Australian Government
Bureau of Meteorology


IGS Workshop 2018

29 October to 2 November

Wuhan, China

Multi-GNSS through Global Collaboration

Impact of strong space weather conditions on GNSS-based navigation

Germán Olivares-Pulido[1], Mike Terkildsen[2], Kirco Arsov[2]

[1]FrontierSI – Geoscience Australia
[2]Space Weather Services - Bureau of Meteorology

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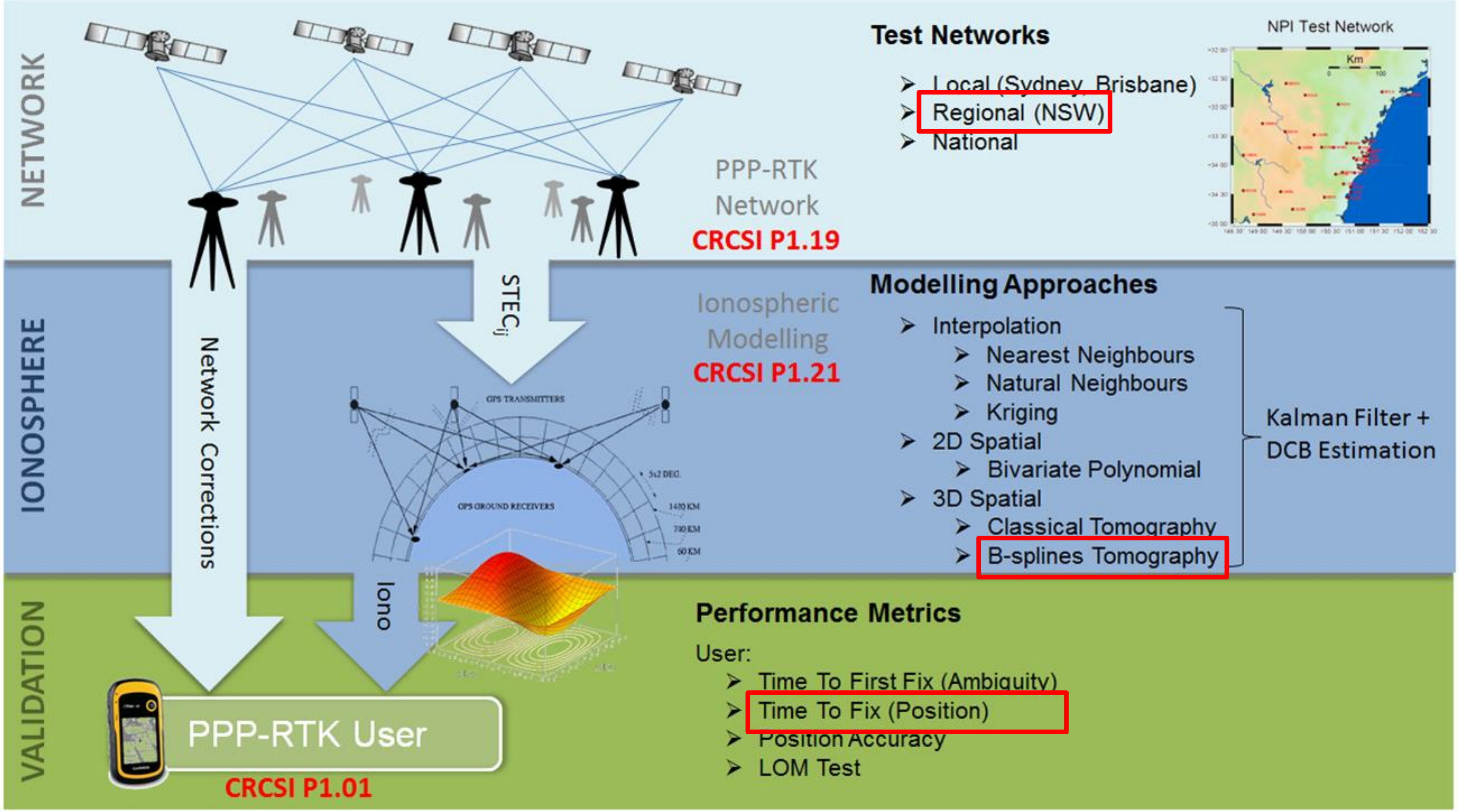
Introduction



PPP-RTK Network
CRCSI P1.19

Ionospheric Modelling
CRCSI P1.21

PPP-RTK User
CRCSI P1.01

Test Networks

- Local (Sydney, Brisbane)
- Regional (NSW)
- National

Modelling Approaches

- Interpolation
  - Nearest Neighbours
  - Natural Neighbours
  - Kriging
- 2D Spatial
  - Bivariate Polynomial
- 3D Spatial
  - Classical Tomography
  - B-splines Tomography

Kalman Filter + DCB Estimation

Performance Metrics

User:
- Time To First Fix (Ambiguity)
- Time To Fix (Position)
- Position Accuracy
- LOM Test

3D Tomographic Ionospheric Model

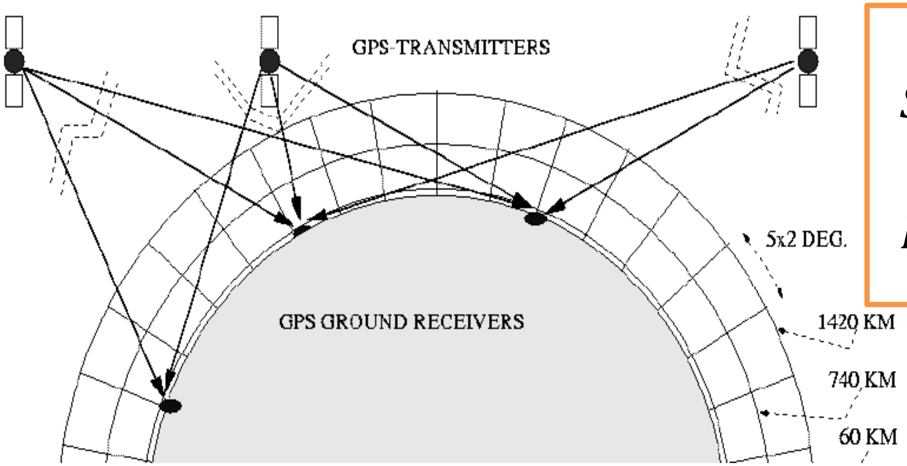


Figure from M. Hernandez-Pajares, J.M. Juan, J. Sanz, O.L. Colombo, Improving the real-time ionospheric determination from GPS sites at very long distances over the equator, J Geo Res, V. 107, No A10, 1296, doi:10.1029/2001JA009203, (2002).

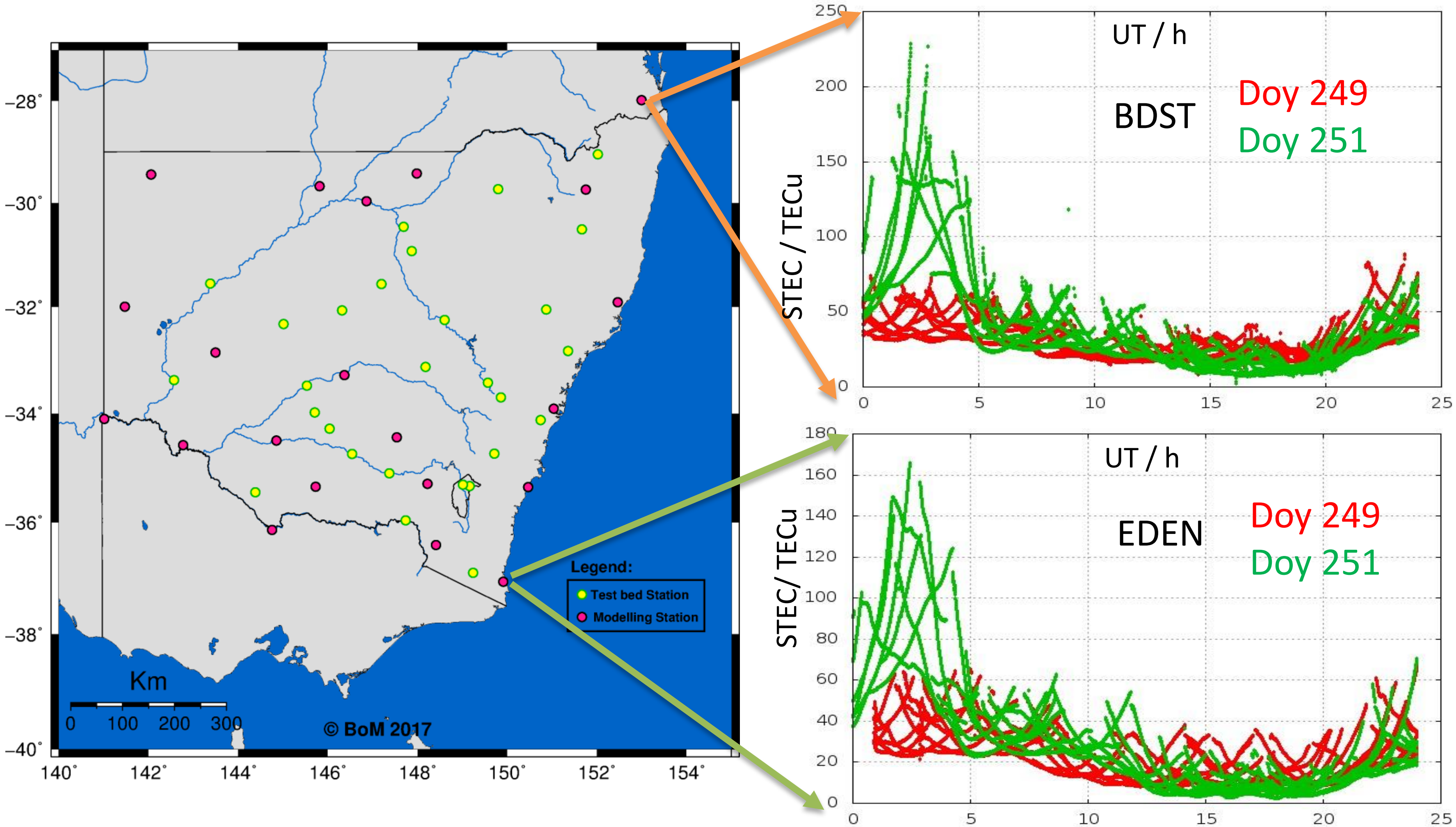
$$\tilde{S}_r^s(t) = \int_{P_r}^{P_s} N_e(t,\vec{r})dl + d_r - d^s$$

$$N_e(t,\vec{r}) \approx \sum_{ijk}^{IJK} c_{ijk}(t) \cdot \psi_i(\lambda) \cdot \psi_j(\theta) \cdot \psi_k(h)$$

