公开

SBAS Ephemeris & Ionospheric Corrections and Integrity

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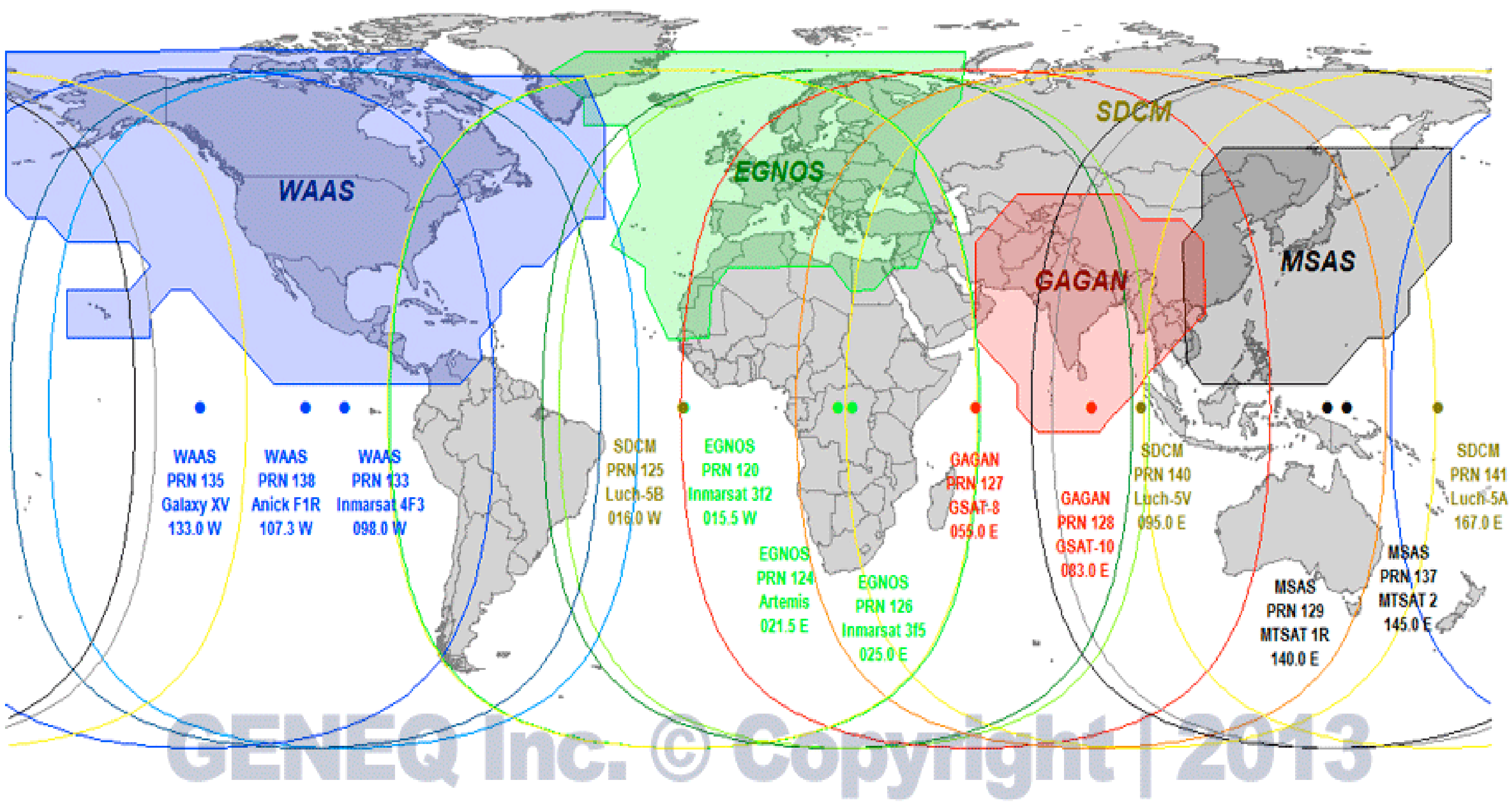
Outline

- Introduction
- SBAS Ephemeris Correction & Integrity
- SBAS Ionospheric Correction & Integrity
- System development
- References

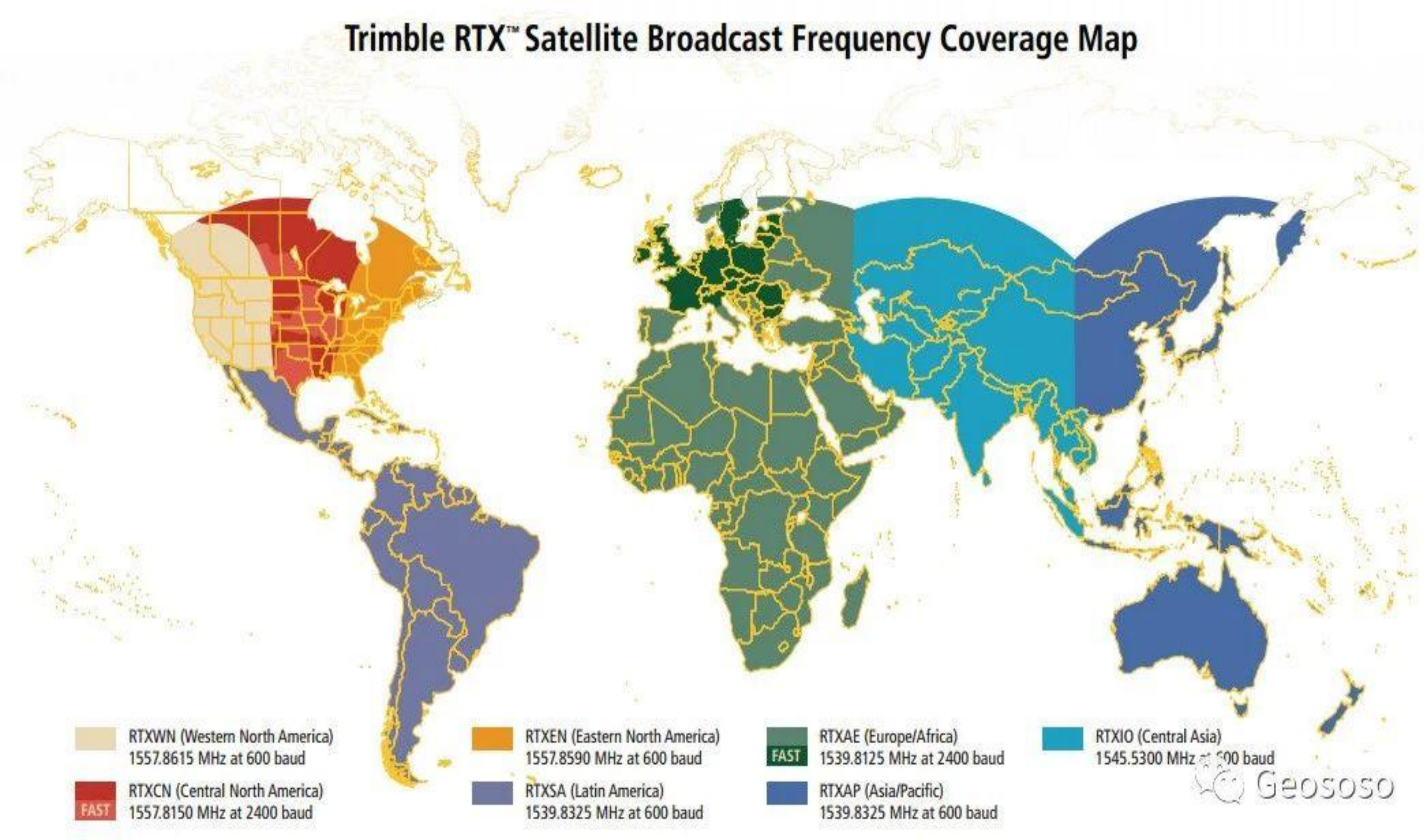
Introduction-SBAS



Introduction-SBAS

Item	Single Frequency SBAS	DFMC
Service	NPA	CAT-I
Service Signal	GPS L1	GPS L5
Augmentated Signal	GPS L1 C/A	GPS L1 C/A & L5 BDS B1C & B2a
Position Accuracy (95%)	Horizontal: 2.5m Vertical: 4.0m	Horizontal: 1.5m Vertical: 2.0m
Time to Alert	10s	6s
Integrity	2×10^{-7}/150s	2×10^{-7}/150s
Continuity	$1-8\times10^{-6}$/15s	$1-8\times10^{-6}$/15s
Availability	99%	99.9%

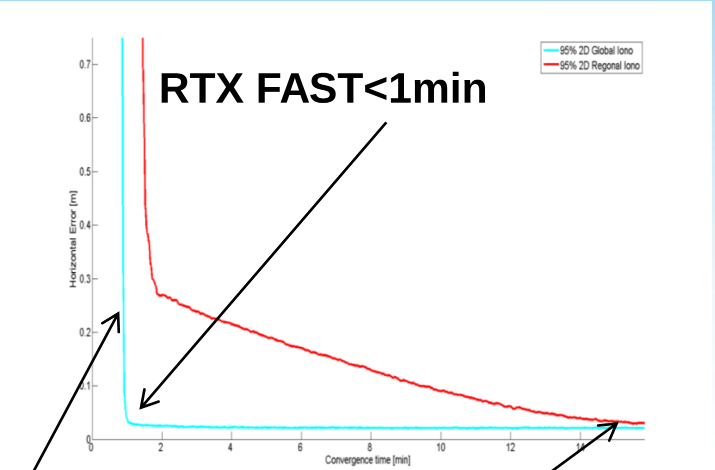
Introduction-WADGNSS



Introduction-WADGNSS

RTX: Real Time eXtended

RTX Standard	RTX Fast
Global Ionosphere model	Regional Iono model
	Regional Tropo model
Biases	Biases
Precise Satellite Clock	Precise Satellite Clock
Precise Satellite Orbit	Precise Satellite Orbit
Global 110 stations	Distance 150-200km



