Assessment Study of Ionosphere Threat Model using Multi-Shell Algorithm approach over Sub-Saharan African region

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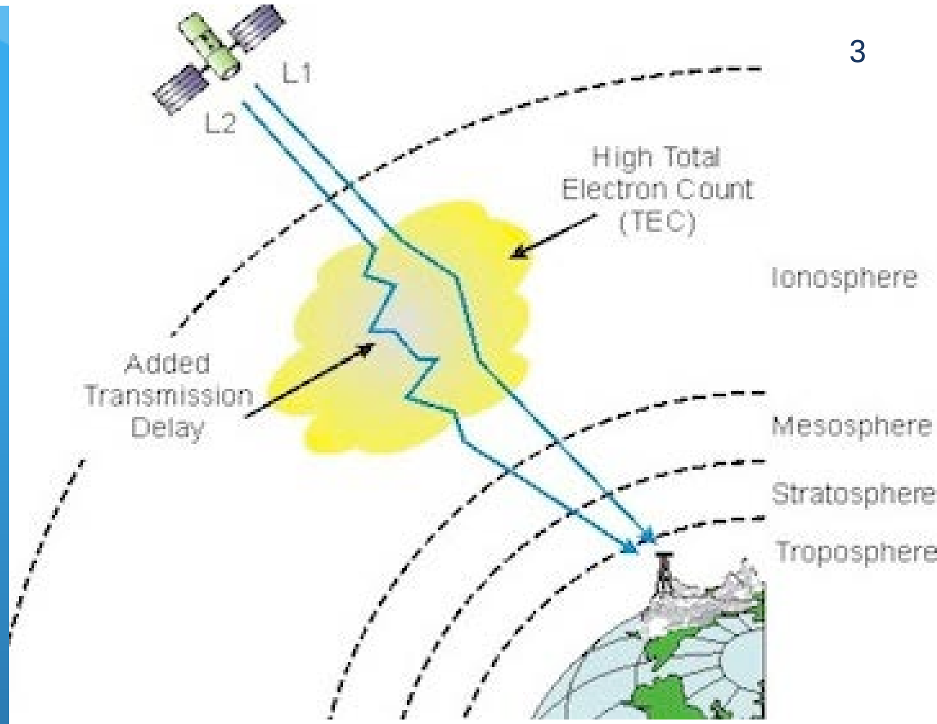
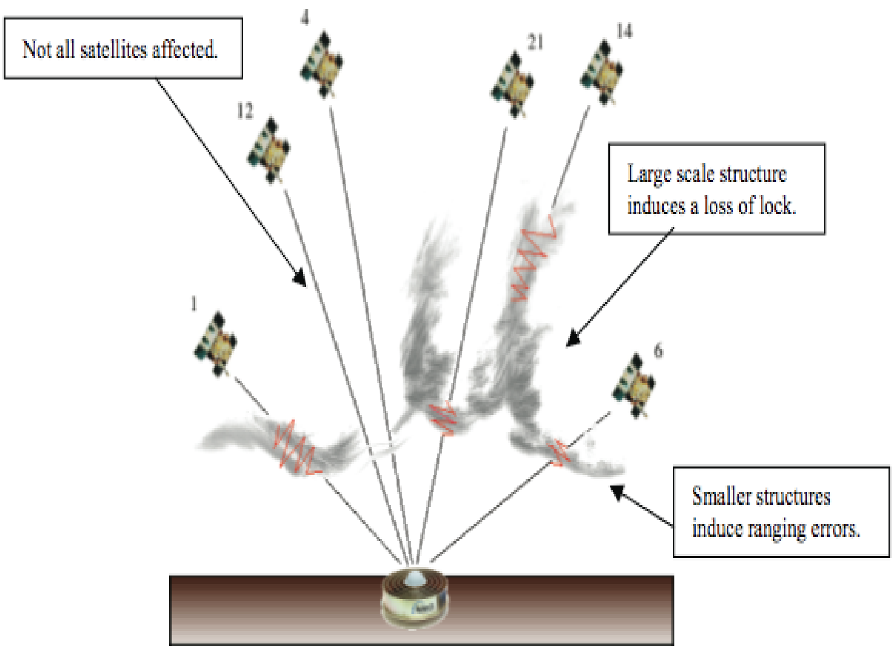
Overview

- Introduction
- Data Source
- SBAS ionosphere corrections algorithm models
- Threat model procedure
- Summary and conclusions

Introduction

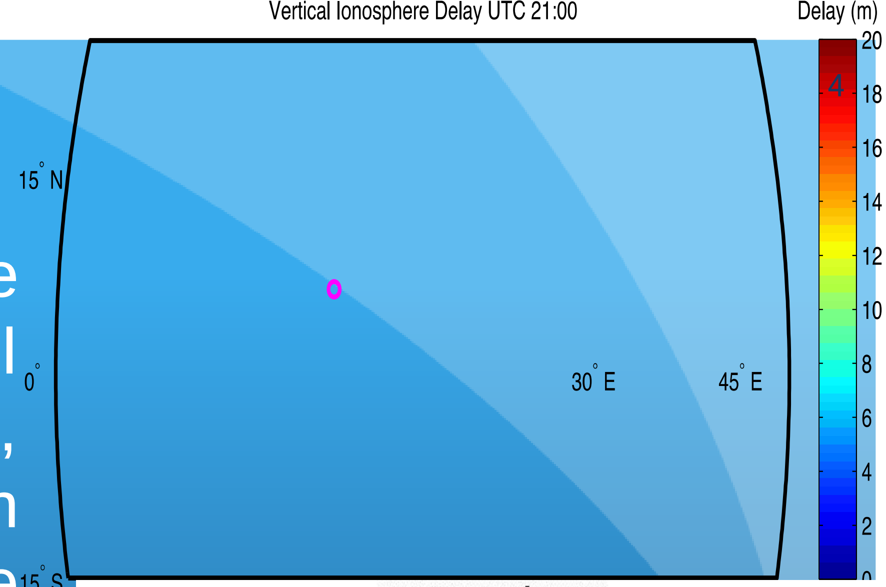
- The study of ionosphere and its variability are essential to navigation and positioning systems like Satellite-Based Augmentation System (SBAS).
- Ionosphere remains a significant issue in the evolution of Global Navigation Satellite Systems (GNSS) and its augmentation systems such as SBAS all over the world
- It is the largest and the least predictable among the error sources, limiting the reliability and accuracy of GNSS-SBAS in safety-of-life applications