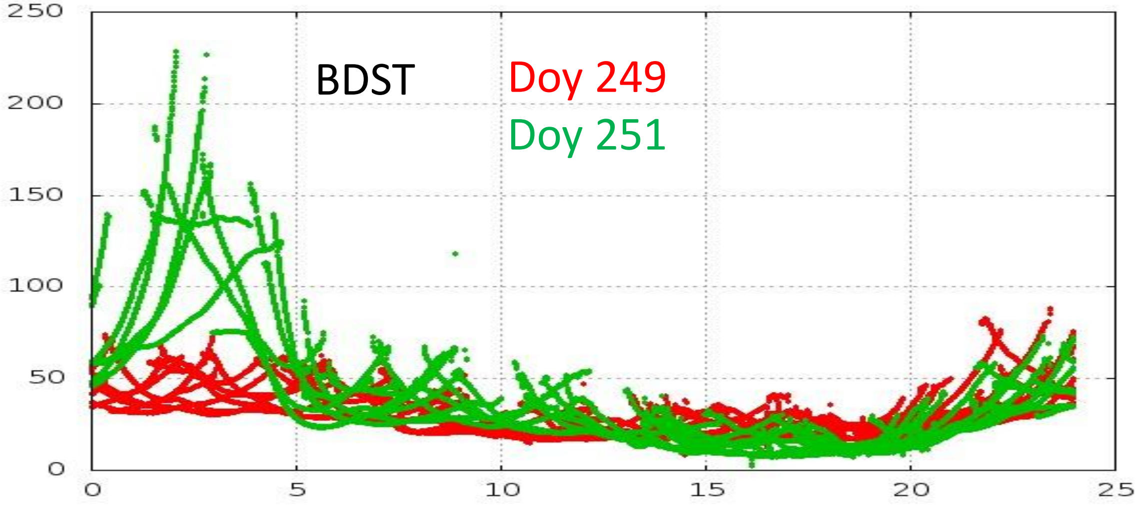
- $\tilde{\boldsymbol{S}}$: Biased Slant Total Electron Content computed by PPP-RTK platform (CRCSI Project 1.19).
- $\vec{\boldsymbol{r}}$: Receiver-satellite distance.
- $\boldsymbol{N_e}$: Electron Density.
- $\boldsymbol{d_r}/\boldsymbol{d^s}$: Receiver/Satellite DCB.
- $\boldsymbol{\psi_i}$: Basis function (e.g. splines, spherical harmonics).
- $\boldsymbol{c_{ijk}(t)}$: Basis function coefficient
- $\boldsymbol{I,J,K}$: Number of basis functions in each dimension.

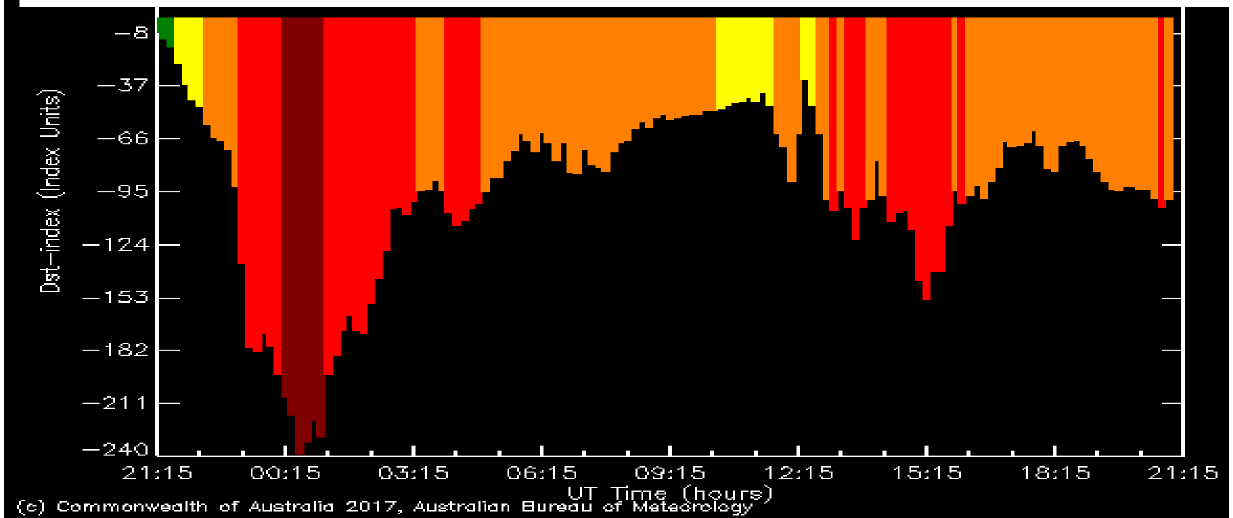
- No thin-shell approach, thus reducing miss-modelling.
- TEC is computed by integration of N_e.
- Offset does not depend on geometry, whereas STEC does → geometrically decorrelated from STEC with a dynamic model.