RTX：

✓Position accuracy: H:2.5cm,V:5cm；

✓Convergence time：＜20min；

✓Service area: Global

RTX FAST：

✓Position accuracy: H:2.5cm,V:5cm；

✓Convergence time：＜1min；

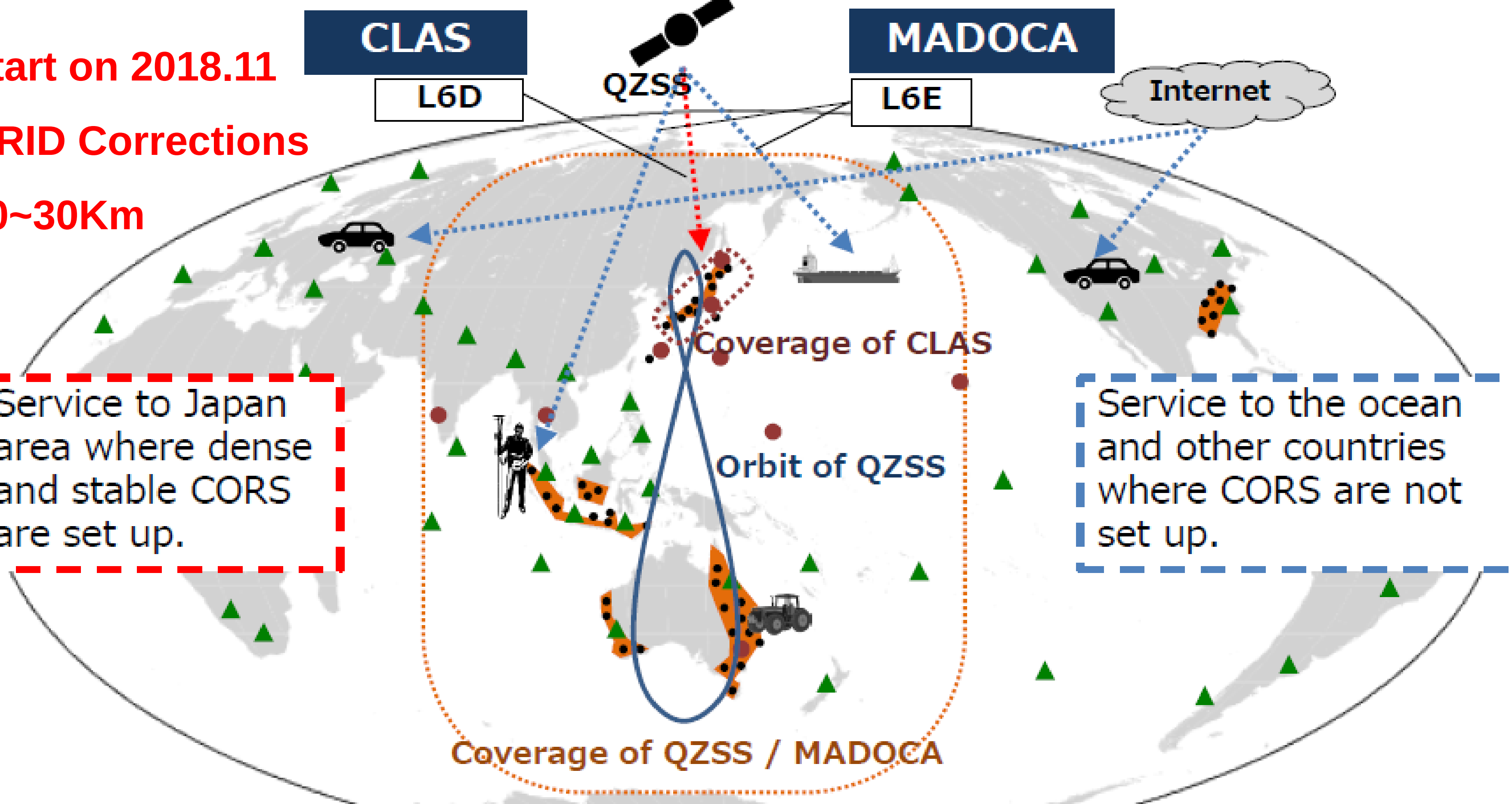
✓Service area: America and Europe

Introduction-WADGNSS

Start on 2018.11

GRID Corrections

20~30Km



Service to Japan area where dense and stable CORS are set up.

Service to the ocean and other countries where CORS are not set up.

Message	Service Area	Accuracy	TTFF	CORS	Data Size
CLAS	Around Japan	cm-level	1min	20 to 30 km interval	2kbps for Japan
MADOCA	Coverage of QZSS *All over the world via internet*	cm-level	30min **1min*	About 100 in the world	2kbps for World

Introduction-WADGNSS

Manufacturer	Coverage	Performance
Trimble	Global Region	RTX：H:2.5cm,V:5cm；Convergence Time: < 15min RTX Fast：H:2.5cm,V:5cm；Convergence Time: < 1min
OmniSTAR（Trimble）	Global	VBS: Sub-meter；HP: 5-10cm； XP: 20-35cm； G2: Decimeter；
TerraStar（Hexagon）	Global	TerraStar-C: 5cm; Convergence Time: 25min； TerraStar-D: 10cm; Convergence Time: 20min；
Veripos（Hexagon）	Global	Apex: H:5cm, V:12cm； Ultra: H:10cm, V:20cm；
StarFIRE	Global	10cm；Convergence Time: 20min
QZSS	Global Region	CLAS: Centimeter; Convergence Time: < 1min; MADOCA: Centimeter; Convergence Time: < 30min;
Atlas/ChinaCM	Global	4cm; Convergence Time: 10-40min;
Hi-RTP	Global	4cm;

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SBAS Ephemeris Correction & Integrity

Model for orbit and clock corrections

Slow clock correction:

$$\rho_i^j = \rho^0 - Gdeph + cdt_i - cdt^j + \varepsilon$$

$$G = \left[\frac{x^{sat} - x}{\left|\vec{r}^{sat} - \vec{r}\right|}, \frac{y^{sat} - y}{\left|\vec{r}^{sat} - \vec{r}\right|}, \frac{z^{sat} - z}{\left|\vec{r}^{sat} - \vec{r}\right|} \right], \quad deph = \left[dx^{sat}, dy^{sat}, dz^{sat} \right]$$

- ✓ First solve the clock errors of satellites and stations;
- ✓ Chose one station as the master station;
- ✓ ignore the orbit error at this step ;
- ✓ Satellite clock error shall absorb the orbit radial direction error.
- ✓ This clock results are treat as slow clock corrections

SBAS Ephemeris Correction & Integrity

Model for orbit and clock corrections

Slow orbit correction:

$$\hat{X}_{MV} = (\Lambda^{-1} + G^T W^{-1} G)^{-1} G^T W^{-1} z$$

$$\hat{P}_{MV} = (\Lambda^{-1} + G^T W^{-1} G)^{-1}$$

- ✓ Minimum variance (MV) estimation method is used;
- ✓ Λ Is the prior variance of the ephemeris;
- ✓ z is the residual after removing the satellite and station clock errors;
- ✓ ignore the clock error at this step ;
- ✓ Carrier phase epoch changes are used to constrain the orbit;
- ✓ This orbit results are treat as slow orbit corrections.
- ✓ After this, clock errors are solved again as fast corrections.

SBAS Ephemeris Correction & Integrity

Integrity check for correction

$$e = (\tilde{P}^{-1} + G^T W G)^{-1} G^T W z$$

$$P = (\tilde{P}^{-1} + G^T W G)^{-1}$$

$$k_{state} = \sqrt{e^T P^{-1} e}$$

- ✓ Calculate the residual or remain ephemeris errors e;
- ✓ $e^T P^{-1} e$ will follow the chi-square distribution while e is Gaussian type function;
- ✓ k_{FA} is 4.3 fault alarm rate is 10^{-3}
- ✓ The satellite is consider as normal when $k_{state} \le k_{FA}$

SBAS Ephemeris Correction & Integrity

Calculation of UDRE:

UDRE is broadcasted to bound the residual errors after application of ephemeris corrections.

$$P_{broadcast} = \sigma_{UDRE}^2 M_{28} \qquad P_{broadcast} = (\frac{1}{5.33})^2 (k_{md} + k_{FA})^2 P$$

Consider station i is fault and in the service area:

$$\sigma_j = \underset{j}{Max}(\sqrt{u_j^T P_i u_j}) \qquad F_0 = \underset{j}{Max}(\frac{\sigma_j}{\sqrt{u_j^T P u_j}})$$

$$P_{broadcast} = (\frac{1}{5.33})^2 (k_{md} + k_{FA})^2 F_0^2 P$$

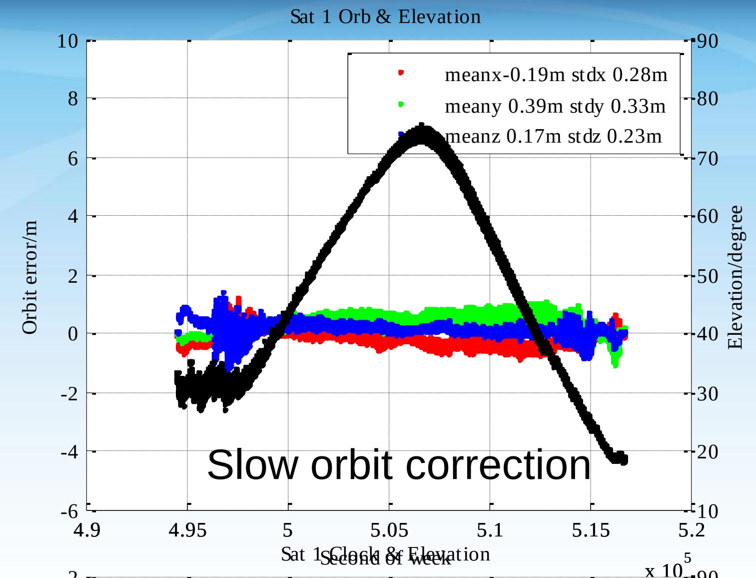
$$P_{broadcast} = \bar{U}^T \bar{U} \qquad UDRE = \bar{U}_{4,4}, MT_{28} = \bar{U} / \bar{U}_{4,4}$$

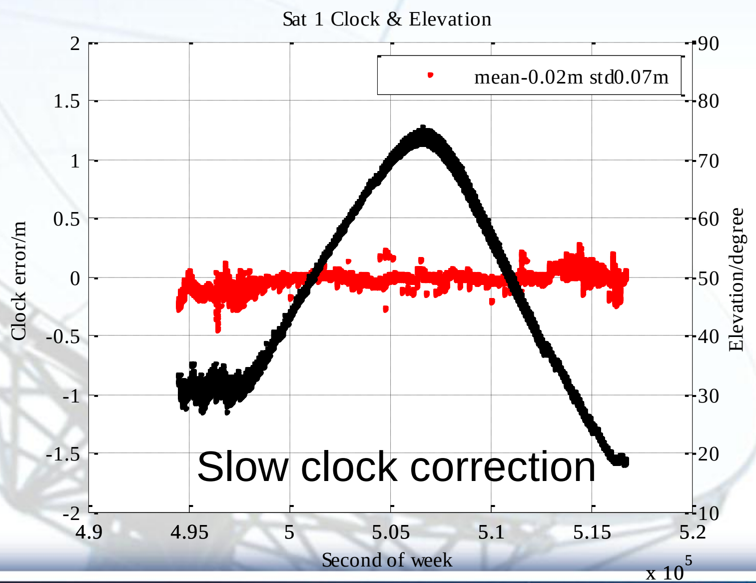
- ✓ k_{md} is 6.13 when the missed detection rate is 4.5×10^{-10}
- ✓ P_i is the posterior covariance without station i