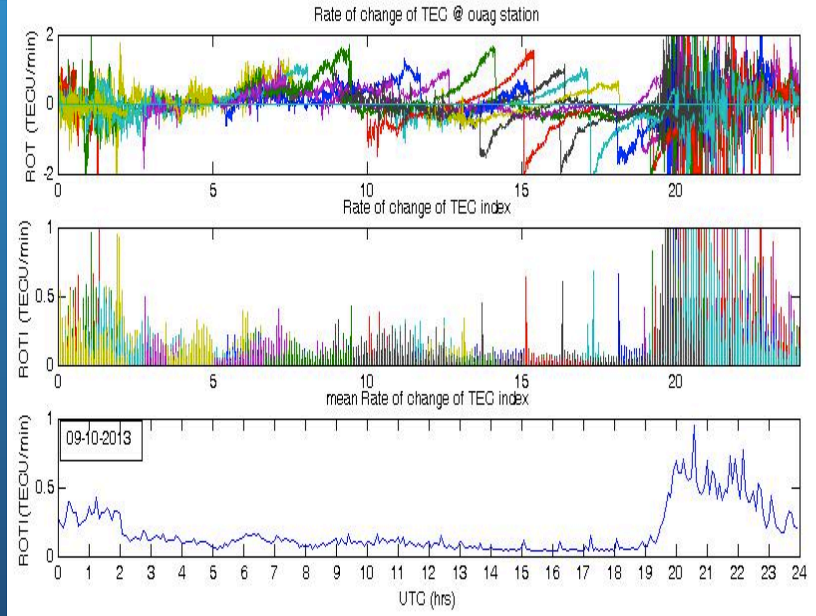




Introduction

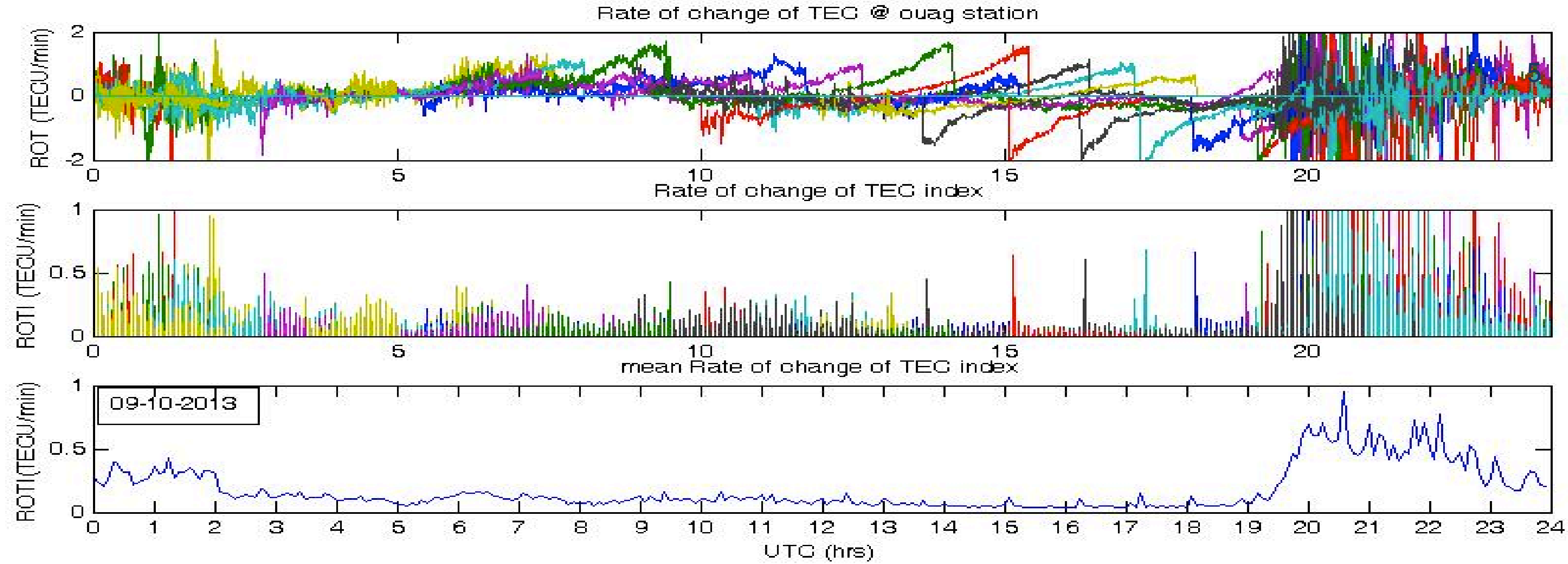
- The situation becomes more critical in the Equatorial Ionization Anomaly (EIA) region, where the daytime ionization distribution is modified by the fountain effect

