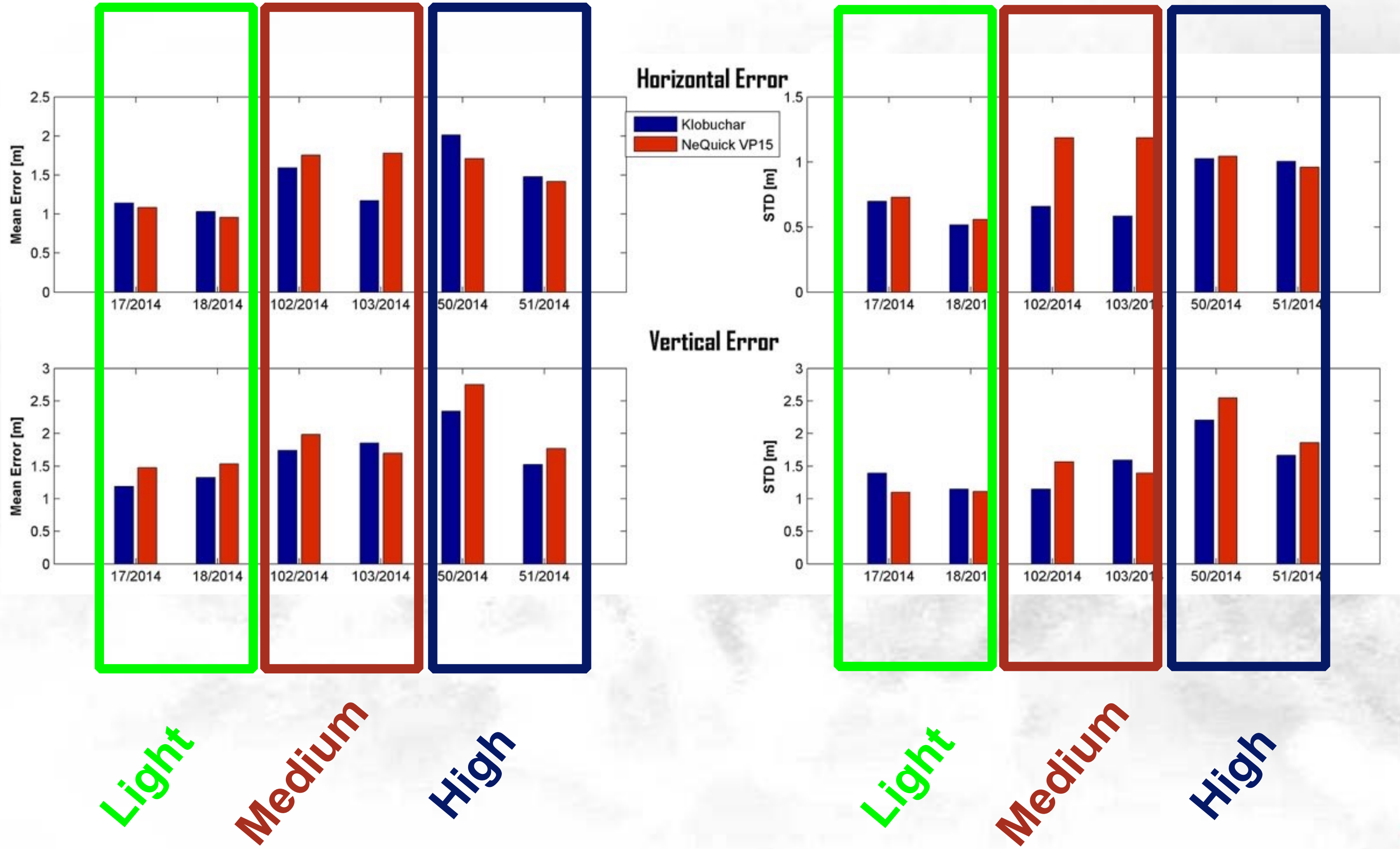
Klobuchar
NeQuick G



Geomagnetic Activity Influence

TLSE Station

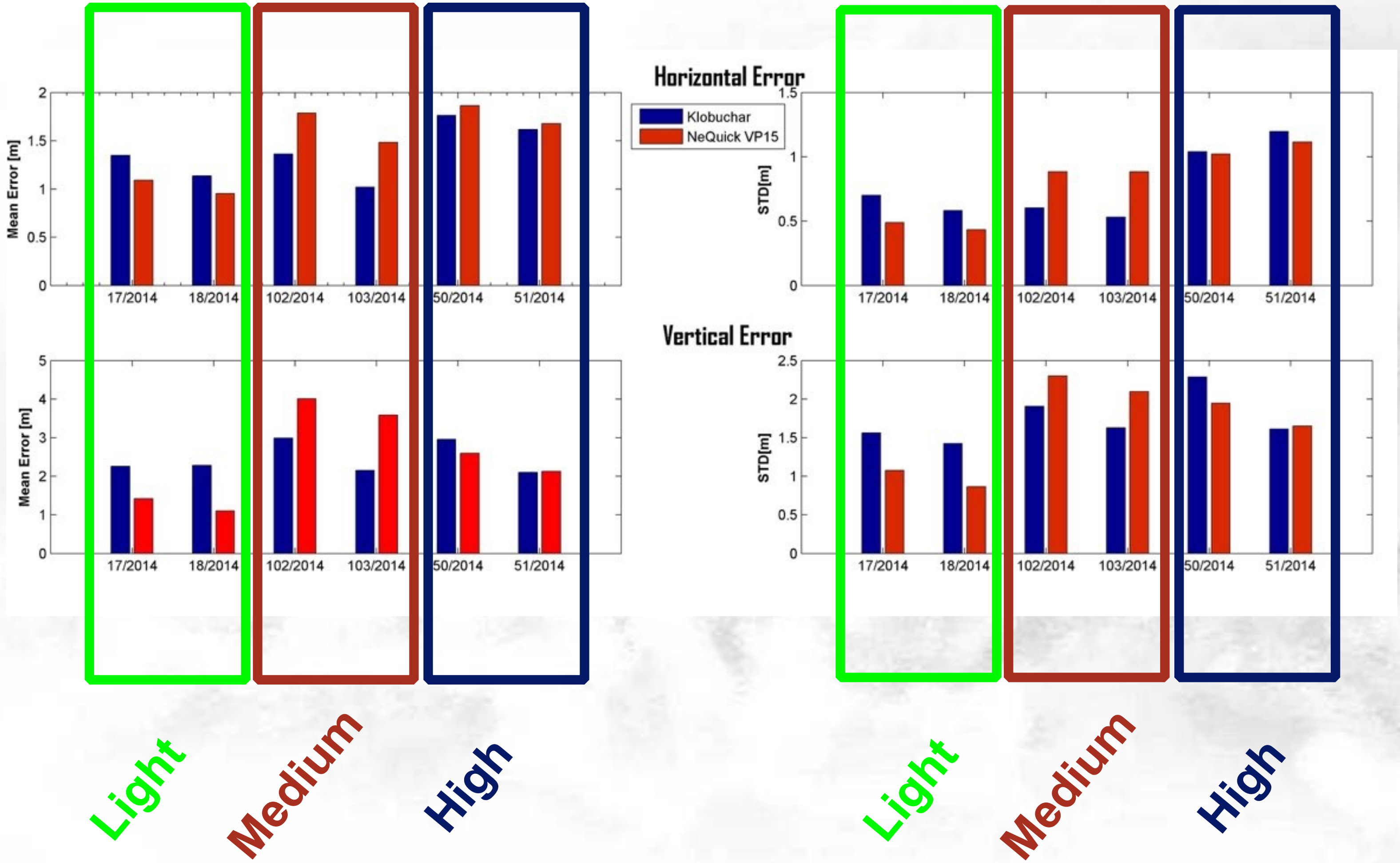
Klobuchar
NeQuick G

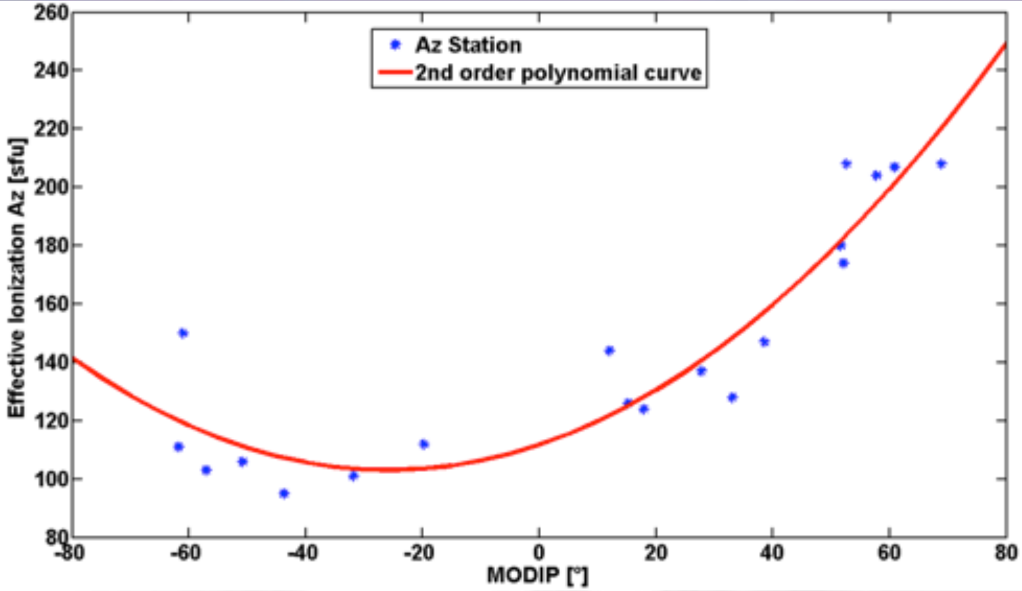


Geomagnetic Activity Influence

KIR8 Station

Klobuchar
NeQuick G





Az parameter is modeled by a second order polynomial

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

$$Az = \arg\min \sum_{i=1}^{n} \left| VTEC_{\text{Reference}} - VTEC_{\text{NeQuick}}(Az) \right|_i^2$$

IGS Stations