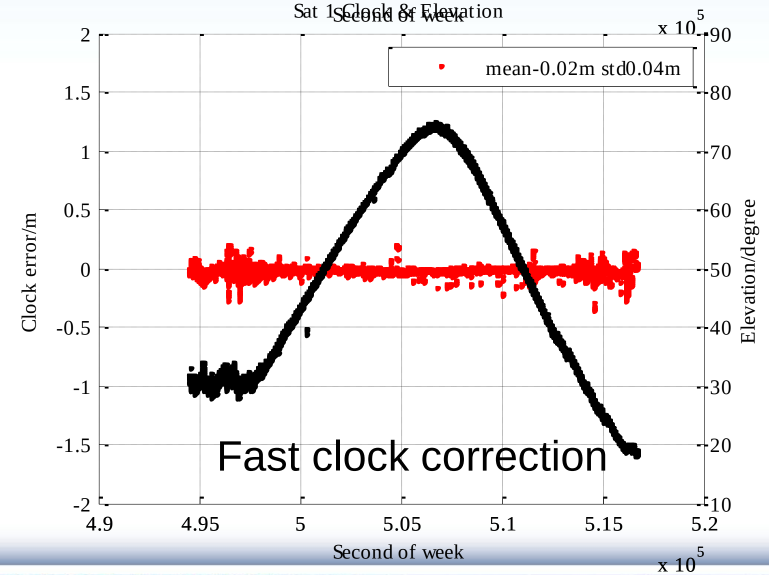
SBAS Ephemeris Correction & Integrity

Corrections for precise orbit and clock

- ✓ Should be close to zero
- ✓ Clock accuracy is about 10cm
- ✓ Orbit accuracy is about 40cm
- ✓ Fast clock correction is small
- ✓ DFMC cancel fast correction



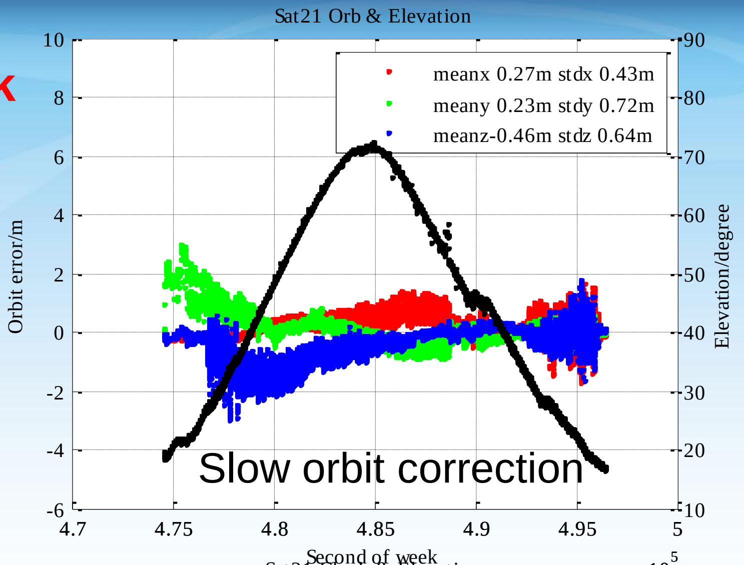


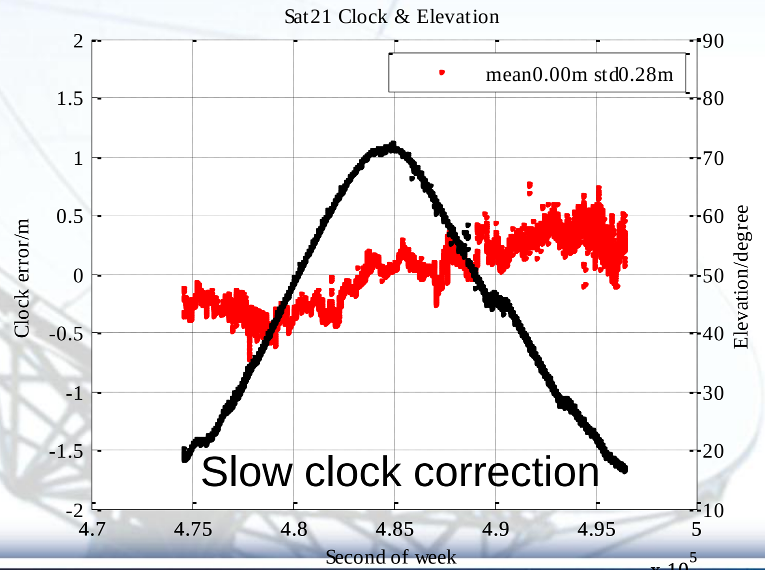


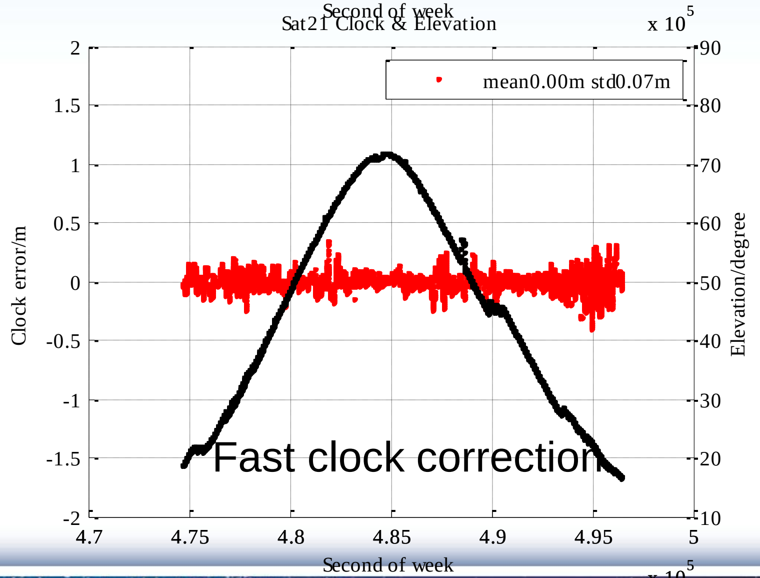
SBAS Ephemeris Correction & Integrity

Corrections for broadcast orbit and clock

- ✓ Clock accuracy is about 10cm
- ✓ Orbit and clock accuracy degrade with satellite growing up
- ✓ Fast clock correction is small



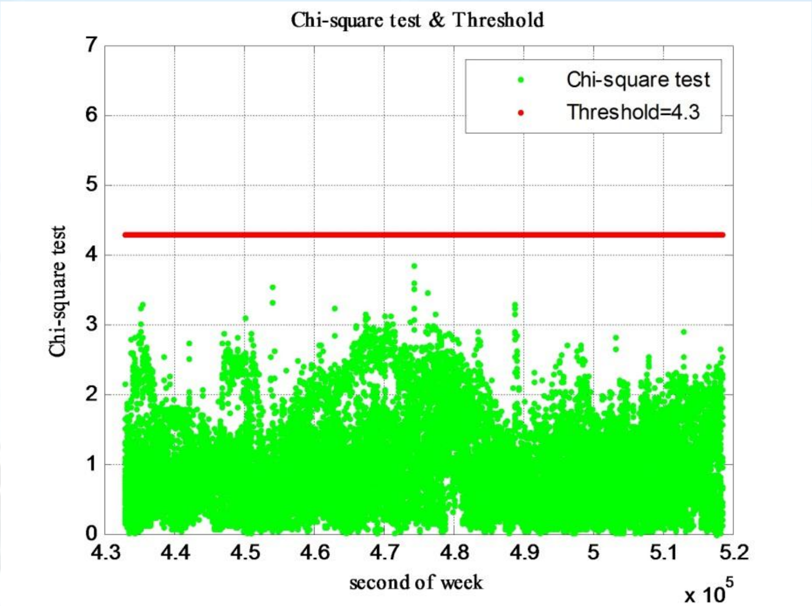


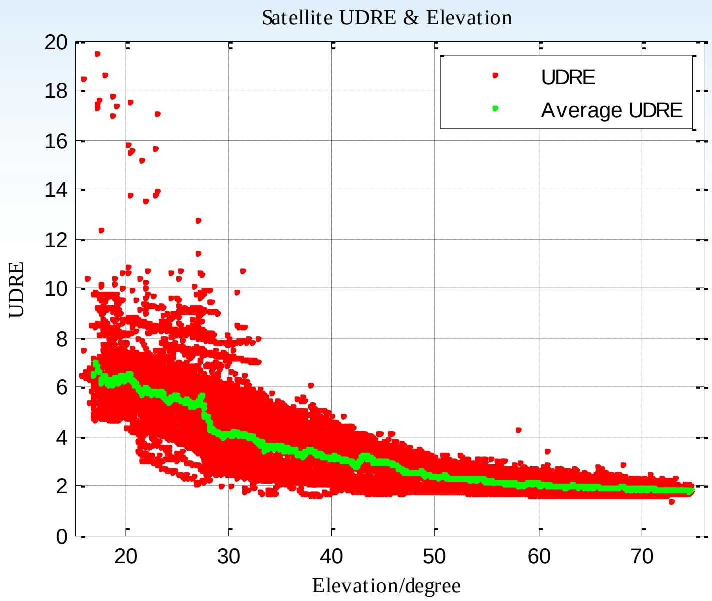


SBAS Ephemeris Correction & Integrity

Integrity test for corrections

- ✓ Chi-square test is used to ensure the integrity
- ✓ Test threshold is 4.3 for 4 parameters
- ✓ UDRE is decreasing while satellite growing up