Data Set. Ionospheric Conditions



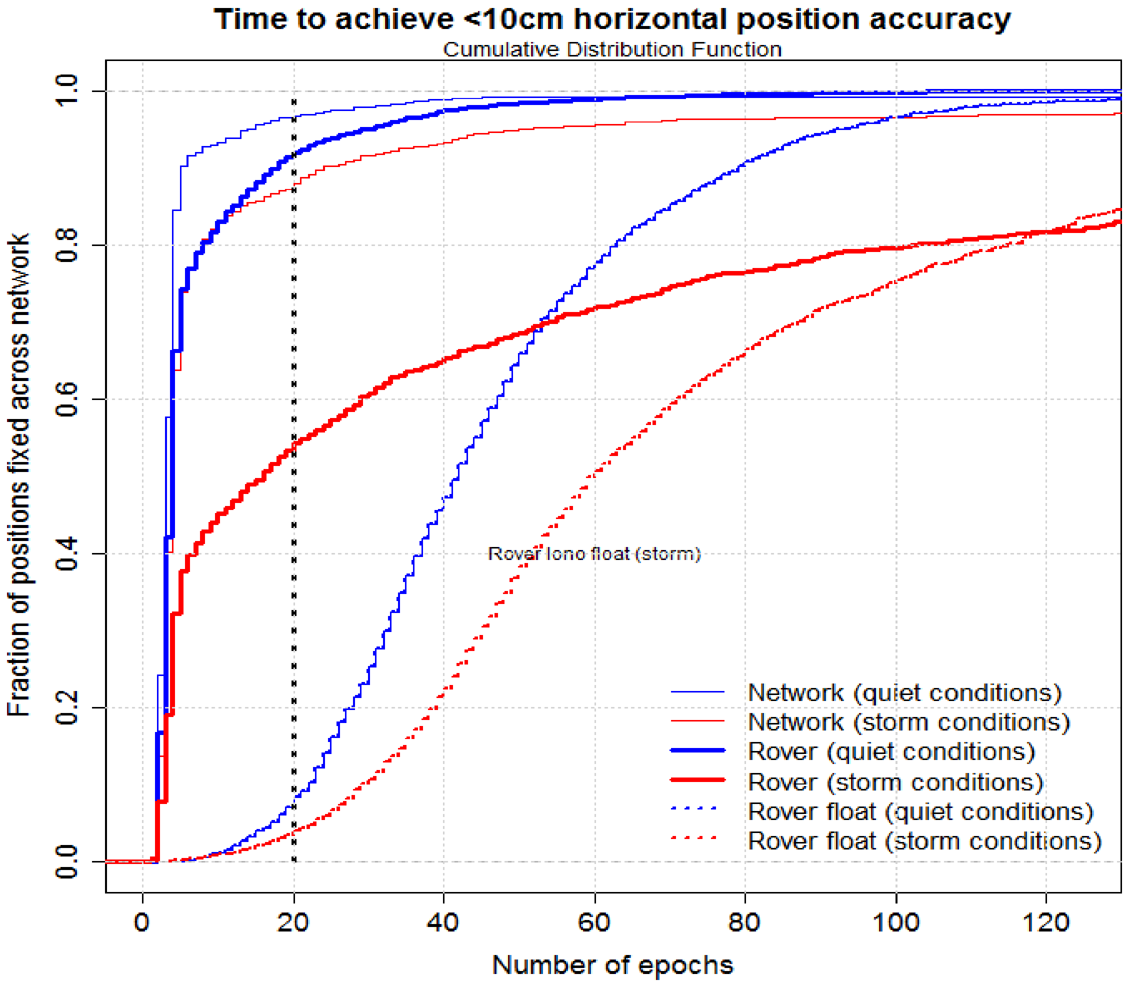
Data Set. Ionospheric Conditions





(c) Commonwealth of Australia 2017, Australian Bureau of Meteorology

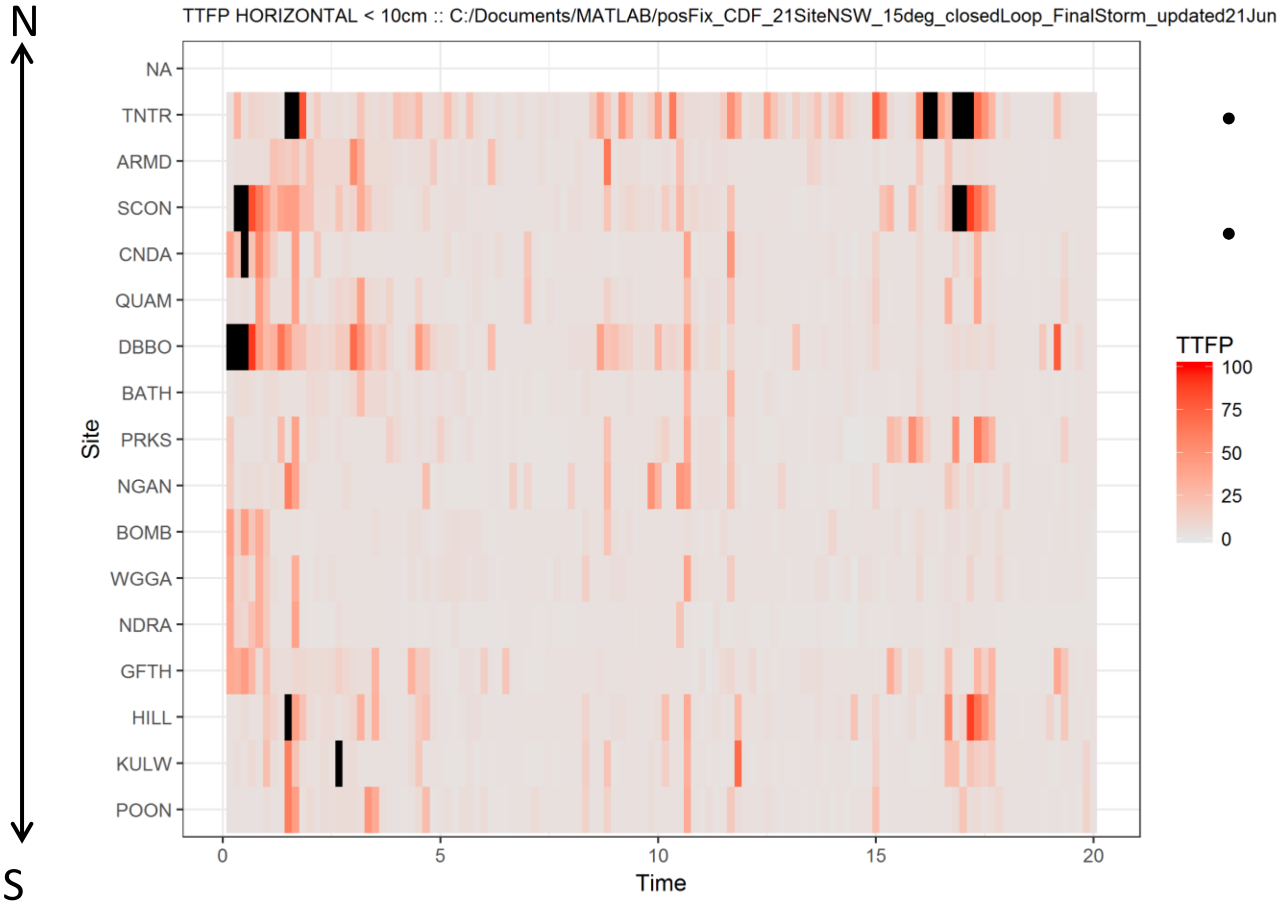
Results. Time To Fix Position



- Baseline ranges from 50 to 230 km.
- 1 epoch = 30 ʺ
- 15^o elevation cutoff

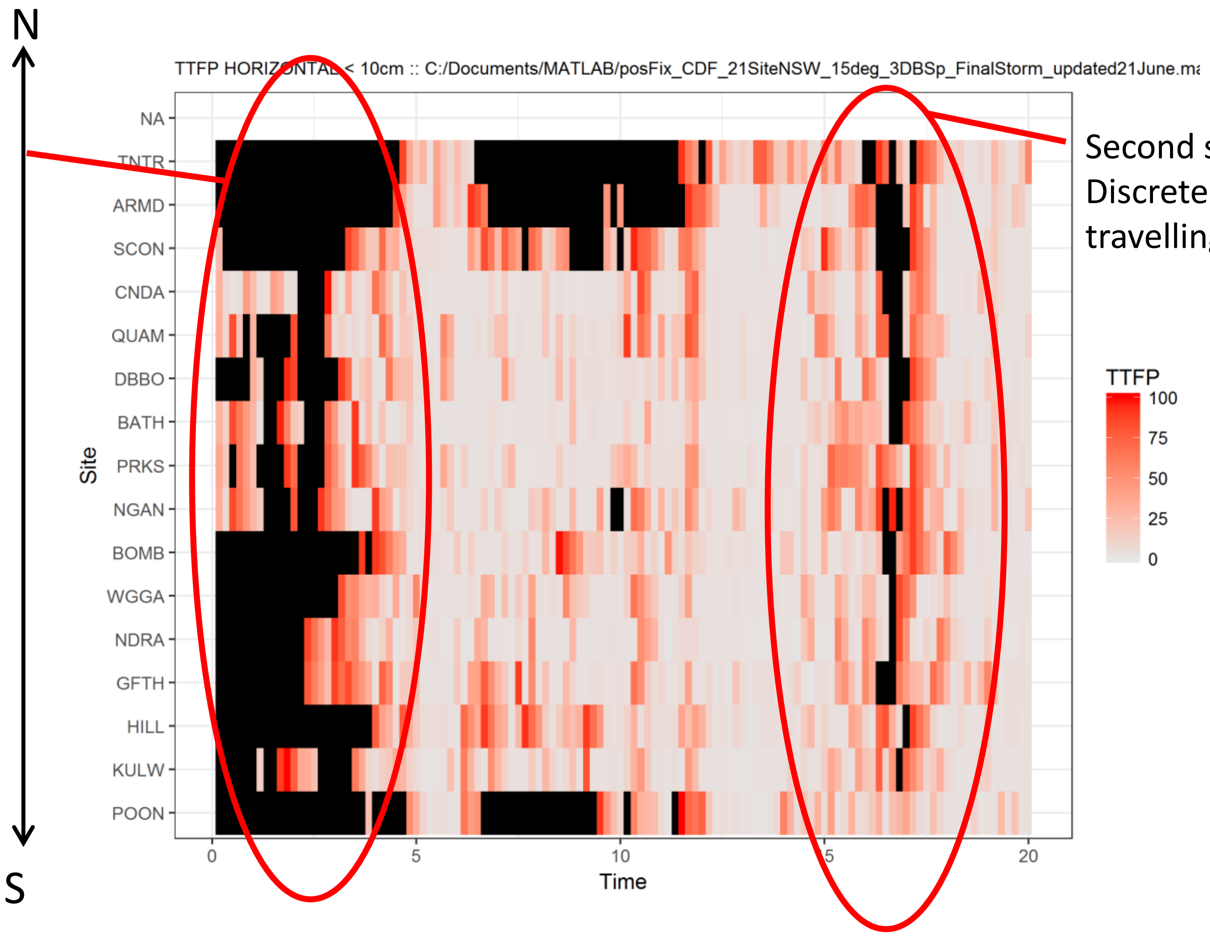
TTFP (epochs) at 90% CDF	Doy 211 2016 (Dst~0)	Doy 251 2017 (Dst~-240)
Network	~5	~25
Rover	~20	>120
Rover float	~80	>120

Results. Time To Fix Position



- Doy 251 2017 – Storm conditions.
- Network performance is rather homogenous.