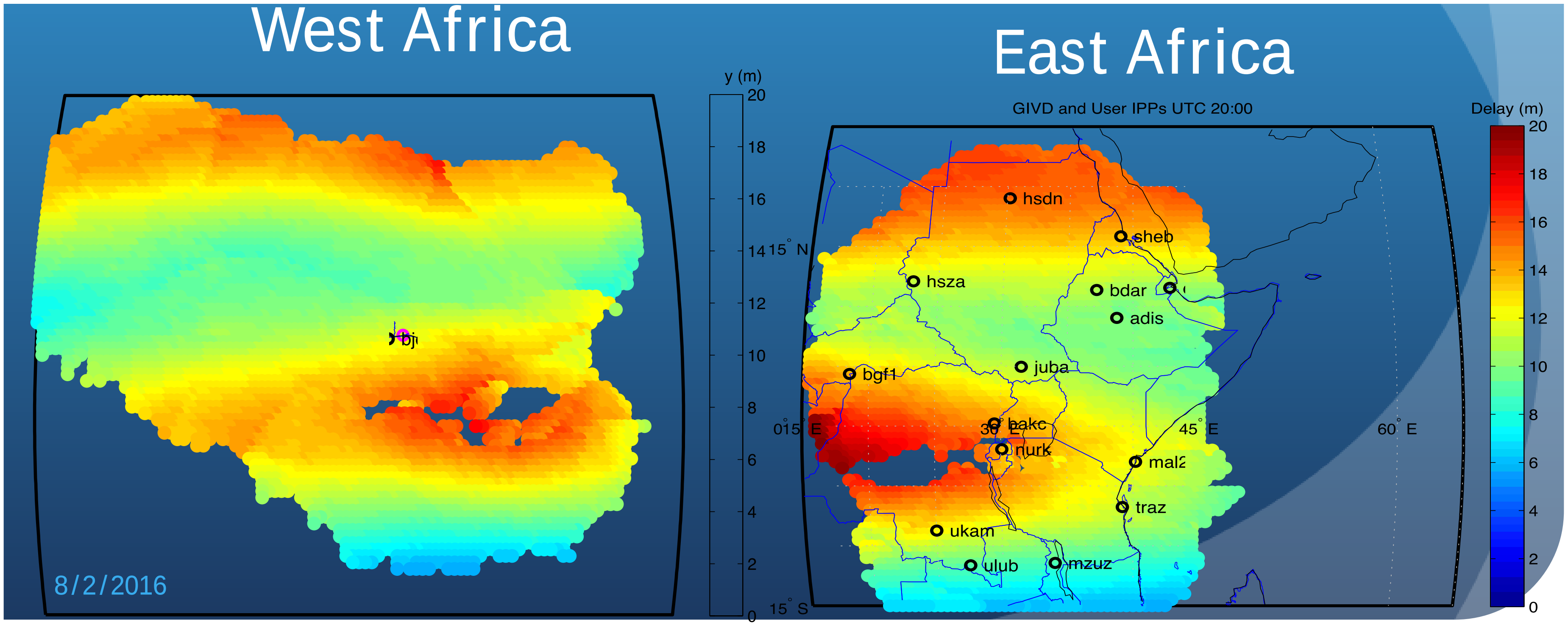




- The consequence of this, results to the development of ionosphere irregularities or plasma bubbles after local sunset

- which reduces the availability and further degrades quality of the service obtained from the GNSS systems at the said periods


Rate of change of TEC @ ouag station
ROT (TECU/min)
Rate of change of TEC index
ROTI (TECU/min)
mean Rate of change of TEC index
ROTI(TECU/min)
09-10-2013
UTC (hrs)


West Africa
East Africa
y (m)
GIVD and User IPPs UTC 20:00
Delay (m)
hsdn
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15° N
15° S
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30° E
45° E
60° E
8/2/2016

Mitigation of ionosphere effects using SBAS

- SBAS was developed to improve the operational reliability and efficiency of GNSS
- USA (WASS), Europe (EGNOS), Indian (GAGAN), Japan (MSAS), China (Beidu) etc
- In order to:
  - provides ionosphere delay corrections to the user;
  - ensures the integrity of the signal received;
  - generates grid warnings during severe disturbance in ionosphere; and
  - enhaces the continuity and availability of a single frequency-based

SBAS ionosphere Correction Algorithm

- There are various models developed to correct the ionosphere error over middle latitude in both theoretical and experimental
- very few among these models give minimum residual errors over the EI A region
- an augmentation system suitable for EIA region needs a certified ionosphere correction procedure that describes well the anticipated events corresponds to the region's peculiarity
- protects the user against any condition by providing reliable safe confidence bound

SBAS ionosphere Correction Algorithm

- equatorial plasma vertical drifts pose a serious challenge to a thin-shell layer based algorithm in providing ionosphere corrections
- using a fixed thin-shell based height algorithm for SBAS in EIA region could limit the optimization of GNSS applications in some particular period of time
- GAGAN SBAS, being the first operational SBAS in EIA region, the ionosphere correction algorithm is based on multi-layer procedure
- This study assesses various ionosphere threat model using both single- and multiple-shell strategy
- this could be useful in the development of the ionosphere corrections procedure and its confidence bound in the Sub-Saharan African region.

Data Source

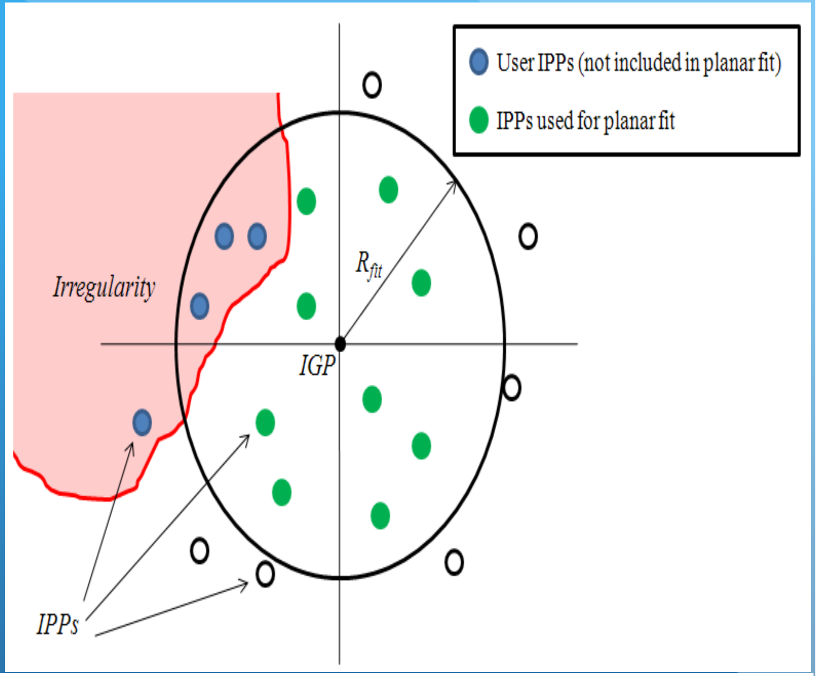
- An ionosphere delay based on a semi-empirical NeQuick 2 model [Nava et al. 2008] was generated to assess the algorithms over the studied area.
- International Telecommunication Union-Radio (ITU-R) has adopted the model as a procedure for TEC estimation To some extent, it allows the creation of a realistic and a controlled ionosphere [Brunini et al. 2011]
- Synthetic data primarily help to isolate the error contributions from TEC calibration and system biases.
- In this case NeQuick 2 model was driven by the solar flux (F10.7) 200 and 150 SFU.