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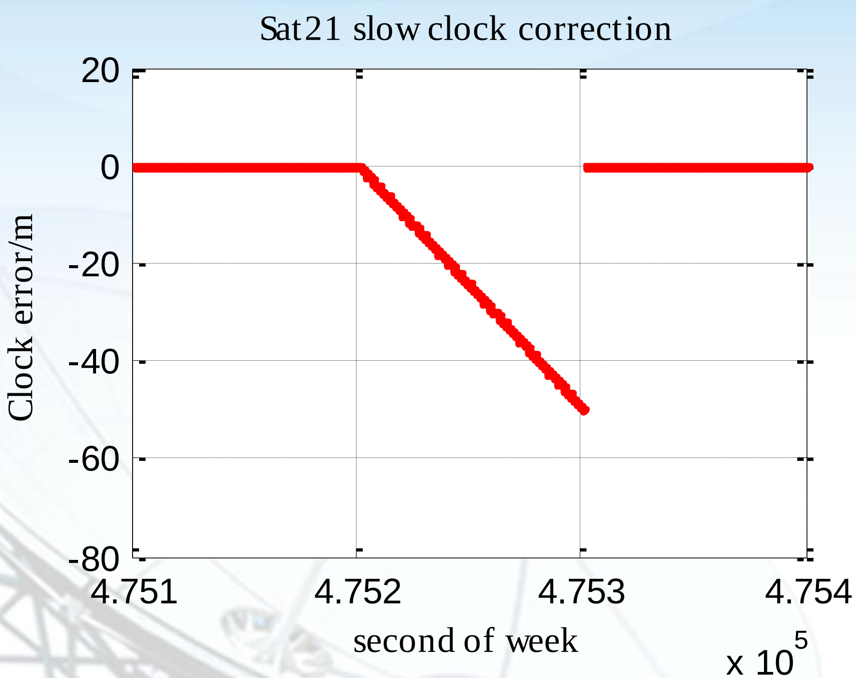
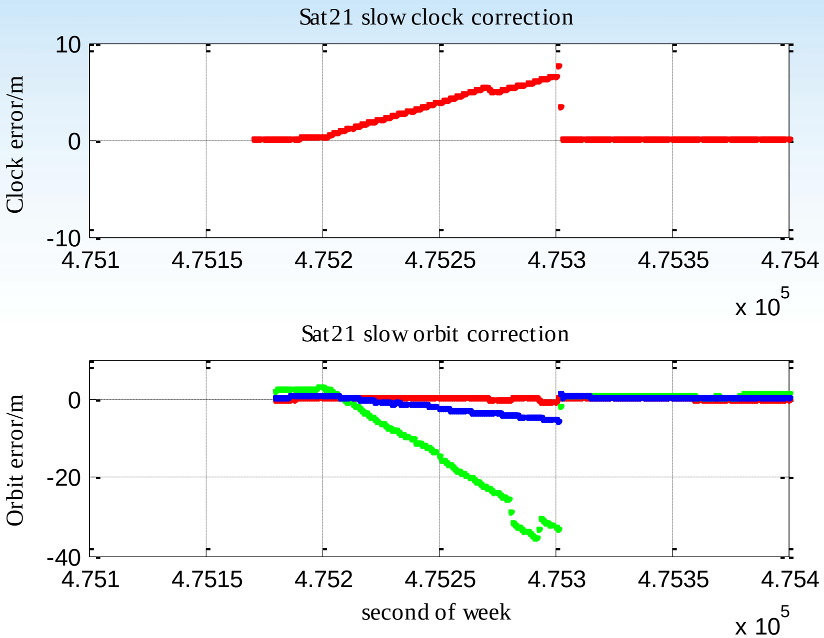
Simulation faults of ephemeris

- ✓ First time, add errors on satellite clock(0.5m/s, last 100s,@475200);
- ✓ Second time, add errors on satellite orbit(Y, 0.5m/s, last 100s,@475200);



Clock errors/faults



Orbit errors/faults

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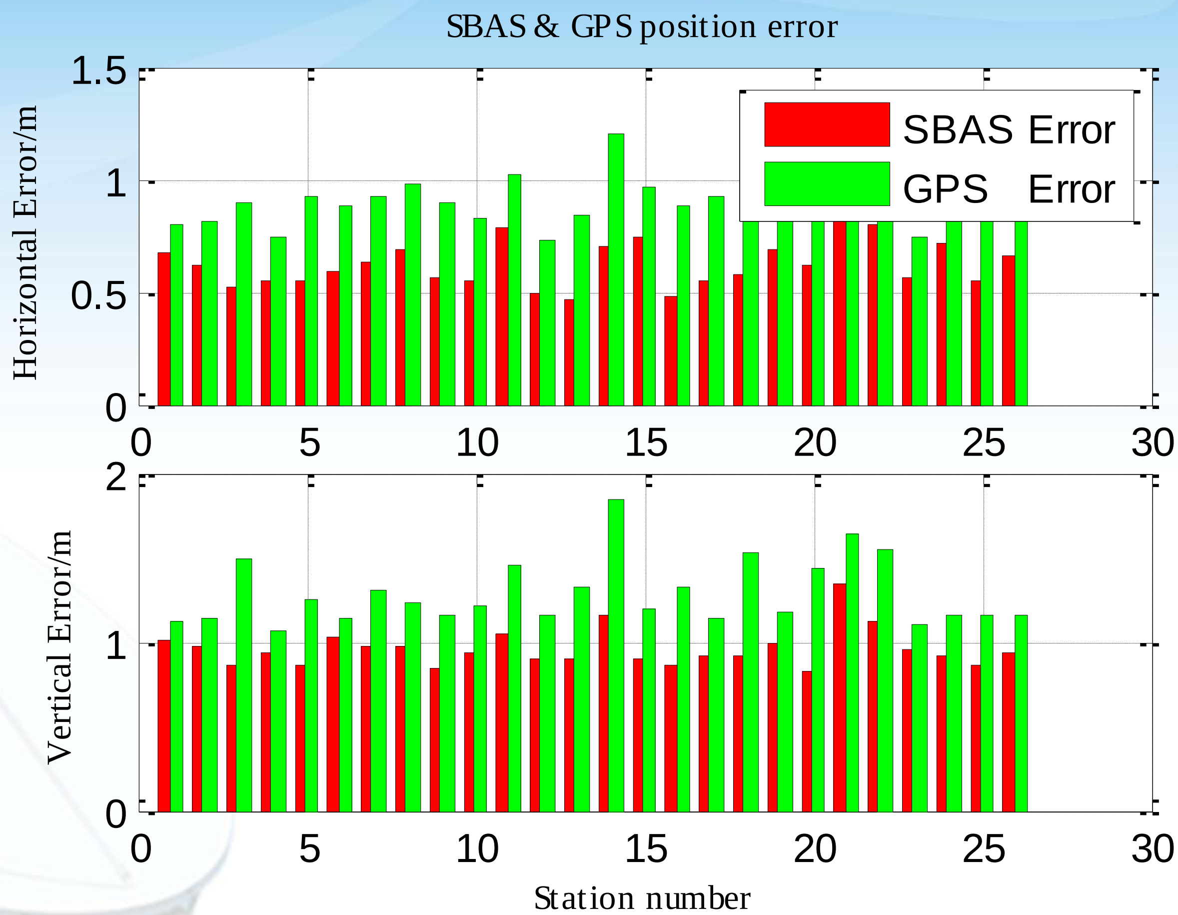
Position results

- ✓ Klobuchar model for ionospheric delay
- ✓ SBAS H<0.8m, V<1.5m
- ✓ Improved about 30% and 20% in Horizontal and Vertical.
- ✓ With SBAS Iono model will be improved further



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SBAS Ionospheric Correction & Integrity

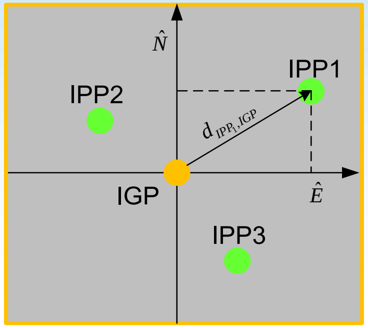
- **Ionospheric delay is a major error source for SBAS**
  - Ionospheric delay on each IGP is broadcasted to improve position accuracy;
  - While a GIVE is also broadcasted to bound the residual error after ionospheric correction;
  - GIVE is inflated by several parameters including $\sigma_{undersampled}$ to meet the integrity requirements;
  - GIVE is a dominant factor of protection levels;
- **Spatial threat model should be built for GIVE calculation**
  - Spatial threat model is necessary for GIVE integrity because of the undersampled IPPs during ionospheric irregularity;
  - Spatial threat model is depend on regions, station distribution;
  - Data deprivation method is used to generate the threat model;

SBAS Ionospheric Correction & Integrity

- **Planar fit is used to estimate the ionospheric delay at an IGP, assume ionospheric vertical delay can be modeled as a plane.**

$$\hat{I}_{v,IGP}(x,y) = \hat{a}_0 + \hat{a}_1 x + \hat{a}_2 y \quad \Rightarrow \quad I_{v,IPP} = G \cdot x$$

$$I_{v,IPP} = \begin{bmatrix} I_{v,IPP_1} \\ I_{v,IPP_2} \\ \vdots \\ I_{v,IPP_N} \end{bmatrix}, G = \begin{bmatrix} 1 & d_{IPP_1,IGP}\cdot\hat{E} & d_{IPP_1,IGP}\cdot\hat{N} \\ 1 & d_{IPP_2,IGP}\cdot\hat{E} & d_{IPP_2,IGP}\cdot\hat{N} \\ \vdots & \vdots & \vdots \\ 1 & d_{IPP_N,IGP}\cdot\hat{E} & d_{IPP_N,IGP}\cdot\hat{N} \end{bmatrix}, x = \begin{bmatrix} \hat{a}_0 \\ \hat{a}_1 \\ \hat{a}_2 \end{bmatrix}, \sigma^2_{I_v,IPP} = \begin{bmatrix} \sigma^2_{I_{v,IPP_1}} \\ \sigma^2_{I_{v,IPP_2}} \\ \vdots \\ \sigma^2_{I_{v,IPP_N}} \end{bmatrix}$$



$$\begin{bmatrix} \hat{a}_0 & \hat{a}_1 & \hat{a}_2 \end{bmatrix} = \left[(G\cdot W\cdot G^T)^{-1}\cdot G\cdot W\cdot I_{v,IPP} \right]^T$$

$$W^{-1} = \begin{bmatrix} \sigma^2_{I_{v,IPP_1}} + \sigma^2_{decorr} & \sigma_{bias,1,2} & \cdots & \sigma_{bias,1,n} \\ \sigma_{bias,1,2} & \sigma^2_{I_{v,IPP_2}} + \sigma^2_{decorr} & \cdots & \sigma_{bias,2,n} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{bias,1,n} & \sigma_{bias,2,n} & \cdots & \sigma^2_{I_{v,IPP_2}} + \sigma^2_{decorr} \end{bmatrix}$$

$$\hat{I}_{v,IGP} = \hat{a}_0 = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}\cdot\left[(G\cdot W\cdot G^T)^{-1}\cdot G\cdot W\cdot I_{v,IPP} \right]$$