Station	Latitude	Longitude	Height
HOLM	70,7364	-117,7609	39,5000
NAIN	56,5370	-61,6887	33,4800
AMC2	38,8031	-104,5246	1912,4898
MKEA	19,8014	-155,4563	3755,0000
CR01	17,7569	-64,5843	-31,9558
BOGT	4,6401	-74,0809	2576,7782
SANT	-33,1503	-70,6686	723,0746
PALM	-64,7751	-64,0511	31,2394
TGCV	16,7548	-22,9828	35,0000
RECF:	-8,0510	-34,9515	20,2000
BUCU	44,4639	26,1257	143,2000
SIMO	-34,1879	18,4396	39,4910
SYOG	-69,0070	39,5837	50,0902
IRKT	52,2190	104,3162	503,3816
GUAO	43,4711	87,1773	2049,2000
PIMO	14,6357	121,0777	95,5320
GUAM	13,5893	144,8683	201,9220
KARR	-20,9814	117,0972	109,2468
MAC1	-54,4995	158,9358	-6,6900

$VTEC_{\text{Reference}}$ = GIM (2 hours resolution)

n is the number of observations from a station for all satellites in a day

Test and Results(2014)- NeQuick-G model

ID	City	Location	Latitude (deg)	Longitude (deg)	Height(m)
AREG	Arequipa	Peru	*16.4654*	*-71.4929*	*2489.3391*
TLSE	Toulouse	*France*	*43.5607*	*1.4809*	*207.1937*
KIR8	Kiruna	*Sweden*	*67.8775*	*21.0602*	*497.9820*