Estimating Ionosphere Delay using Planar Fit Model

- The vertical ionosphere delay at the IGP (I_{IGP}) is obtained following standard planar fit approach algorithm outlined in Conker et al. (1996), Walter et al. (2001) and Prasad & Sarma (2004).

- Because of the high spatial gradients in the EIA region and the sparsity of the GNSS stations distribution

- The maximum search radius of target IPPs considered for the estimation of ionosphere delay at the IGPs is 1000 Km with the minimum number of 8 IPPs.



$$W = \sum_{i=1}^{N} (\sigma^2_{IPP(i)} + \sigma^2_{decorr(i)})^{\wedge} - 1$$

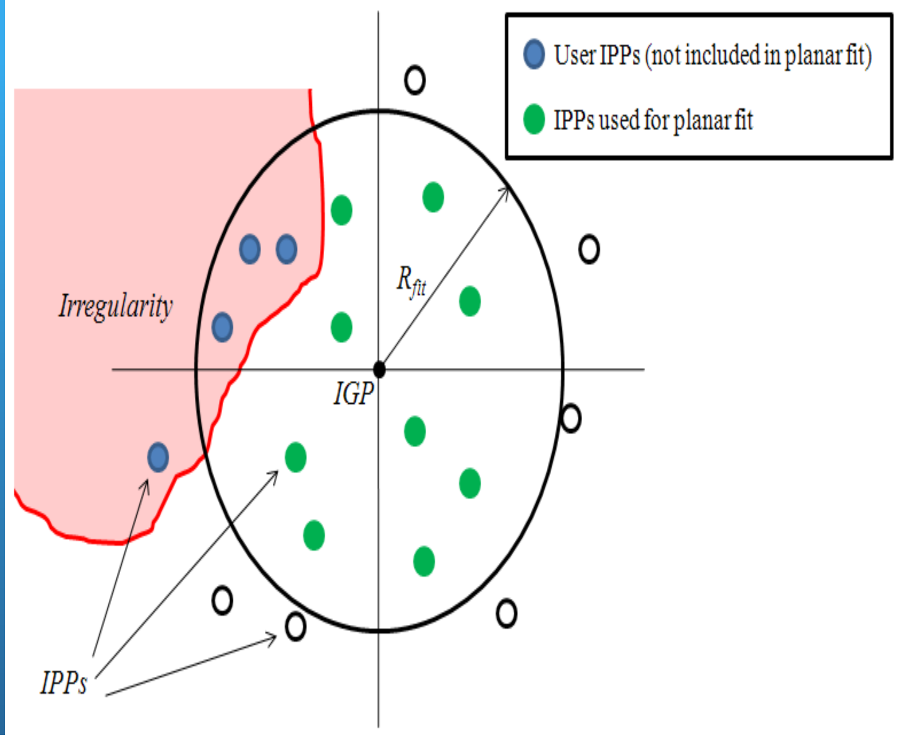
$$I_{IGP}(\Delta x, \Delta y) = a_0 + a_1 \Delta x + a_2 B \Delta y$$

$$\therefore I_{IGP} = [100][(GWG^T)^{-1} GWI_{IPP}]$$

where G is the matrix of the distance aligns with the East and North directions. Detail could be found in Walter et al. 2001 and the reference therein

Estimating Ionosphere Delay using Kriging Technique

- Whereas in WAAS as example, the minimum number of IPPs used to construct the delay at IGP is 10 and maximum number of target is 30. Also the minimum search radius distance is 800 Km and the maximum search radius of target is 2100 Km



- Within the radius of target, more weights are given to the IPPs having good correlation with the IGP as well as higher elevation angle in comparison with the lower ones

$$\hat{I}_{IGP} = \sum_{i=1}^{N} w_i I_{IPP}$$

$$w = [W - WG(G^T WG)^{-1} G^T W]c + WG(G^T WG)^{-1}$$

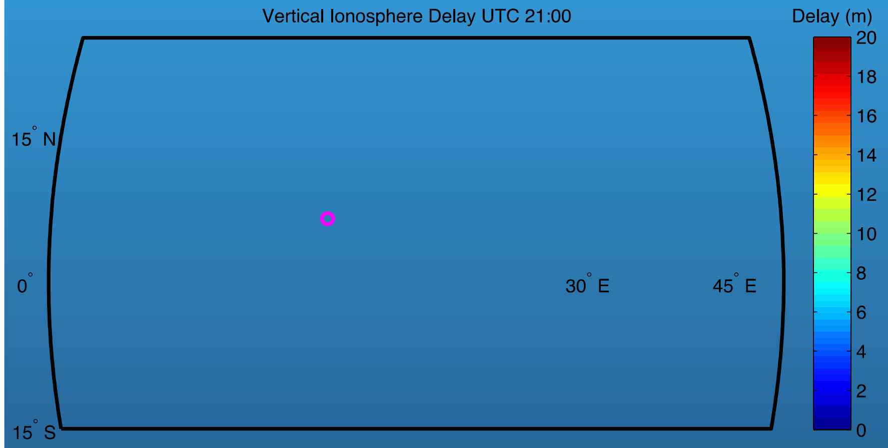
where W is the weighting matrix, c is the covariance of the vector and scala field. Detail could be found in Sparks et al. 2011; Blanch et al. 2002 and 2003 and the references