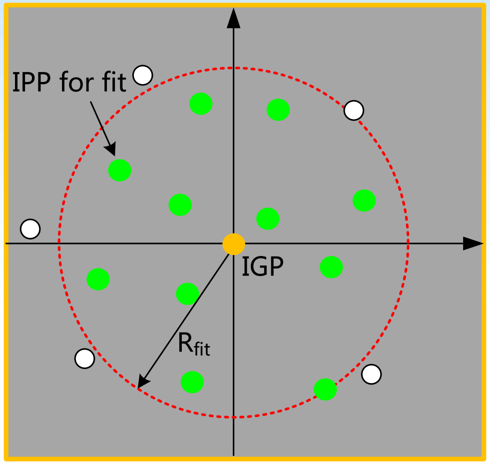
$$\hat{\sigma}^2_{\hat{I}_{v,IGP}} = \left[(G\cdot W\cdot G^T)^{-1} \right]_{1,1} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}^T \left[(G\cdot W\cdot G^T)^{-1} \right] \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

SBAS Ionospheric Correction & Integrity

IPP search method for planar fit

- Chose IPP with satellite elevation greater than 5° ;
- If IPP number more than N_{target} in the region with radius of R_{min}, then R_{fit} is R_{min};
- Or, expand R_{fit} until it defines a circle that surrounds N_{target} IPPs;
- If R_{fit} attains a maximum value of R_{max} and IPP number still less than N_{target} ,but more than N_{min}, a estimation is also performed;
- Or, the GIVE to be broadcast is set to Not Monitored.

$$R_{\min} = 800km, N_{target} = 30, R_{\max} = 2100km, N_{\min} = 10$$



SBAS Ionospheric Correction & Integrity

Irregularity detection and GIVE inflation

- Chi-square is used to evaluate the goodness of fit

$$\chi^2 = (I_{v,IPP} - \hat{I}_{v,IPP})^T W (I_{v,IPP} - \hat{I}_{v,IPP}) = I_{v,IPP}^T \cdot W \cdot [I - G^T \cdot (G \cdot W \cdot G^T)^{-1} \cdot G \cdot W] \cdot I_{v,IPP}$$

- With the degree of freedom and false alarm rate a threshold can be determined, if the test value of χ^2 is greater than threshold then the GIVE is set to Not Monitored,
- Or a GIVE based on the formal variance is inflated to guarantee integrity

$$\sigma_{GIVE}^2 = R_{irreg}^2 \sigma_{IGP_k}^2 + \max(R_{irreg}^2 \sigma_{decorr}^2, \sigma_{undersampled}^2) + \sigma_{rate-of-change}^2 + \sigma_{antenna\_bias}^2$$

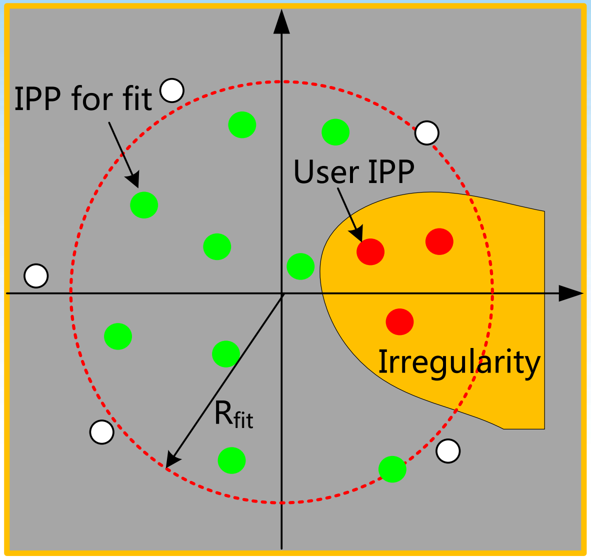
Formal Variance | Spatial Threat | Temporal Threat | Antenna Bias

$R_{irreg}^2(P_{fa}, P_{md}) = \frac{\chi_{1-P_{fa}}^2}{\chi_{P_{md}}^2}$,depend on false alarm rate and miss detection rate

SBAS Ionospheric Correction & Integrity

Undersampled threat

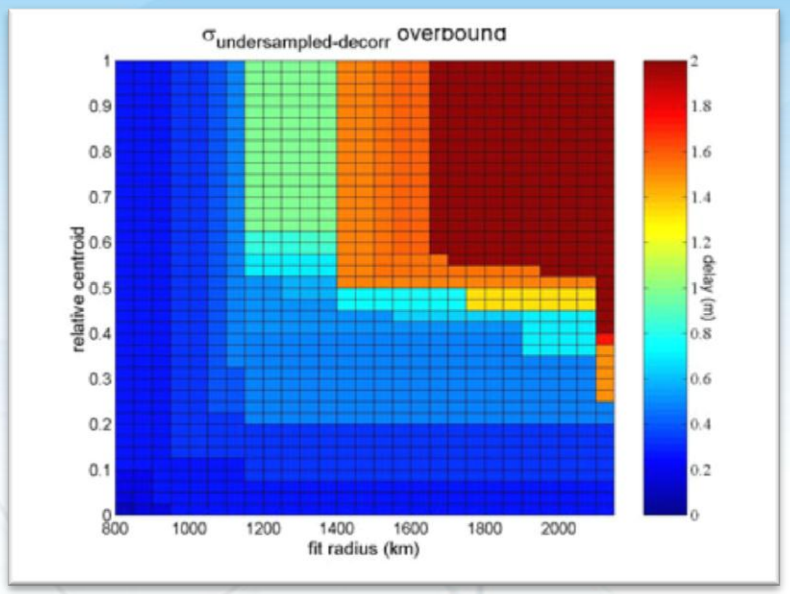
- Ionospheric delay on IGP is estimated with IPPs measured by SBAS monitor stations;
- Local Ionospheric irregularities might not be sampled by sparse monitor stations;
- Users might have IPPs within the irregularities but still use surrounding IGPs to estimate the delay which will lead to potential threat of large position error;



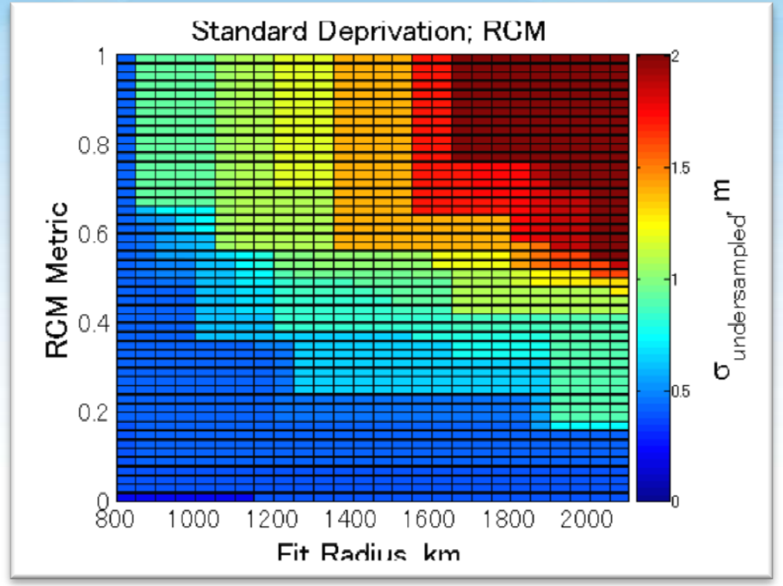
- So a spatial threat model should be built and added to GIVE to protect users against such a condition;
- Spatial threat model created based on the historical ionospheric storm data.

SBAS Ionospheric Correction & Integrity

Undersampled threat model examples



WAAS



MSAS

- Function of R_{fit} (fit radius) and RCM (Relative Centroid Metric);
- Monotonic function of the two metrics;
- Created with data deprivation method.

SBAS Ionospheric Correction & Integrity

Data deprivation method

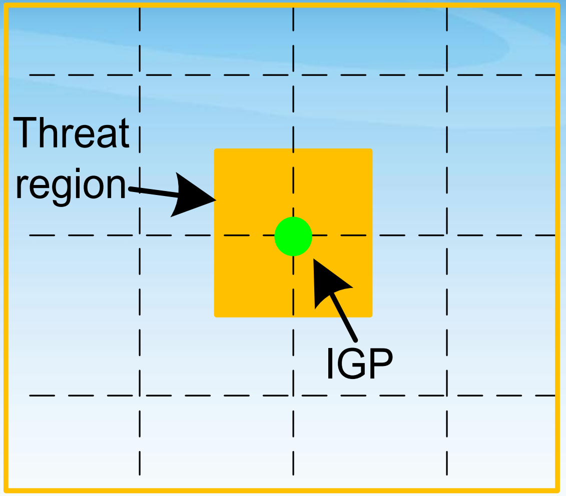
- Threat region: the region between the centers of the surrounding ionospheric grid squares for any IGP;
- Annular deprivation:

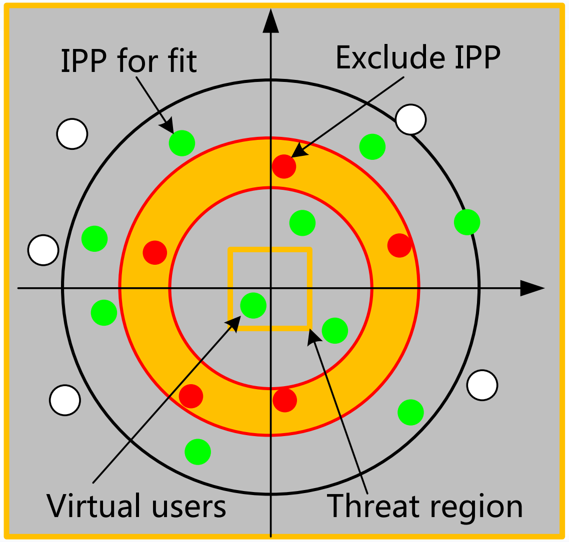
✓ separate out data in successive annuli, IPPs on an annulus (red plots) are not used for fit;

✓ The width of each annulus is 200km;

✓ The inner radius of annuli changes from 200km (exclude the threat region) to 2000km;

✓ IPPs in threat region are as virtual users.