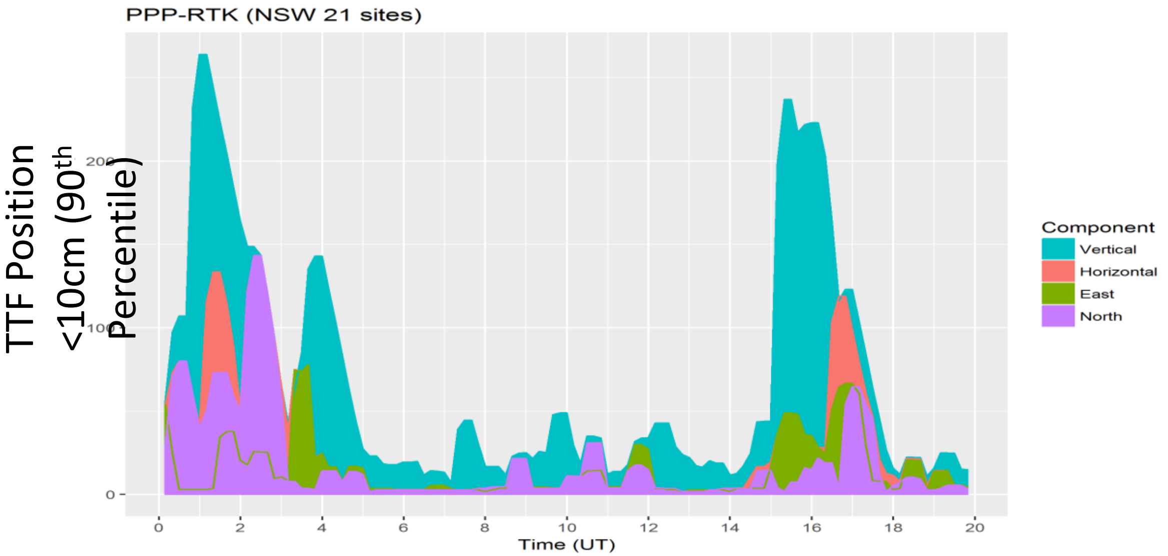
Results. Time To Fix Position

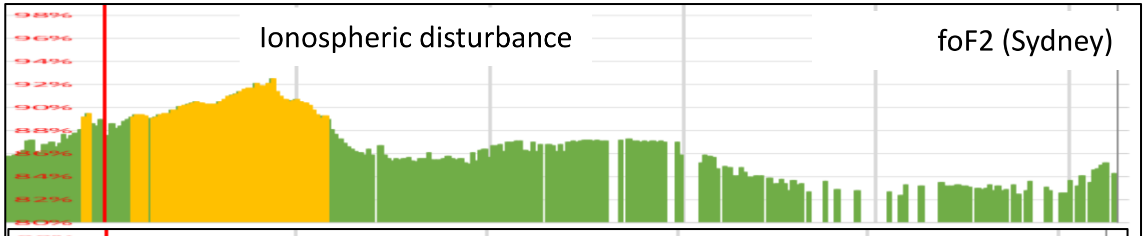


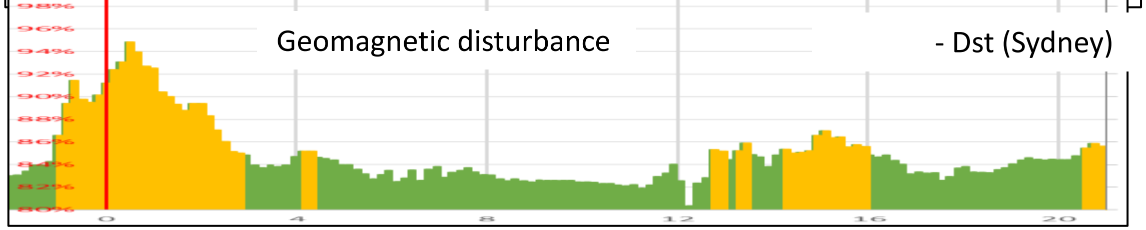
Main storm onset. Dayside; classical large scale positive phase ionospheric disturbance

Second storm onset. Nightside. Discrete TID-like disturbances travelling NW

Results. Time To Fix Position







- Both storm periods (dayside and nightside) degrade positioning performance
- Lagged response to the geomagnetic disturbance by ~2hrs
- Well correlated with the large scale ionospheric disturbance during the day (summarised by foF2).
- Nightside event not seen by ionosonde foF2: Either topside or small spatial scale density structure

Conclusions

- TTFP test-bed – 21 NSW (baseline [50-230] km) @ doy 212 (2016), which is representative of quiet ionospheric conditions.
- TTFP test-bed – 21 NSW @ doys 250 and 251 (2017) during a storm event.
- **Quiet conditions:** 3D Ionospheric model corrections → 90% CDF for TFP:
  - closed-loop (ground truth) is 10 epochs (H).
  - Ionospheric model is 20 epochs (H).
- **Storm conditions**: 3D Ionospheric model corrections → 90% CDF for TFP:
  - closed-loop (ground truth) is 20 epochs (H).
  - Ionospheric model is above 120 epochs (H). → Current interpolation method is not good enough to support PPP-RTK. → **Possible solution: addition of other GNSS constellations.**
- **Storm conditions:** 3D Ionospheric model corrections → General increase of TTFP for user across the network area.
- Correlation and delay between Dst and TTFP depending on user latitude coordinates.
- Influence of the plasmasphere on the PPP-RTK platform? → Increase of TTFP at local night time (~16:00-17:00 UT).
- **Space weather forecasting proxies for satellite-based navigation performance?**

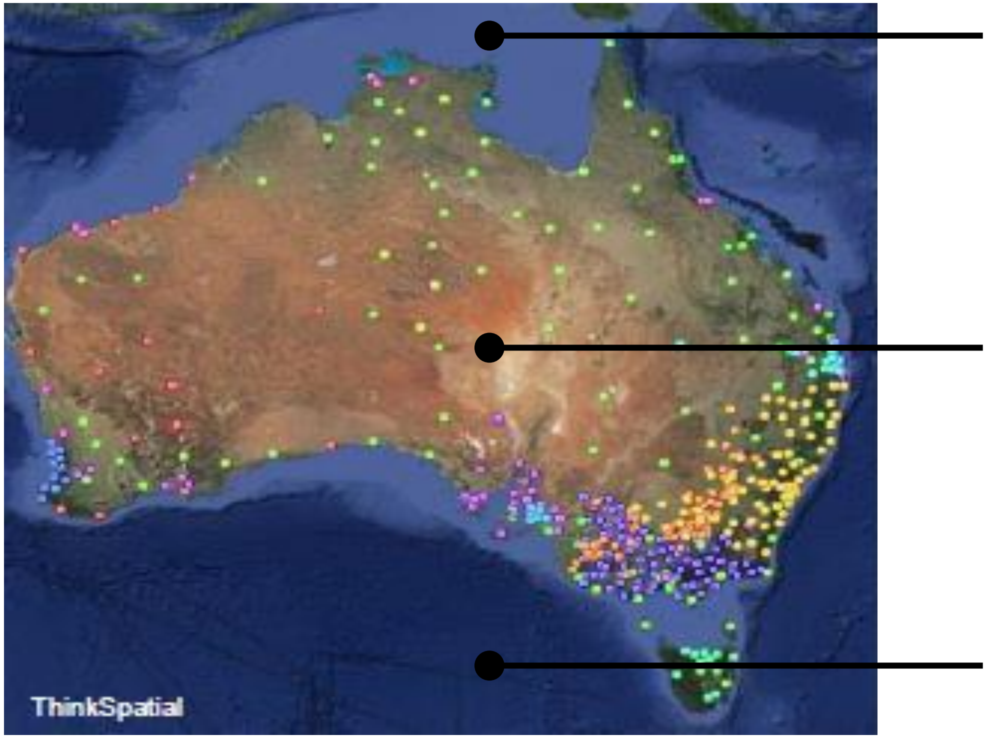
http://www.crcsi.com.au/research/1-positioning/1-21-ionospheric-modelling/

Thanks for your attention.
Any questions?

Introduction. Ionospheric scenario

http://www.crcsi.com.au/research/1-positioning/1-21-ionospheric-modelling/

- Non-homogeneous data distribution requires methods that properly handle data gaps.



Low latitudes

Equatorial Plasma Bubbles (EPB)

Large spatial gradients

Ionospheric Scintillation

Mid latitudes

Storm-Enhanced Density (SED)

Medium Scale Travelling Ionospheric Disturbances (MSTID)

High latitudes

Storm-Enhanced (Sub-Auroral) gradients

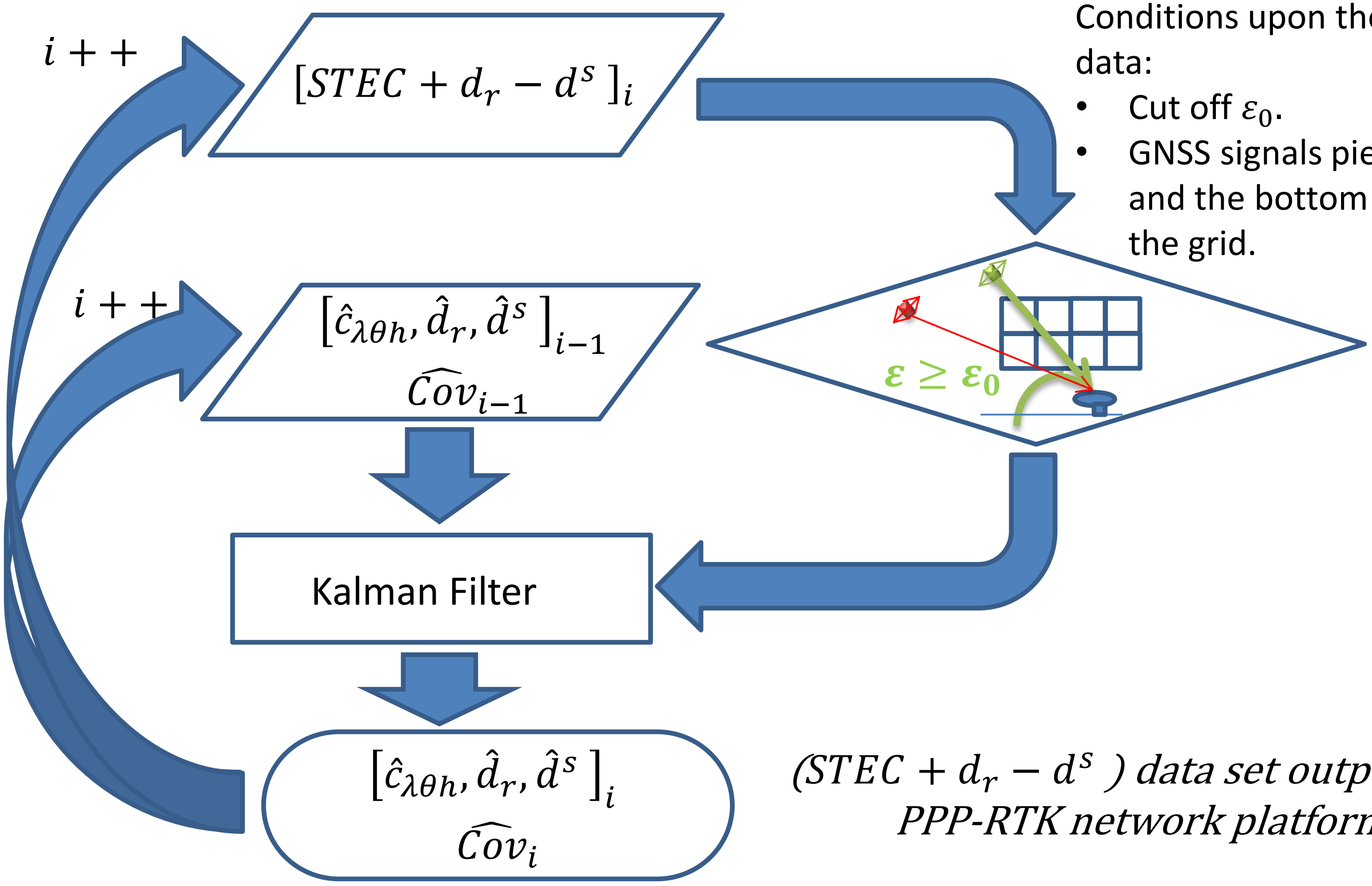
3D Tomographic Ionosphere model. Basis functions