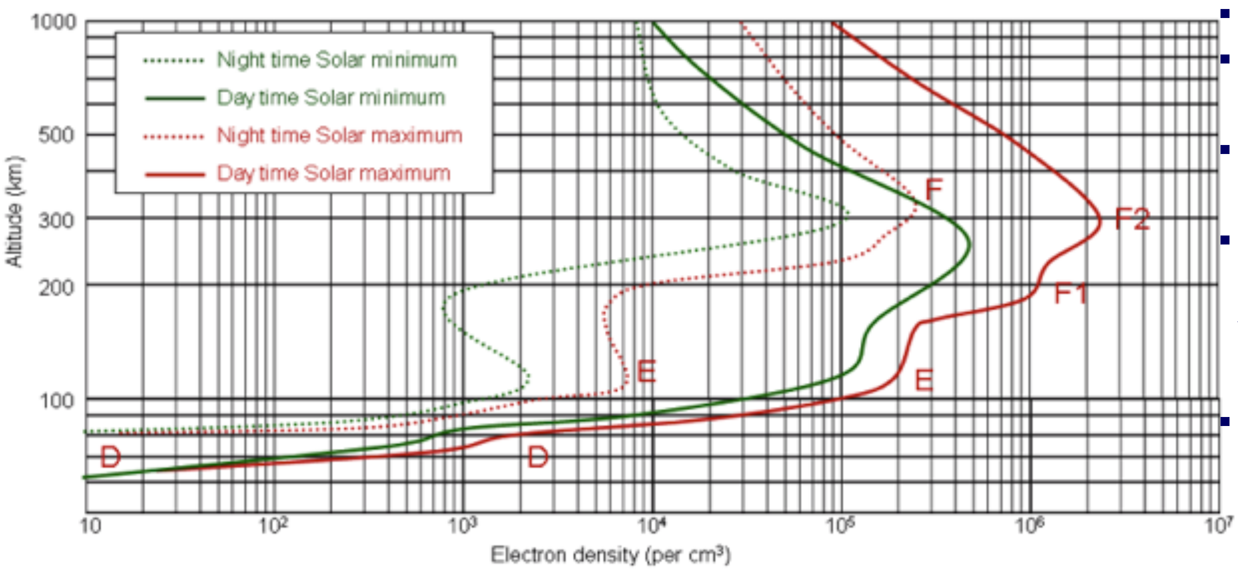
Static Session

- One week, 30 sec
- from 236/2012 to 242/2012

STATION	DOY	Models	Hor RMS	Up RMS	Hor Max	Up Max
AREG	236-242	Klobuchar	1,3053	3,2210	4,4696	12,9320
		Nequick	1,4005	2,7667	4,7691	11,7484
		NeQuick_VP15	1,4301	2,8308	5,1617	12,9429
TLSE	236-242	Klobuchar	1,6266	2,0986	7,2696	13,1145
		Nequick	1,1607	1,8675	6,2978	11,0737
		NeQuick_VP15	1,1871	1,9088	5,3209	12,9804
KIR8	236-242	Klobuchar	1,2260	2,0535	6,0199	12,2046
		Nequick	1,1676	2,0617	5,5048	12,8685
		NeQuick_VP15	1,1512	2,1259	5,3853	11,0145