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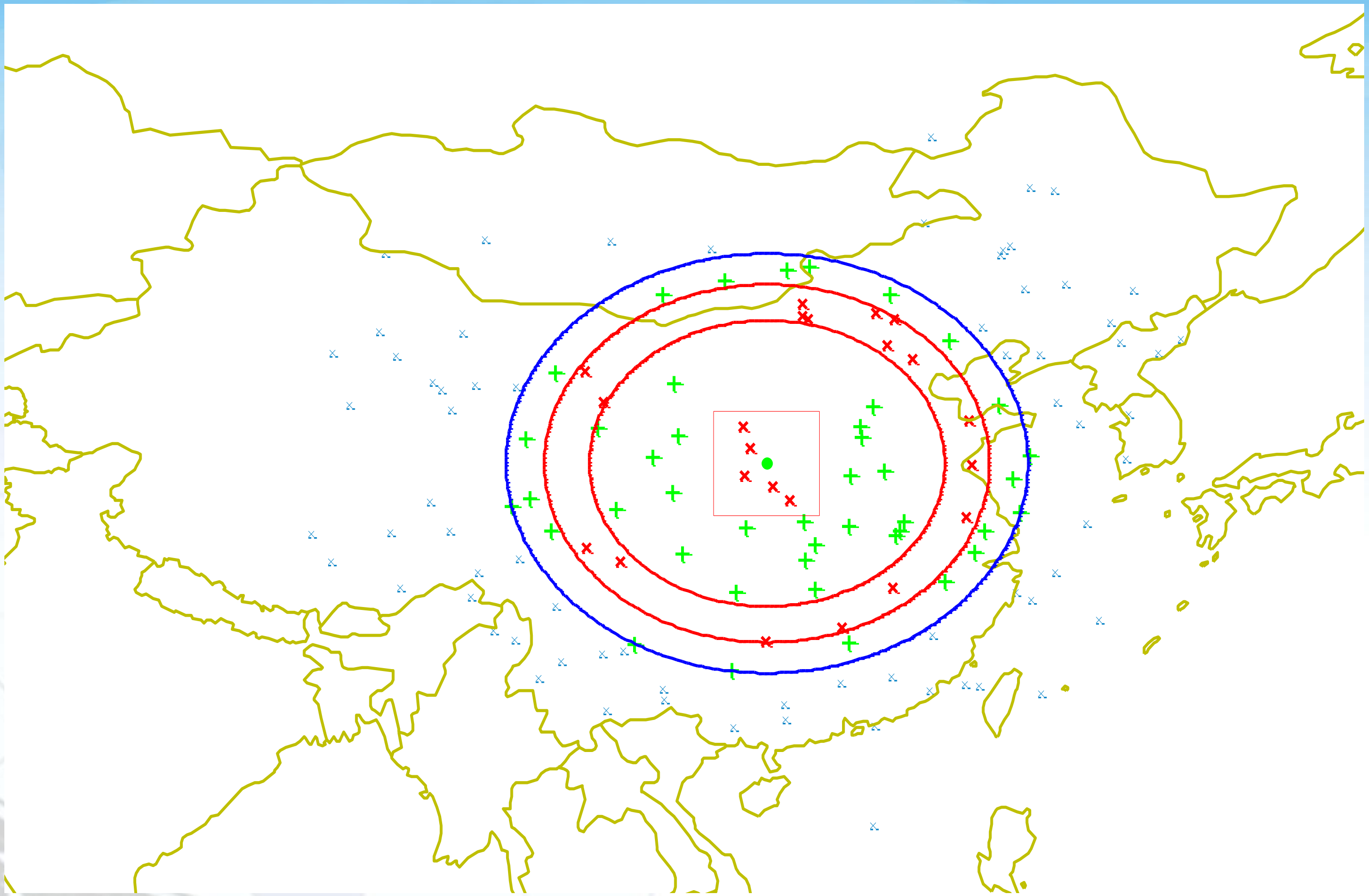
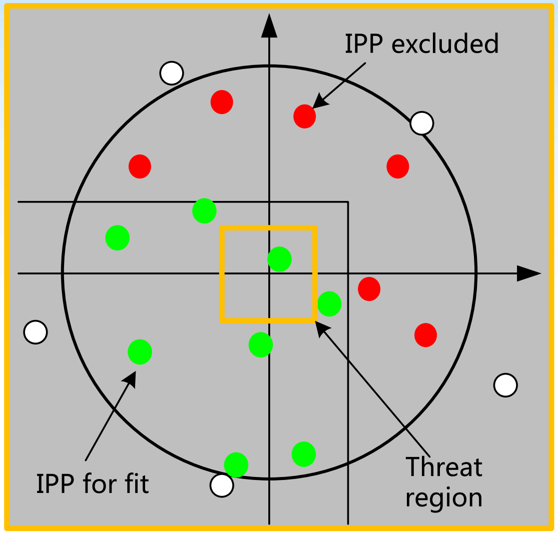


SBAS Ionospheric Correction & Integrity

Data deprivation method

- Three quadrant deprivation:
  - ✓ IPPs in three quadrants are excluded form fit algorithm;
  - ✓ IPPs in the remain quadrant are used to perform the planar fit;
  - ✓ the cutoffs are done at every 100km within a 500km range in four directions.
- Residuals between measurements and estimation from planar fit of IPPs in the threat region are prepared for creating the threat model.



SBAS Ionospheric Correction & Integrity

Calculation of $\sigma^{raw}_{undersampled}$

$$\sigma^{raw}_{undersampled}(R_{fit}, RCM) = \max \sqrt{\frac{\left|I_{v,IPP} - \hat{I}_{v,IPP}\right|^2}{K^2} - R^2_{irreg}\sigma^2_{IGP}}$$

$\sigma_{undersampled}$ is monotonic

$I_{v,IPP}$:is ionospheric delay measurement of an IPP

K :is nominal 5.33

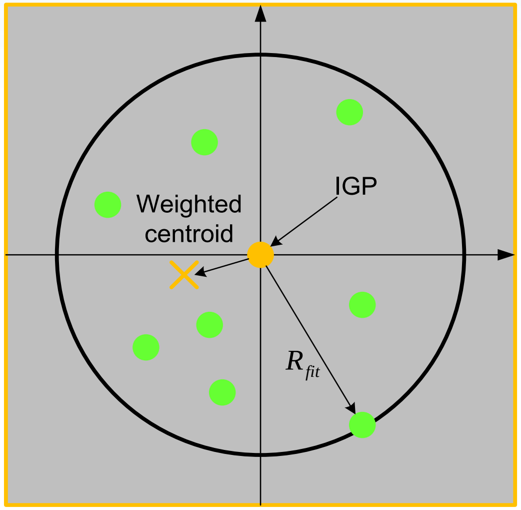
R_{irreg} :is a inflation factor from chi-square test

$\hat{I}_{v,IPP}$:is planar fit estimation

σ_{GIVE} :is formal variance form planar fit of the IGP

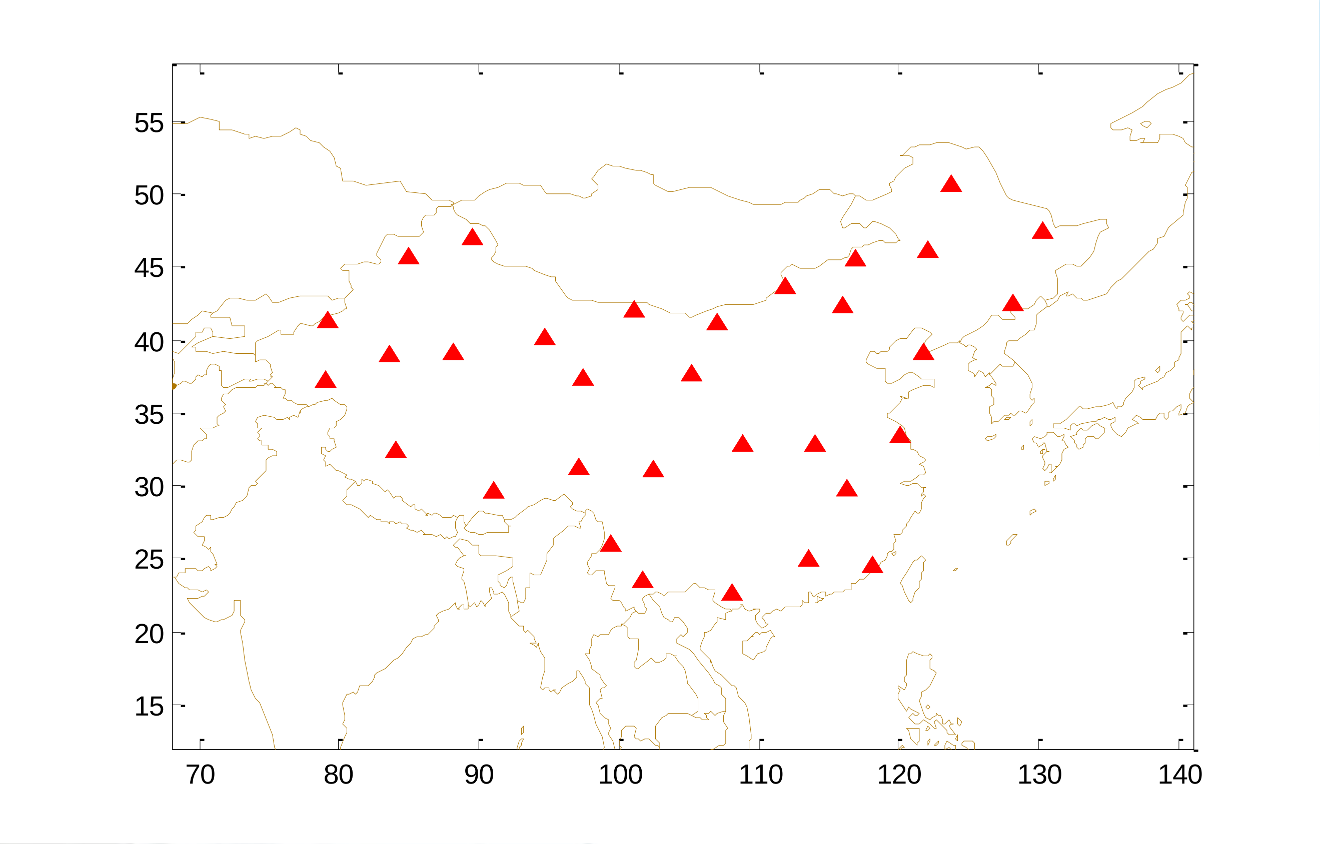
R_{fit} and RCM metric

$$\begin{bmatrix} 1 \\ d_{cent,x} \\ d_{cent,y} \end{bmatrix} = \frac{G^T \cdot W \cdot 1}{1^T \cdot W \cdot 1} \qquad RCM = \sqrt{d^2_{cent,x} + d^2_{cent,y}} \,/\, R_{fit}$$



SBAS Ionospheric Correction & Integrity

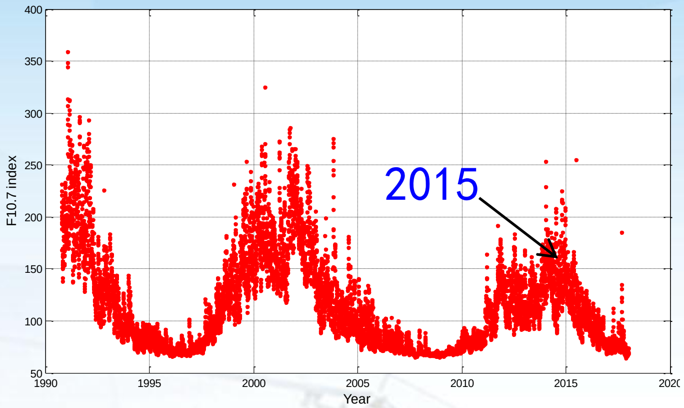
26 stations in Crustal Movement Observation Network of China are selected.