- Local support basis functions → B-splines
- Global support basis functions → Spherical Harmonics
- Local-support functions are zero everywhere except for a subinterval of the grid, as oppose to global-support functions.
- Implications of such difference are three:
    1. Faster computation of linear combinations of local-support functions (e.g. LOS path-integral).
    2. Computed VTEC maps based on local-support functions are lest affected by data gaps. [e.g. Schmidt, M., Dettmering, D., Möβmer, M., Wang, Y., and Zhang, J., Comparison of spherical harmonic and B spline models for the vertical total electron content, Radio Sci., 46, RS0D11, doi:10.1029/2010RS004609 (2011)].
    3. SH basis functions can compute global VTEC maps even with gaps in the input-data set. B-splines coefficients can be estimated only in areas with data.

3DB-tomion flow chart

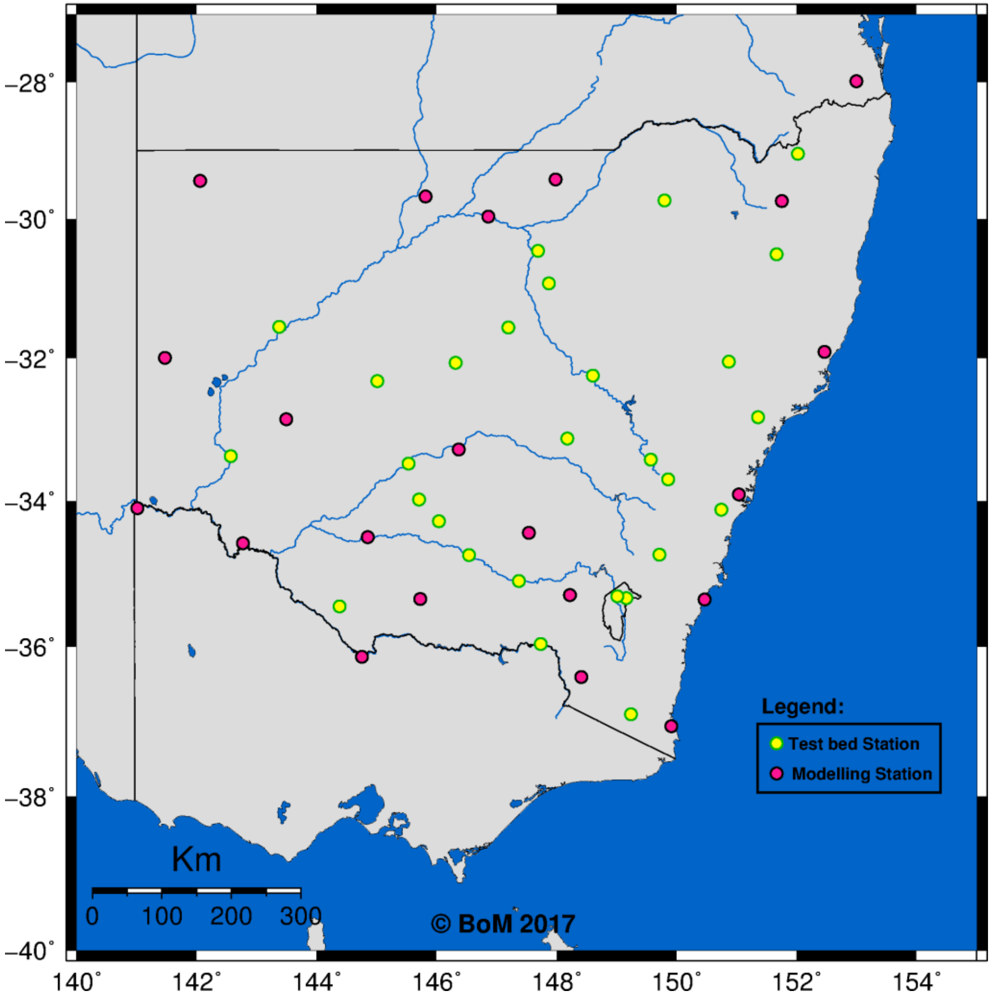
Conditions upon the input data:

- Cut off ε_0.
- GNSS signals pierce the top and the bottom sides of the grid.



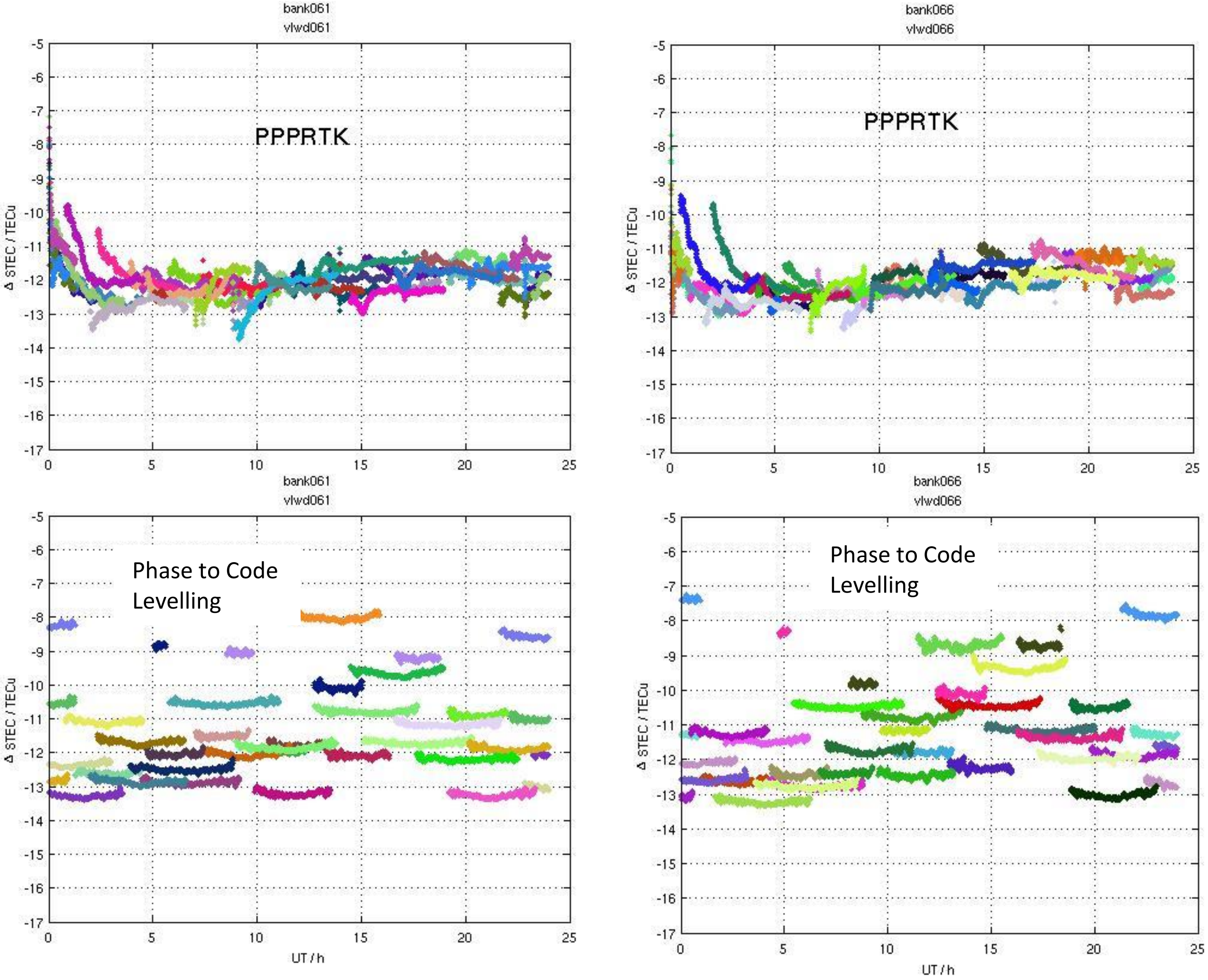
($STEC + d_r - d^s$) data set output from PPP-RTK network platform.

Ionospheric sounding. Quiet conditions. NSW data Set



- The multiscale analysis of the post fit residuals revealed that 5 receivers had issues → 21 GPS receivers (red dots) network for 3D ionospheric modelling in NSW, year 2016, doys 211, 212.
- 28 dual-frequency GPS rovers (yellow dots).