Ionosphere

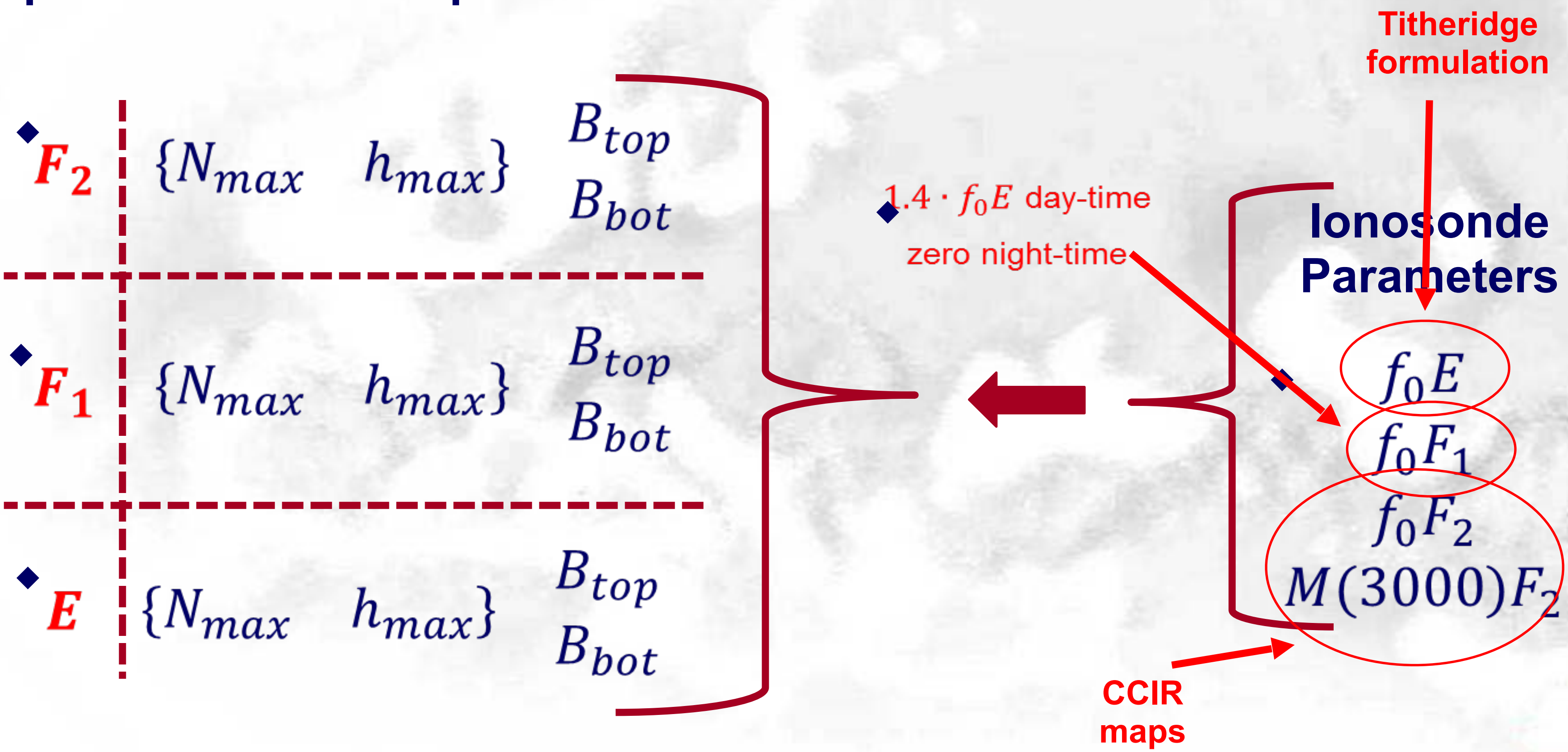
- atmospheric region with gases ionized by solar radiation
- extending, in various layers, from about 50 to 1000 km
- dispersive medium (frequency-dependent) wrt the GPS radio signal
- varies widely from day to day and also has a large diurnal fluctuation
- electrons density N_e produces most of the effects on GPS signals



- D, 50-90 km, no effects on GPS
- E, 90-140 km, minimal effects on GPS
- F1, 140-210 km, up to 10% of the ionosphere delay of GPS signals
- F2, 210-1000 km, is the most dense and has the highest variability, causing most of the potential effects on GPS
- H+, >1000 km, low density, extends up to the GPS orbital height

NeQuick Model

- uses the peaks of the E, F1 and F2 layers as anchor points
- 6 semi-Epstein layers
- 12 parameters to compute



NeQuick 1 Vs NeQuick G

INPUT

Real Time

Solar Flux

(12 months mean)

↓

NeQuik 1

Effective Ionoization Level

↓

NeQuik G

MODIP

International Geomagnetic Reference Field (IGRF)

DIPLATS files

↓

NeQuik 1

MODIP file

↓

NeQuik G

NeQuick G

- **based on Epstein layers:**

- **there is a different Epstein amplitudes, E and F1 layer bottom and top thickness, and peak height ***