Estimating Ionosphere Delay using Multi-Shell Approach

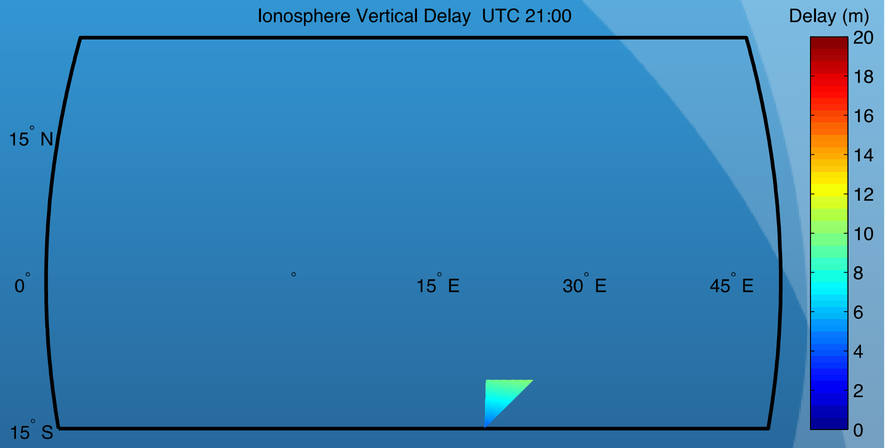
- Multi-shell height is a simple algorithm technique that
  - caters for the upward and downward movement of the maximum height of the electron density
  - takes into account the large spatial and temporal gradients in the EIA region
  - The ionosphere vertical profile-based algorithm captures better the potential threat in both sampled and undersampled of horizontal and vertical gradients.