Ionospheric sounding. Quiet conditions. NSW. STEC retrieval



- PPP-RTK is more accurate fixing ambiguities than the standard phase-to-code levelling method

↓

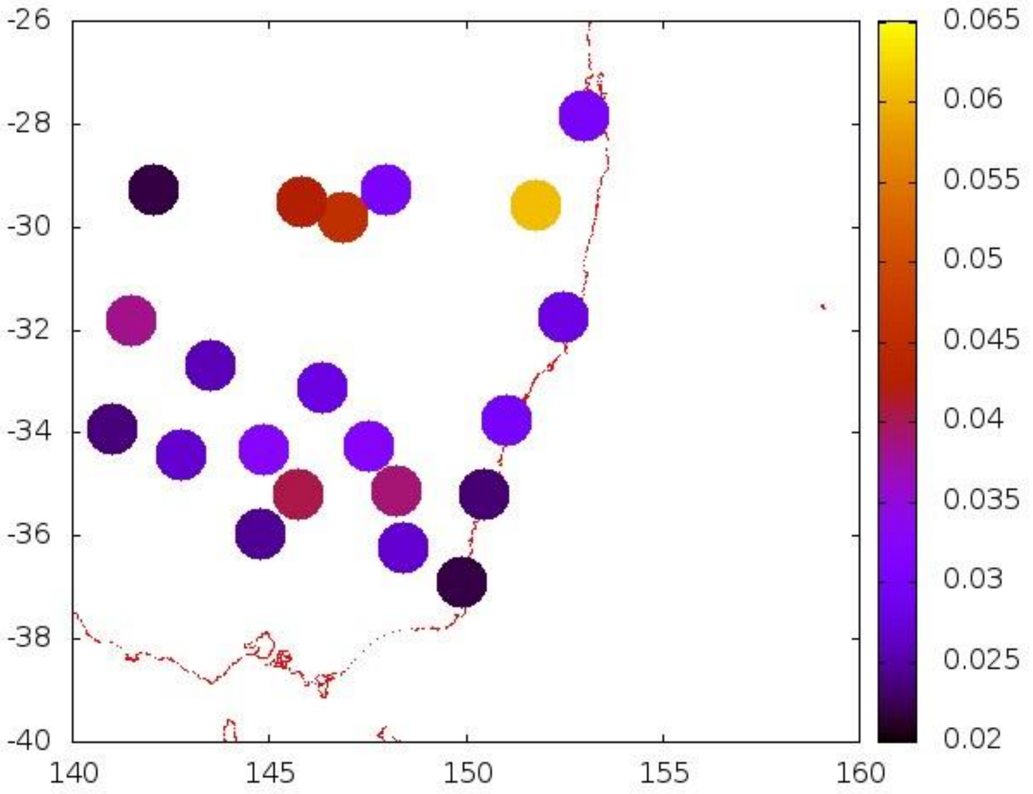
- PPP-RTK STEC output is more accurate and much less scattered than the STEC estimated by the standard phase-to-code levelling.
- Baseline is $\sim 7\ km$ → $S_1^s \approx S_2^s$

$$\boxed{\tilde{S}_1^s - \tilde{S}_2^s = d_{1,GF} - d_{2,GF}}$$

- In good agreement with other authors, e.g. Wenfeng Nie et al. GPS Solutions Nie, W., Xu, T., Rovira-Garcia, A. et al. GPS Solut (2018) 22: 85. https://doi.org/10.1007/s10291-018-0753-7.

Ionospheric sounding. Quiet conditions. NSW. Post fit analysis

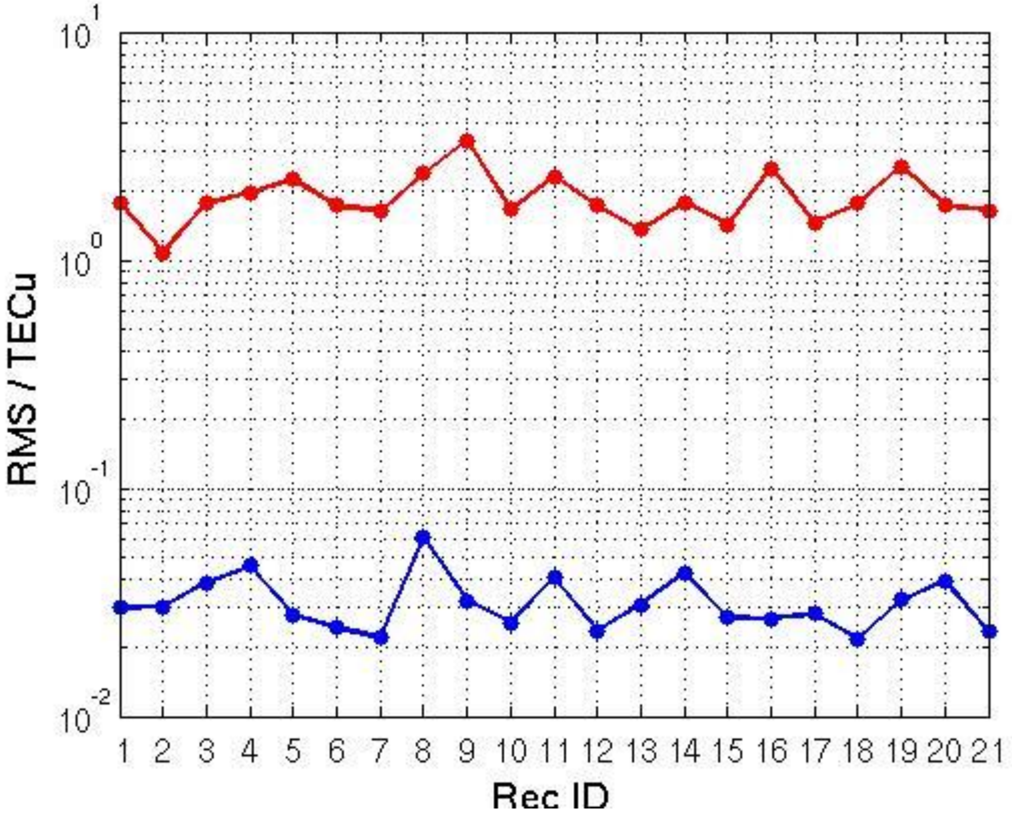
- Post fit analysis assesses the consistency of the ionospheric model with the receivers used in the modelling.



- RMS ranges from 0.02 to 0.07 TECu.
- No geographical trend due to the local-support feature of B-splines.

Ionospheric sounding. Quiet conditions. NSW. Post fit analysis

- Post fit analysis assesses the consistency of the ionospheric model with the receivers used in the modelling.
- 2D or 3D ionospheric model?



- RMS for 2D model is ~100 times higher than for 3D models.
- 2D residual RMS is at TECu level (1 TECu ~ 0.1 m) → Cannot support positioning techniques to achieve RMS at cm level in real-time.
- 3D residual RMS is at 10^{-2} TECu level (i.e ~ mm) → It might support positioning techniques to achieve RMS at cm level in real -time.

3D Tomographic Ionosphere model. B-Splines

$$\boldsymbol{\psi_i^1(x) = \begin{cases} 1 \ if \ x_i \le x < x_{i+1} \\ 0 \qquad otherwise \end{cases}}$$

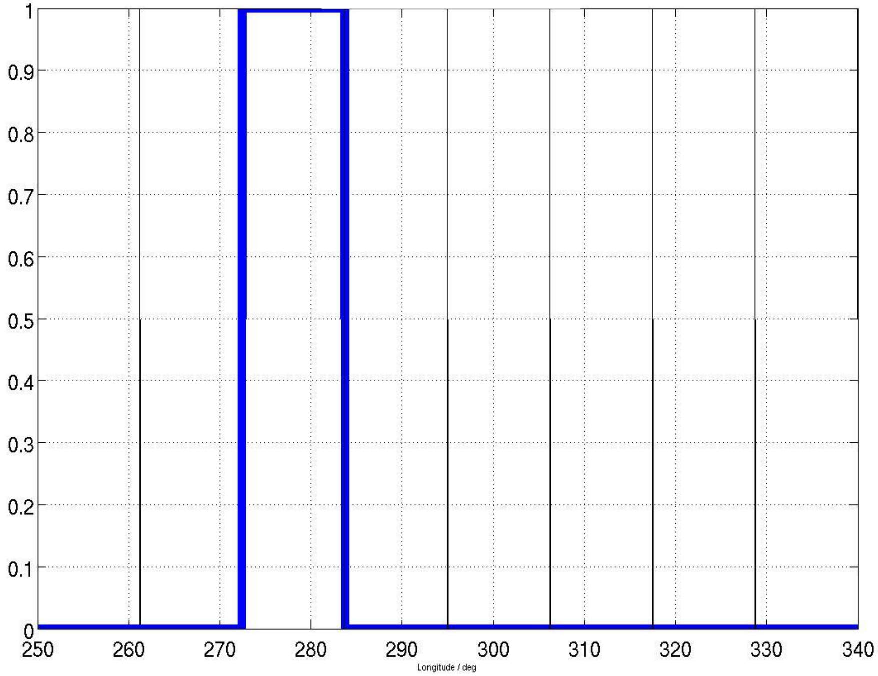
$$\psi_i^{p+1}(x) = \frac{x - x_i}{x_{i+1} - x_i}\psi_i^p(x) + \frac{x_{i+p+1} - x}{x_{i+p+1} - x_{i+1}}\psi_{i+1}^p(x)$$

For further details see E.J. Stollnitz et al. (1995).

- p: Spline order ∈ $\mathbb{N}$.
- J: Resolution level ∈ $\mathbb{N}$.
- K: Number of m-order Splines ∈ $\mathbb{N}$.
- x_i: ith knot.

- B-splines have **local support**→ local data at 280° do no affect modelling at 320°.
- Data compression algorithms based on B-splines.

$$J = 3, p = 1 \rightarrow K = 2^J + p - 1 = 8$$



- E.J. Stollnitz, T.D. DeRose, D.H. Salesin, "Wavelets for Computer Graphics: A Primer, Part 2", IEEE Computer Graphics and Applications, 15(4):75-85, July 1995.