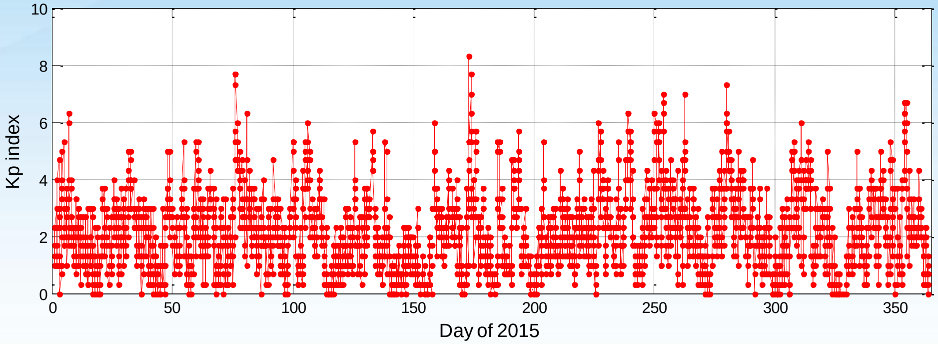


SBAS Ionospheric Correction & Integrity

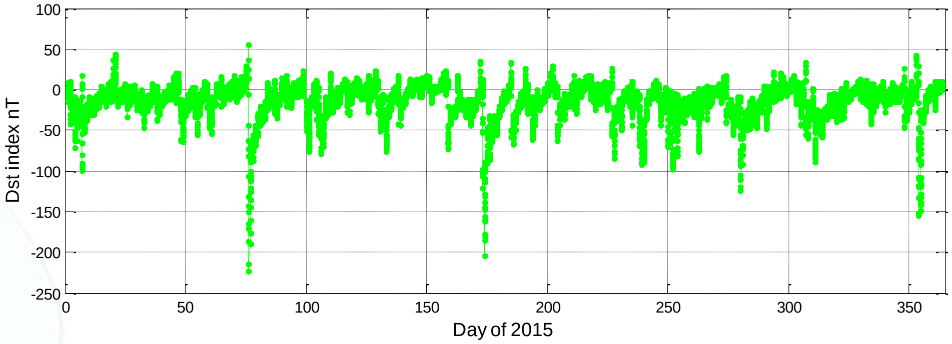
Data chosen according to Kp and Dst index

Four days of data in 2015 will be used in the analysis.





Day	Kp index	Dst index/nT
76	7.7	-223
174	7.7	-204
280	6.0	-124
354	6.3	-155



Data source is from: https://omniweb.gsfc.nasa.gov/form/dx1.html

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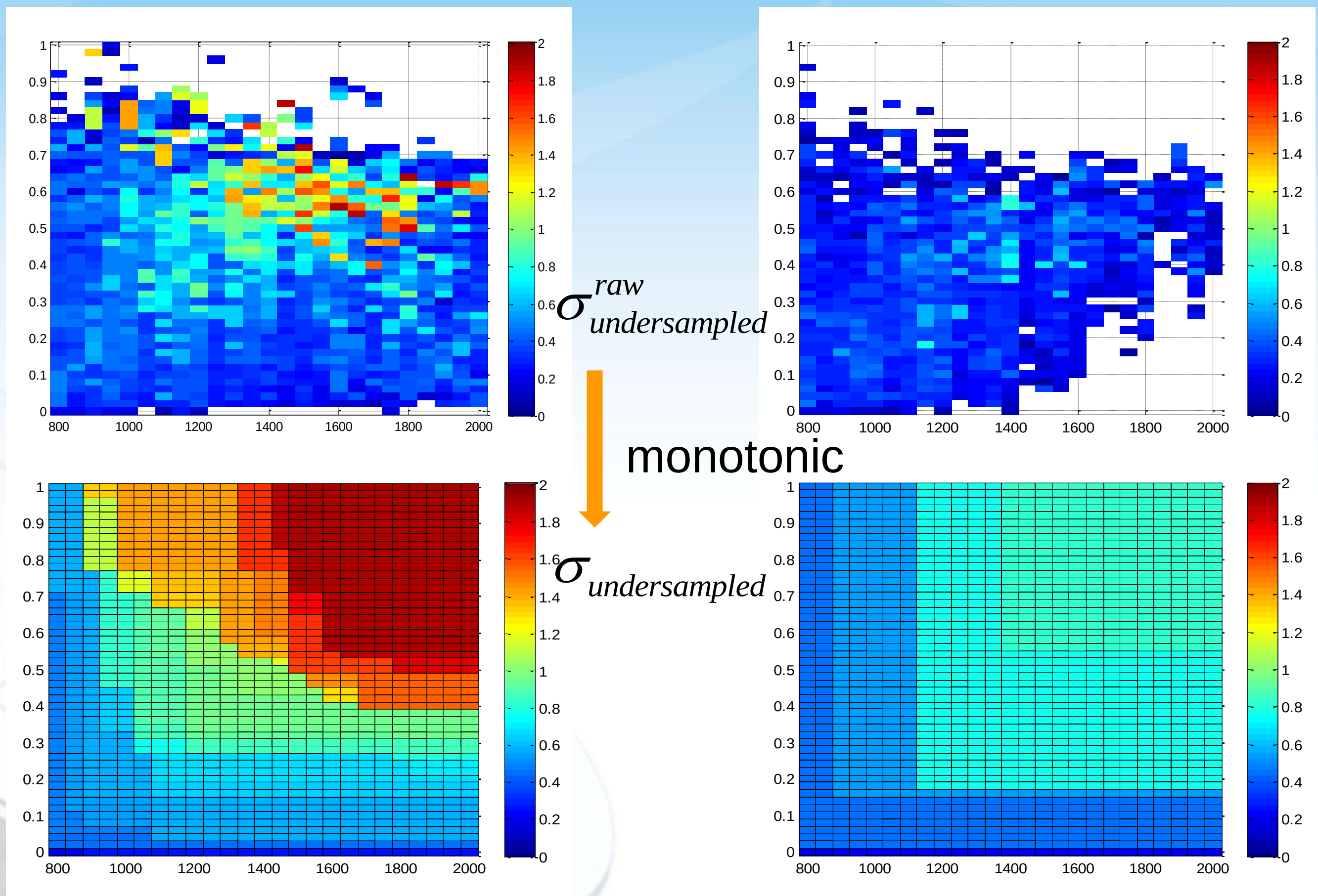
Annular Deprivation VS Three Quadrant Deprivation (Day 176)



Three Quadrant Deprivation

Annular Deprivation

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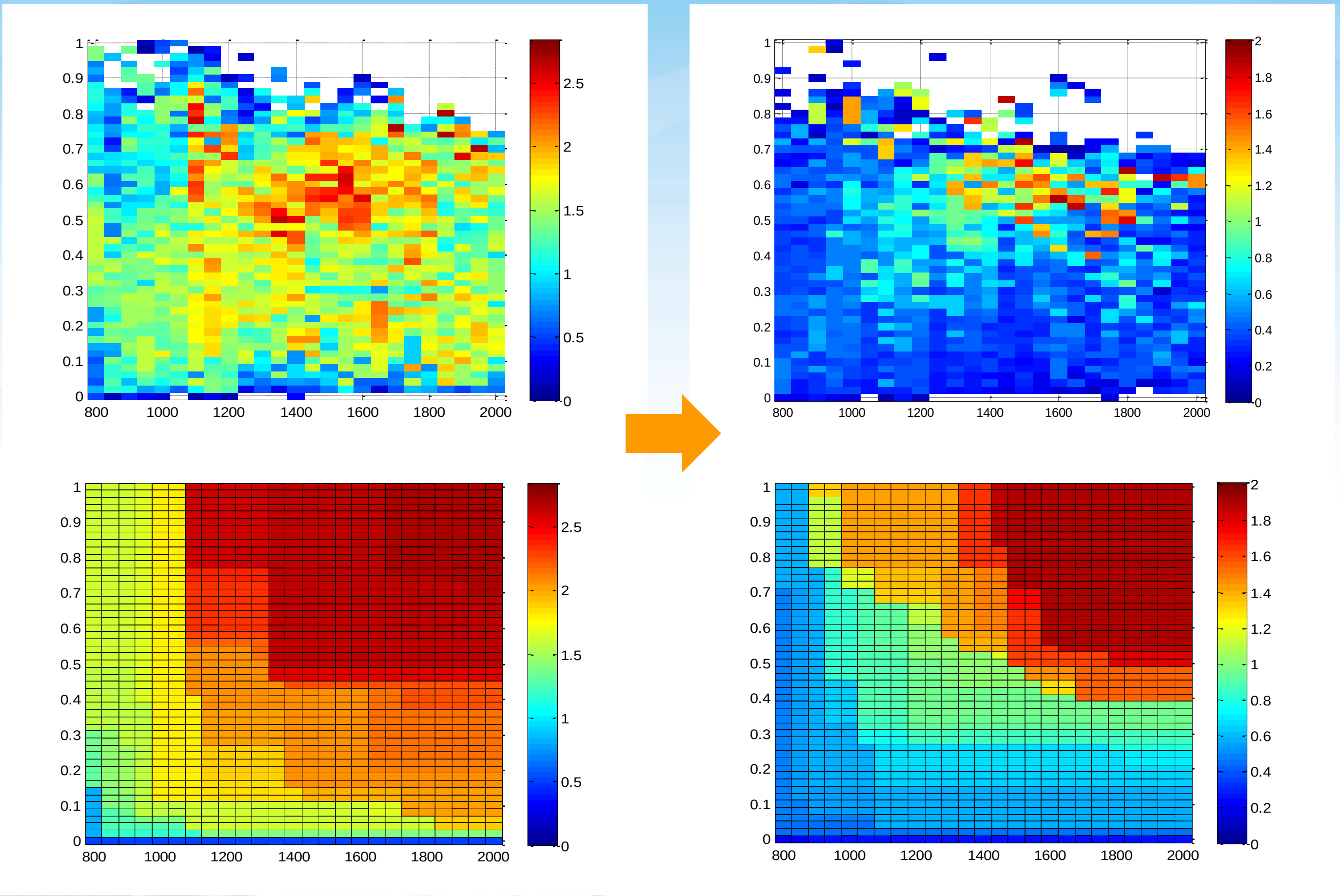
□ With VS without Irregularity detection