Delay Estimated Using Different Ionosphere correction Models

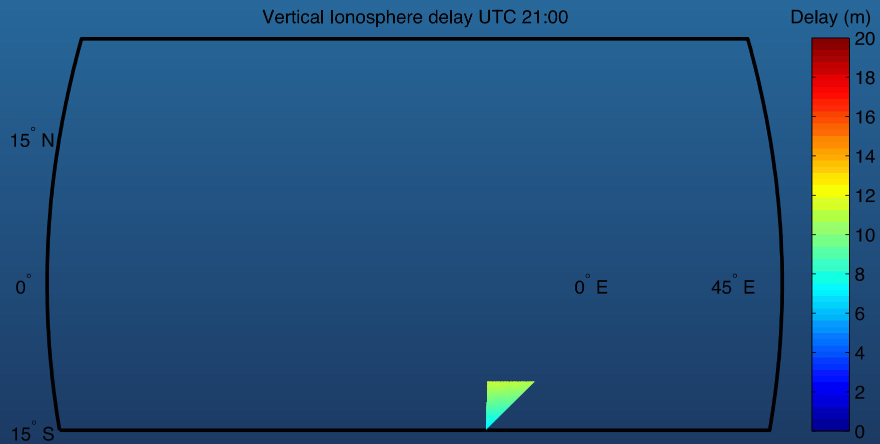
Planar Fit Single-shell



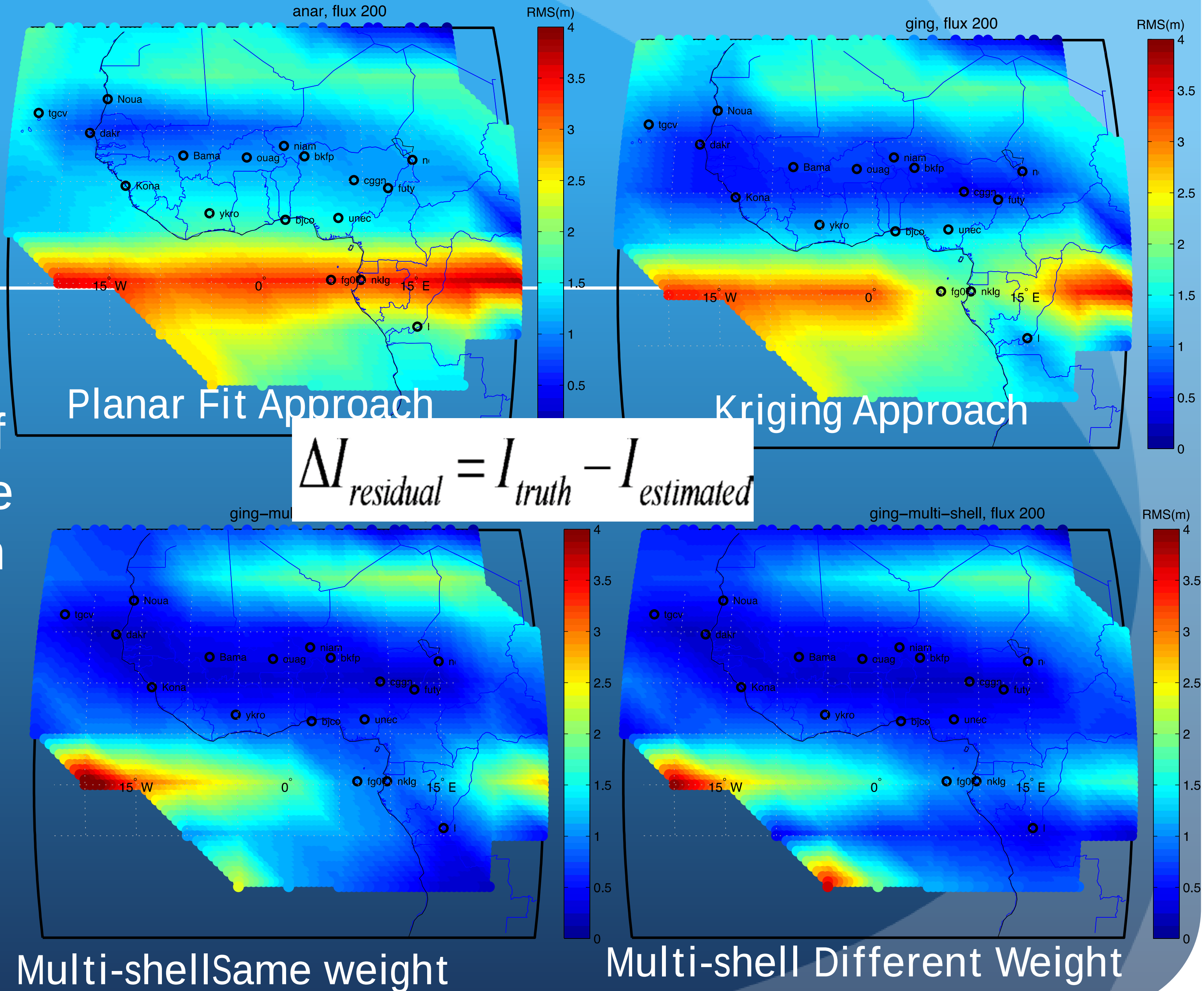
Kriging Single-shell



Multi-shell

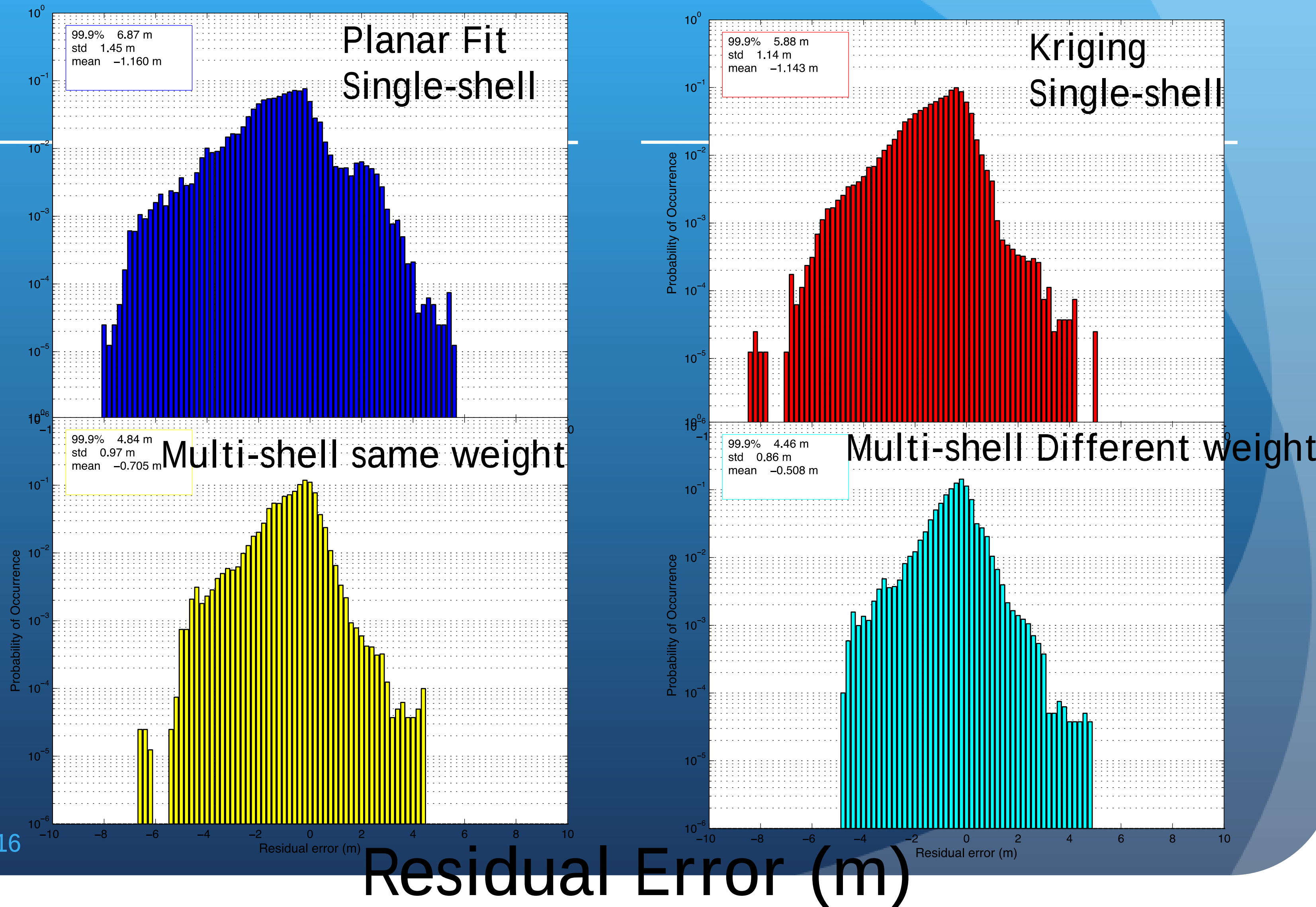


RMS Residual Error Analysis of Ionosphere Correction models

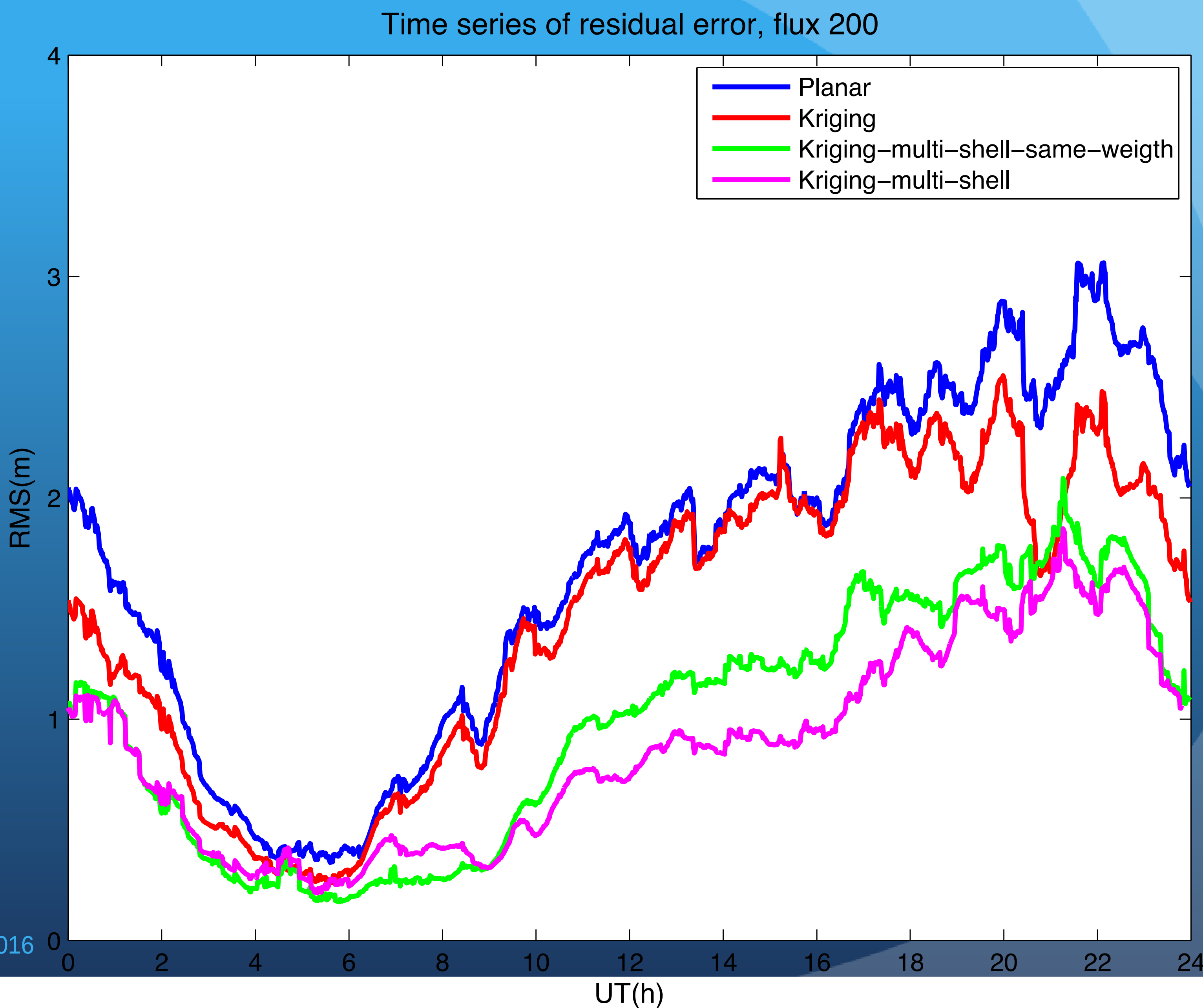


$$\Delta I_{residual} = I_{truth} - I_{estimated}$$

Distribution of residual errors



Residual Error time series



Ionosphere Threat Model (1)

- The SBAS does not only provide ionosphere corrections but also ensure the integrity bound of the corrections being provided (Bang and Lee 2014).
- Ionosphere threat model contains a parameter GIVE (grid ionosphere vertical error)
- GIVE guarantees the error bound on the corrections being sent to the user at the IGP.