- The change to **numerical integration method** **

* Leitinger, R.; Zhang, M.-L.; Radicella, S.M.,(2005) An improved bottomside for the ionospheric electron density model NeQuick, Ann. Geophys., Vol. 48, No.3, p. 525-534
** Knezevich, M.; Radicella, S.M. (2004), Development of an ionospheric NeQuick model algorithm for GNSS receivers, in NAVITEC 2004, Noordwijk

Test and Results – 2011 studies

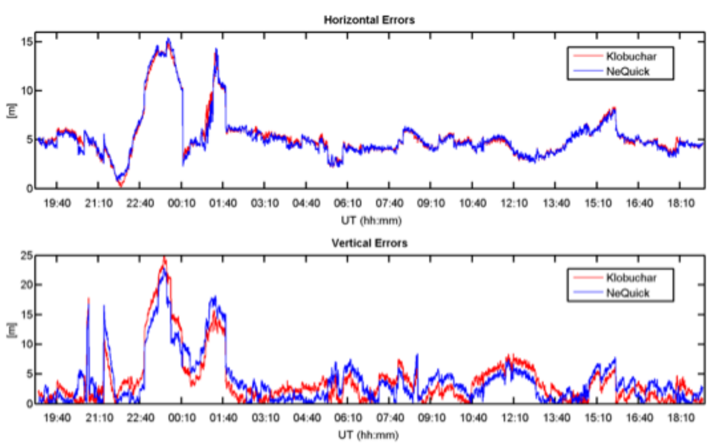
Static Session

- 24 hours, data rate = 30 sec
- 296/10 day
- IGS station Ceduna (Australia) - TRIMBLE NETR8 receiver

TUSREQ Definition

$$STEC \geq 66.7 \Rightarrow \Delta M = 0.3$$
$$STEC < 66.7 \Rightarrow \Delta I = 3.25 \ [m]$$

Position Domain Analysis



Model	RMS		Maximum Error	
	Horizontal	*Vertical*	*Horizontal*	*Vertical*
Klobuchar	5.92	6.01	15.87	22.58
NeQuick	*5.92*	*6.04*	*15.63*	*22.58*

- Horizontal and Vertical Error of two models with the application of TUSREQ parameters

Test and Results – 2011 studies

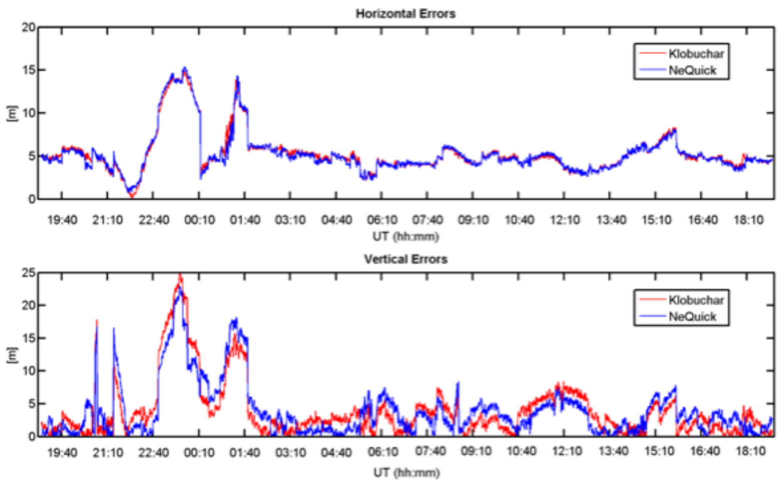
- **Static Session**

Tuned Solution

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

$$STEC < 66.7 \Rightarrow \Delta I = 3.25 \cdot \Delta M_1 \ [m]$$

Position Domain Analysis



$$\Delta M_1 = 3.5 \cdot (1.5 + 0.59 \cdot \sqrt{\cos(El_{SAT})})$$

Model	RMS		Maximum Error	
	Horizontal	*Vertical*	*Horizontal*	*Vertical*
Klobuchar	5.92	6.01	15.87	22.58
NeQuick	*5.78*	*5.76*	*15.43*	*22.92*

- **Horizontal and Vertical Error of two models with the application of Tuned parameters**