Without detection

With detection

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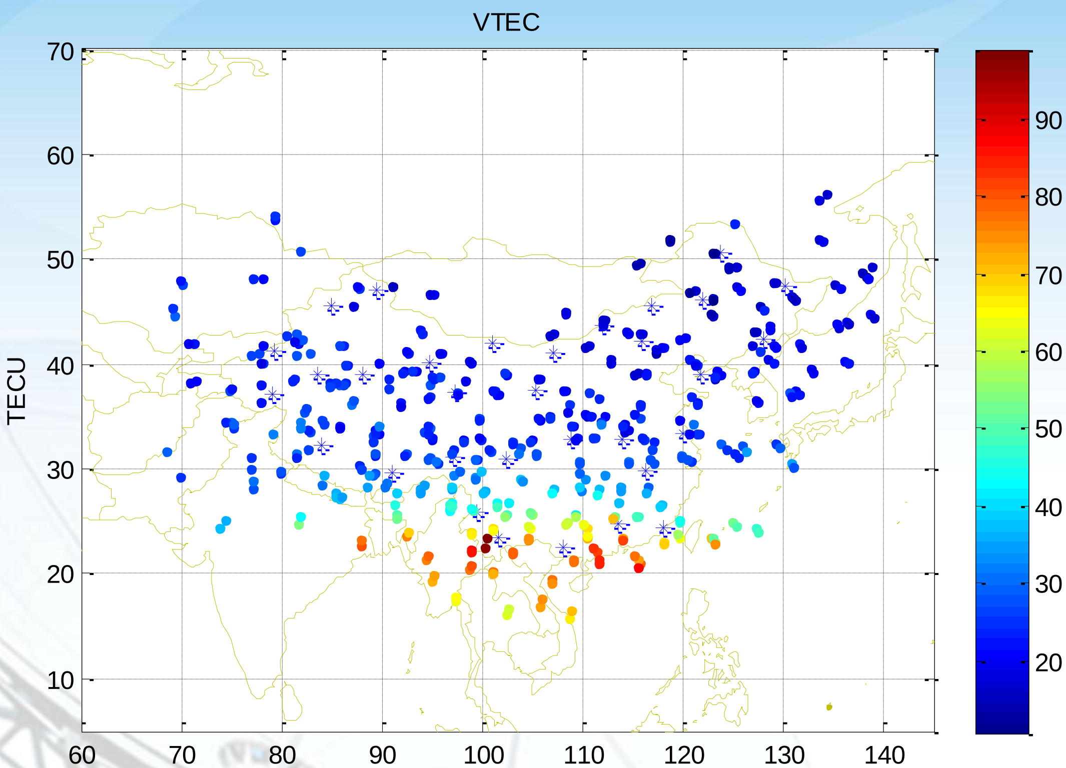
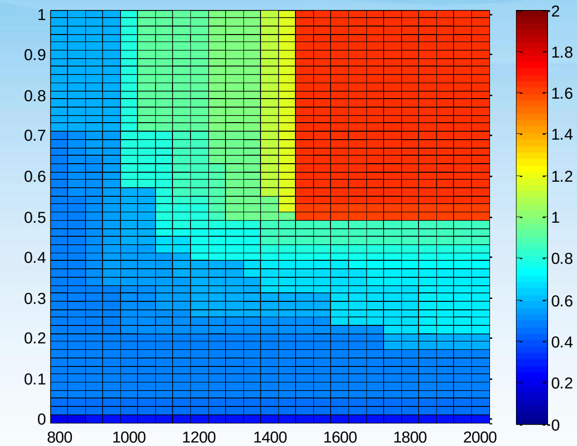
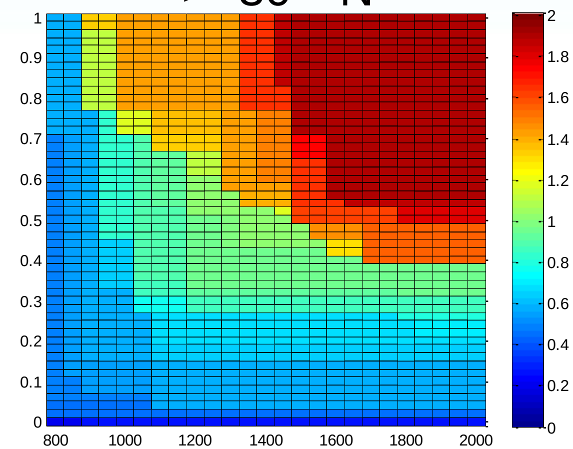
Threat model of different latitude



VTEC of IPP



>=30° N



>=15° N

Outline

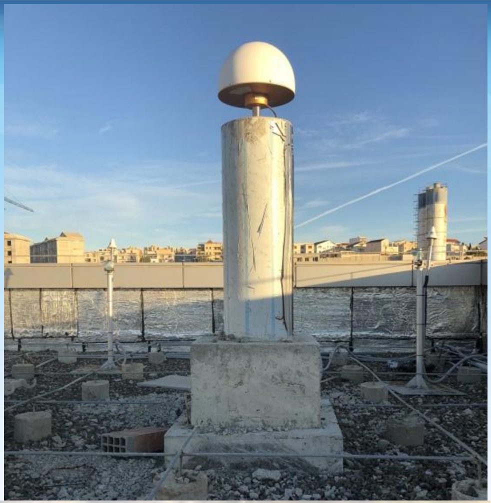
航天恒星科技有限公司(503所)
Space Star Technology Co.,Ltd
中国航天

- Introduction
- SBAS Ephemeris Correction & Integrity
- SBAS Ionospheric Correction & Integrity
- System development
- References

System development

GPS PRN:147&148

System provides PPP and SBAS (Non SOL) service.



System development

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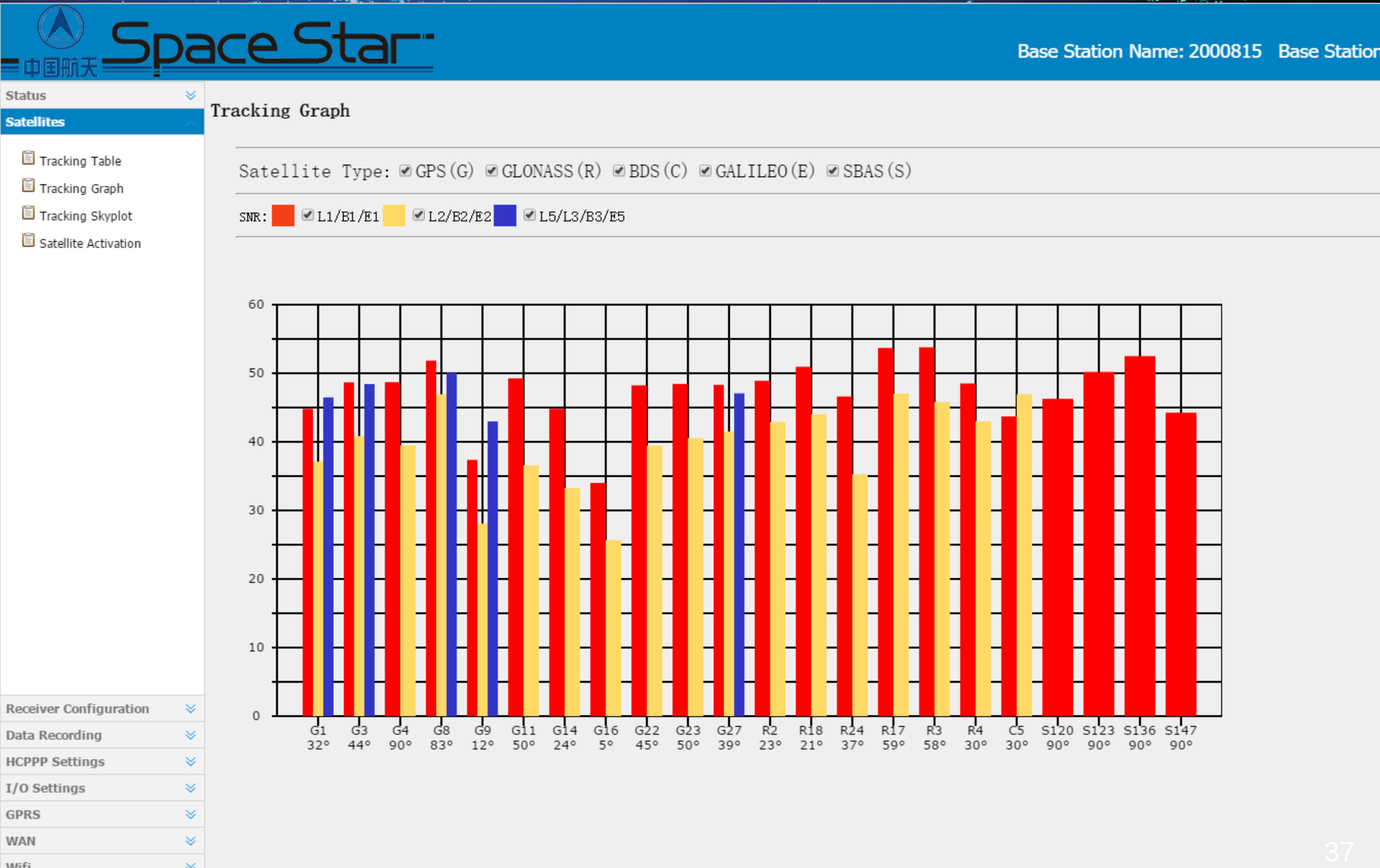
Space Star Technology Co.,Ltd



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Thank you !