3D Tomographic Ionosphere model. B-Splines

$$\psi_i^1(x) = \begin{cases} 1 \; if \; x_i \le x < x_{i+1} \\ 0 \qquad otherwise \end{cases}$$

$$\boldsymbol{\psi_i^p(x) = \frac{x - x_i}{x_{i+1} - x_i}\psi_i^{p-1}(x) + \frac{x_{i+p+1} - x}{x_{i+p+1} - x_{i+1}}\psi_{i+1}^{p-1}(x)}$$

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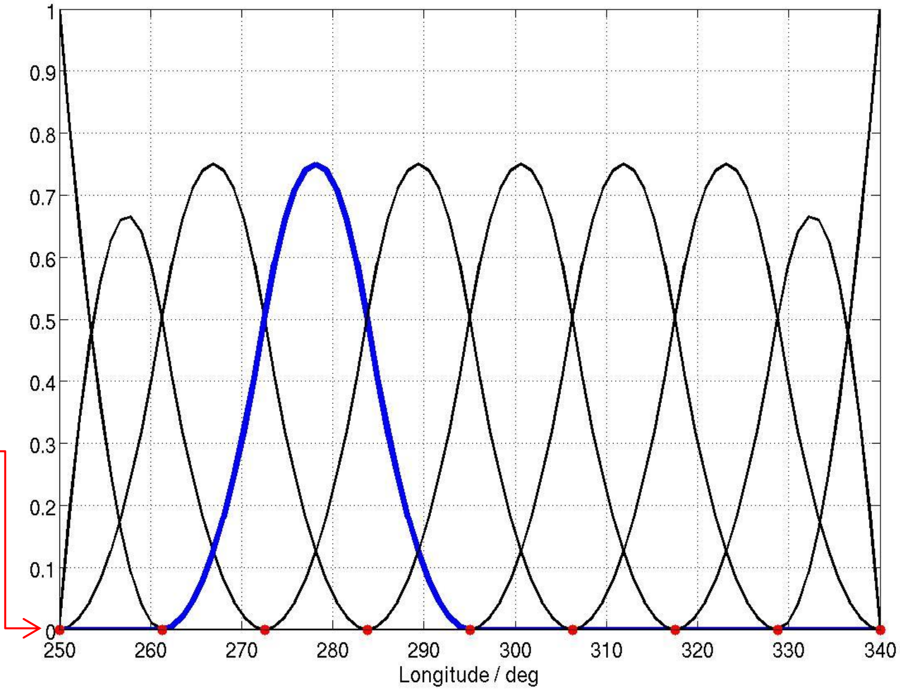
- x_i: ith knot.

- B-splines have **local support**→ local data at 280° do no affect modelling at 320°.
- Data compression algorithms based on B-splines.

$$J = 3, p = 3 \rightarrow K = 2^J + p - 1 = 10$$

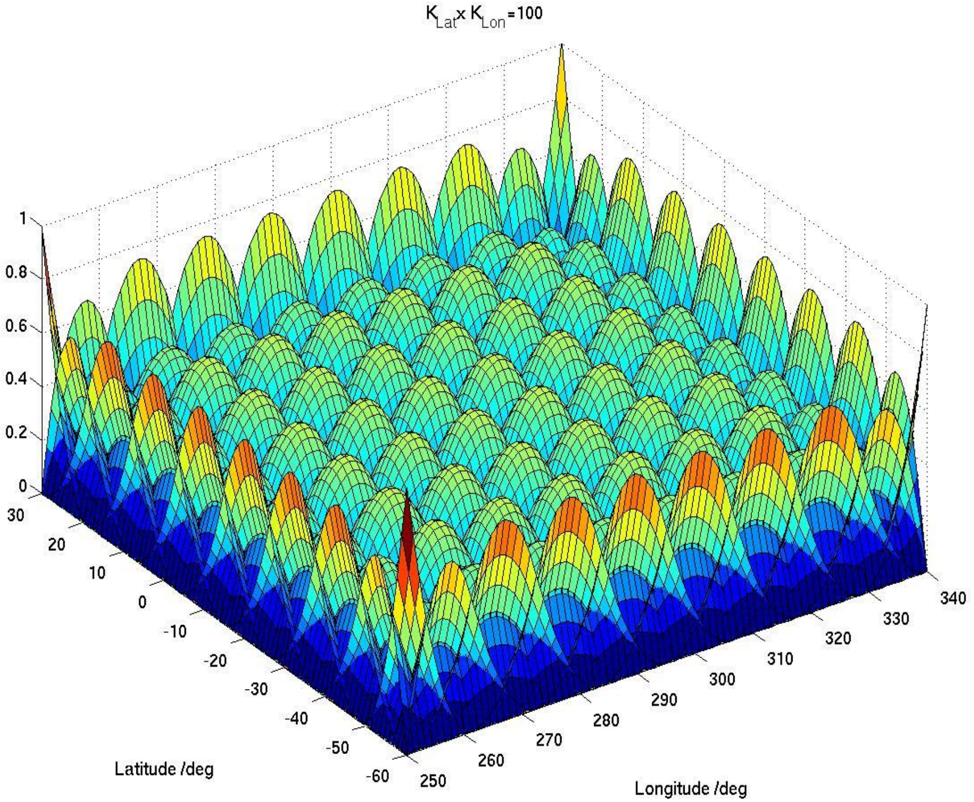


- E.J. Stollnitz, T.D. DeRose, D.H. Salesin, "Wavelets for Computer Graphics: A Primer, Part 2", IEEE Computer Graphics and Applications, 15(4):75-85, July 1995.

3D Tomographic Ionosphere model. B-Splines

- Functions of higher dimensions (i.e several order and resolution levels) are computed by the tensor product of 1D B-splines, e.g:

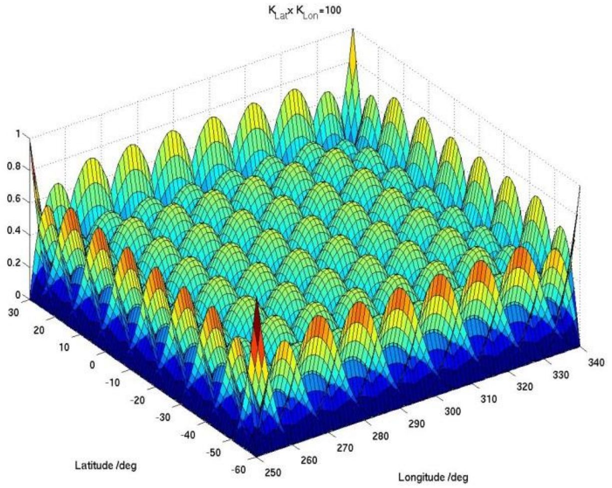
$$f(x,y) = \sum_{i=1}^{K_{Lon}} \sum_{j=1}^{K_{Lat}} \psi_i^p(x) \cdot \varphi_j^q(y)$$

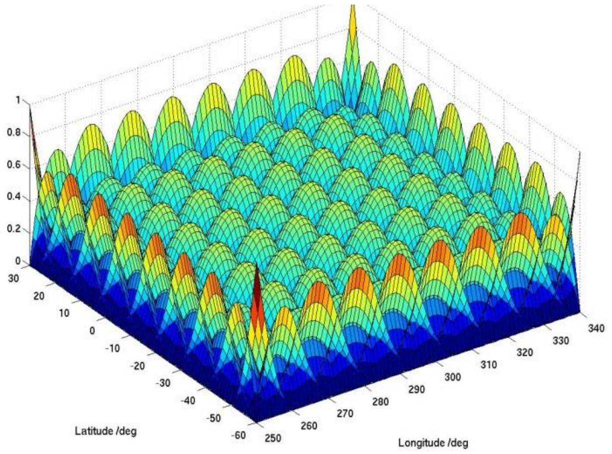


3D Tomographic Ionosphere model. B-Splines

- Ground-based data provide horizontal high-resolution and vertical low-resolution → Simplest 3D Ionospheric model with B-splines: High order B-splines in longitude (λ) and latitude (θ) and two vertical wide layers (h).

$$f(\lambda,\theta,h)=\sum_{i=1}^{K_{Lon}}\sum_{j=1}^{K_{Lat}}\sum_{k=1}^{2}\psi_i^p(\lambda)\cdot\psi_j^q(\theta)\cdot\psi_k^1(h)$$





Ionospheric sounding. STEC retrieval

- STEC is computed as a PPP-RTK parameter.
- PPP-RTK is integer ambiguity resolution enabled PPP.
- PPP-RTK provides satellite orbit and clock models, information about satellite phase and code biases, and the atmosphere.
- Un-differenced and un-combined method:

$$\phi^s_{r,j} = \rho^s_r + (dt_r - dt^s) + \tau^s_r - \mu_j S^s_r + \lambda_j\left(\delta_{r,j} - \delta^s_{,j} + z^s_{r,j}\right) + \epsilon^s_{r,j} \; ; \qquad \mu_j \equiv {}^{\lambda_j^2}\!/_{\lambda_1^2}$$

$$p^s_{r,j} = \rho^s_r + (dt_r - dt^s) + \tau^s_r + \mu_j S^s_r + \left(d_{r,j} - d^s_{,j}\right) + \xi^s_{r,j}$$

Rank deficiency is overcome by S-basis theory

$$\phi^s_{r,j} = \rho^s_r + (d\tilde{t}_r - d\tilde{t}^s) + \tau^s_r - \mu_j \tilde{S}^s_r + \lambda_j\left(\tilde{\delta}_{r,j} - \tilde{\delta}^s_{,j} + \tilde{z}^s_{r,j}\right) + \epsilon^s_{r,j}$$

$$p^s_{r,j} = \rho^s_r + (d\tilde{t}_r - d\tilde{t}^s) + \tau^s_r + \mu_j \tilde{S}^s_r + \xi^s_{r,j}$$

$$\tilde{z}^s_{r,j} \equiv \left(z^s_{r,j} - z^1_{r,j}\right) - \left(z^s_{1,j} - z^1_{1,j}\right) \in \mathbb{N}$$

$$\boxed{\tilde{S}^s_r = S^s_r + d_{r,GF} - d^s_{,GF}} \qquad (\cdot)_{GF} \equiv -\frac{1}{\mu_2 - \mu_1}\left[(\cdot)_1 - (\cdot)_2\right]$$

Ionospheric sounding. Data Set

- 21 GPS receivers network for 3D ionospheric modelling in NSW, year 2016, doys 211, 212.