- It takes into account the uncertainty associated to the model based on monitoring stations measurements, the inflation factor in order to handle worse case scenario and any form of irregular behaviour of the ionosphere unable to capture by the monitoring stations measurements.
- this is obtained from the variance of the delay at the four nearby IGPs

Ionosphere Threat Model (2)

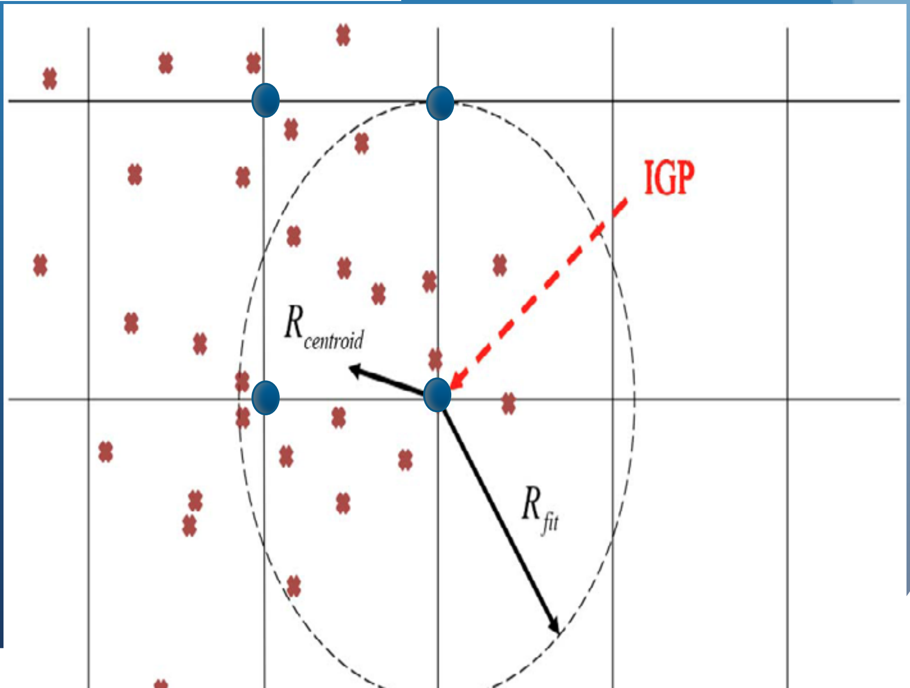
$$GIVE = 3.29\sqrt{\sigma^2_{GIVE}}$$

$$\sigma^2_{GIVE} = R^2_{irreg}(\sigma^2_{IGP} + \sigma^2_{decorr}) + \sigma^2_{undersampled} + \sigma^2_{rateofchnage}$$

$$R^2_{irreg} = \alpha_n I^T_{mean}(W - WG^T(G^T WG)^{-1} GW) I_{mean}$$

$$\sigma^2_{IGP} = [100](GWG^T)^{-1}[100]^T$$

where W is the weighting matrix, c is the covariance of the vector and scalar field. Detail could be found in Sparks et al. 2011; Blanch et al. 2002 and 2003 and the references



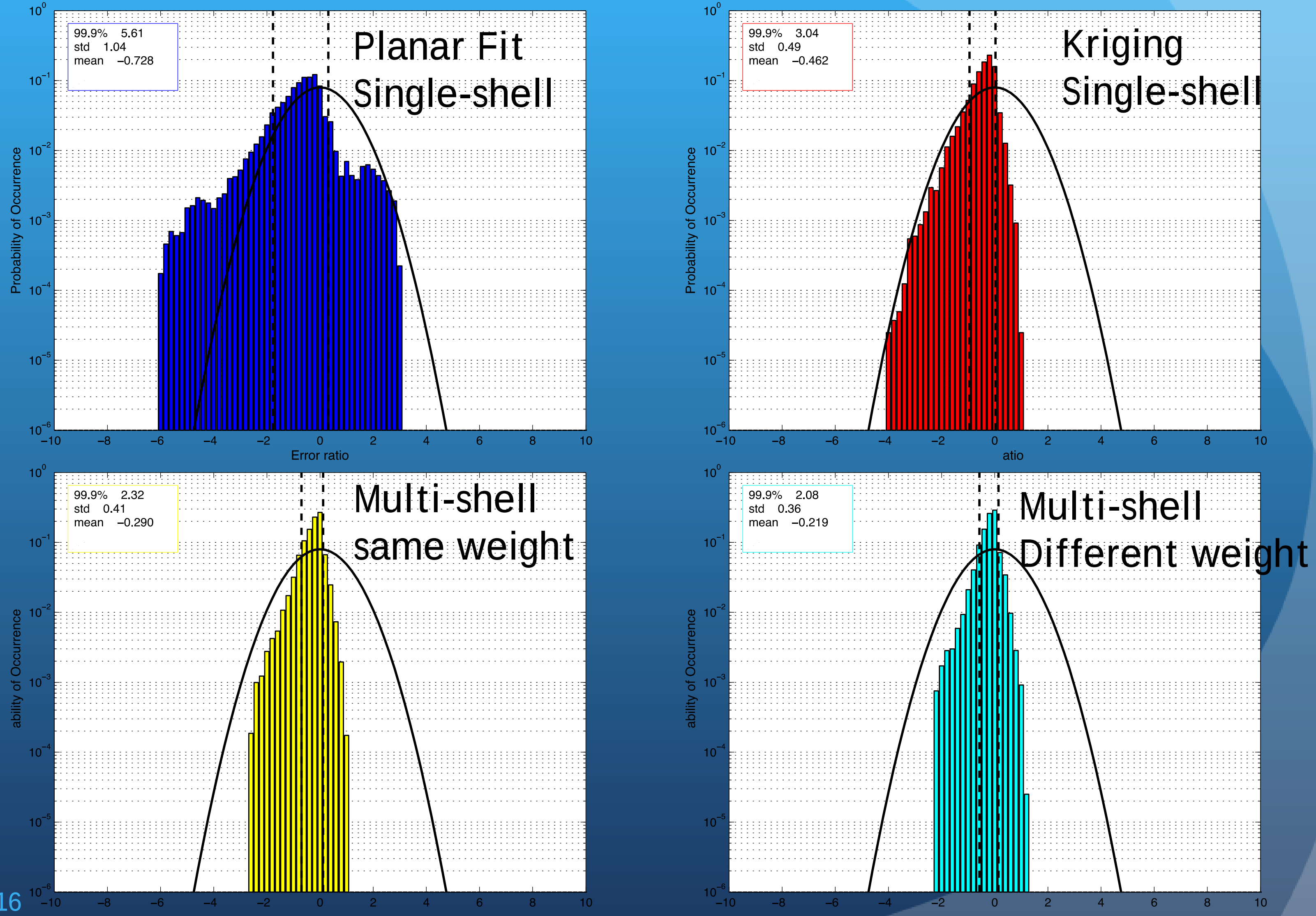
Ionosphere Threat Model (3)

- The normalised residual error (bounding error ratio) is obtained using

$$\Gamma_{normalised} = \frac{\Delta I_{residual}}{\sigma^2_{GIVE}}$$

- ensures the integrity bound of the corrections being provided
- overbounds the residual error obtained
- gives a confident bound on the uncertainty of the estimation including spatial and temporal threats
- protect the user from the local irregularities threat unable to capture by the monitoring stations

Distribution of bounding error ratio



Result of Ionosphere correction and threat models

Solar Flux (F10.7) 200 SFU High Solar Activity	Residual Error (m)			Bounding Error ratio (m)		
	99.9 %	STD	Mean	99.9 %	STD	Mean
Planar Fit (Single-Shell)	6.87	1.45	-1.16	5.61	1.04	-0.728
Kriging (Single-Shell)	5.88	1.14	-1.14	3.04	0.49	-0.46
Kriging (Multi-Shell same weight)	4.84	0.97	-0.71	2.32	0.41	-0.29
Kriging (Multi-Shell different weight)	4.46	0.86	-0.51	2.08	0.36	-0.22

Result of Ionosphere correction and threat models

Solar Flux (F10.7) 150 SFU Moderately High Solar Activity	Residual Error (m)			Bounding Error ratio (m)		
	99.9 %	STD	Mean	99.9 %	STD	Mean
Planar Fit (Single-Shell)	3.18	0.78	-0.57	2.53	0.55	-0.35
Kriging (Single-Shell)	2.76	0.58	-0.56	1.33	0.24	-0.23
Kriging (Multi-Shell same weight)	2.48	0.52	-0.35	0.92	0.20	-0.12
Kriging (Multi-Shell different weight)	2.15	0.50	-0.29	0.91	0.19	-0.13

Percentage of Algorithm improvent over Planar fit procedure

Flux (F10.7) (SFU)	**Kriging**		**Multi-Shell with the same height**		**Multi-Shell with the different height**	
	$\Delta I_{residual}$	$\Gamma_{normalised}$	$\Delta I_{residual}$	$\Gamma_{normalised}$	$\Delta I_{residual}$	$\Gamma_{normalised}$
200	16.84	36.99	41.94	60.27	54.04	69.86
150	15.22	34.29	28.23	65.71	47.91	65.98

Summary and conclusions

- In order meet SBAS integrity requirements in EIA region, there is a need for ionosphere threat model, able to capture the irregularities unable to observe by the monitoring stations measurements and protect the user
- the preliminary results obtained with the synthetic TEC is an indication that
- a multi-layer algorithm procedure gives minimum residual error over EIA region
- its threat model as well overbound the error
- it caters more for the equatorial plasma vertical drifts.

Summary and conclusions

- the ionosphere vertical profile-based algorithm captures better the potential threat in both sampled and undersampled of horizontal and vertical gradients
- it could detect small and large scales structure of ionosphere irregularities in time, space and seasons

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