- **Quiet ionospheric conditions.**

- 3D grid: $\lambda = [130^o, 170^o], \Delta\lambda = 2.5^o; \theta = [-40^o, -26^o], \Delta\theta = 0.9^o;\ h = [50, 1500]\ km, \Delta h = 725\ km$
- Period sample = $30''$.
- Cubic Splines.

- Assessment is performed by computing the post fit analysis, the LOOCV, external data set comparison.

Ionospheric model for PPP-RTK. Data Set

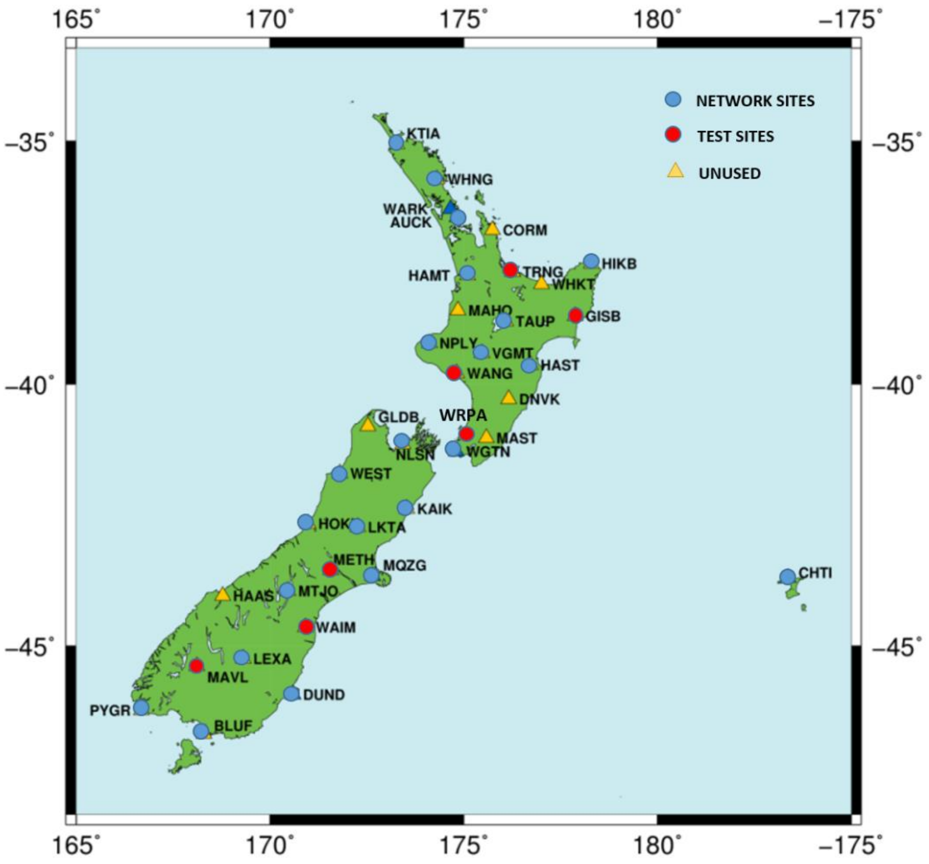
- 21 GPS receivers network for 3D ionospheric modelling in NSW, year 2016, doys 211, 212.

- Quiet ionospheric conditions.

- 3D grid: $\lambda = [100^o, 200^o],\ \Delta\lambda = 3.12^o;\ \theta = [-50^o, +10^0],\ \Delta\theta = 3.75^o; h = [50, 1500]\ km,\ \Delta h = 725\ km$.
- Period sample = $30''$.
- Cubic Splines.

- Assessment is performed by computing the time to first fix (TTFF) ambiguity and time to achieve positioning accuracy for each rover.

Ionospheric model for PPP-RTK. NZ Data Set

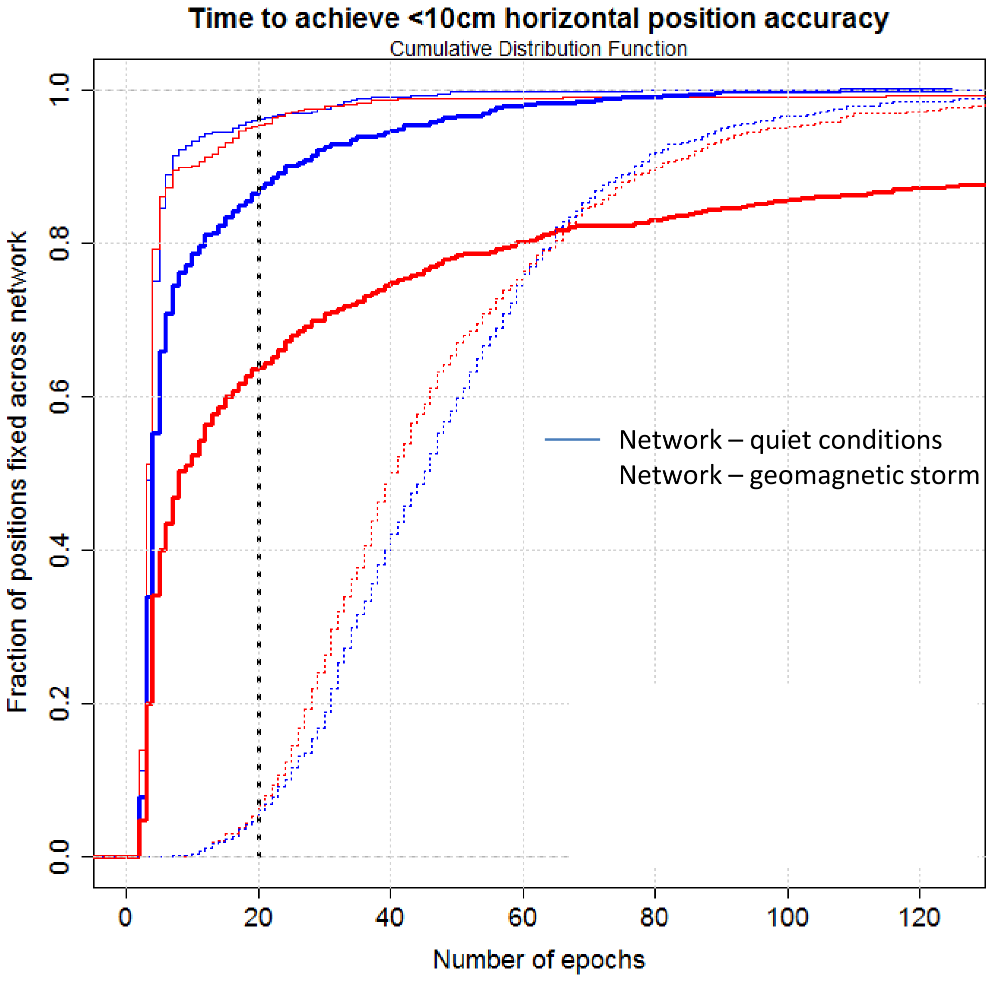


- 22 dual-frequency GPS network receivers
- 7 dual-frequency GPS rovers

- Assessment is performed by computing the time to achieve positioning accuracy (e.g. < 10 cm) for each rover.

- Doys 250 and 251 in 2017 (geomagnetic storm, Dst~-240).

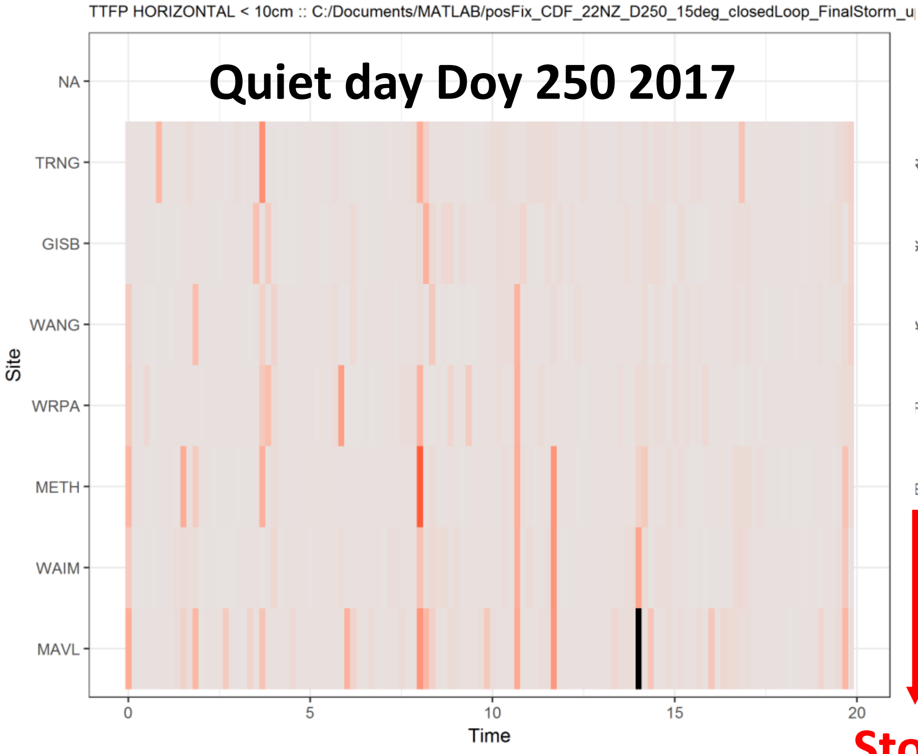
Ionospheric model for PPP-RTK. NZ. TTFHP

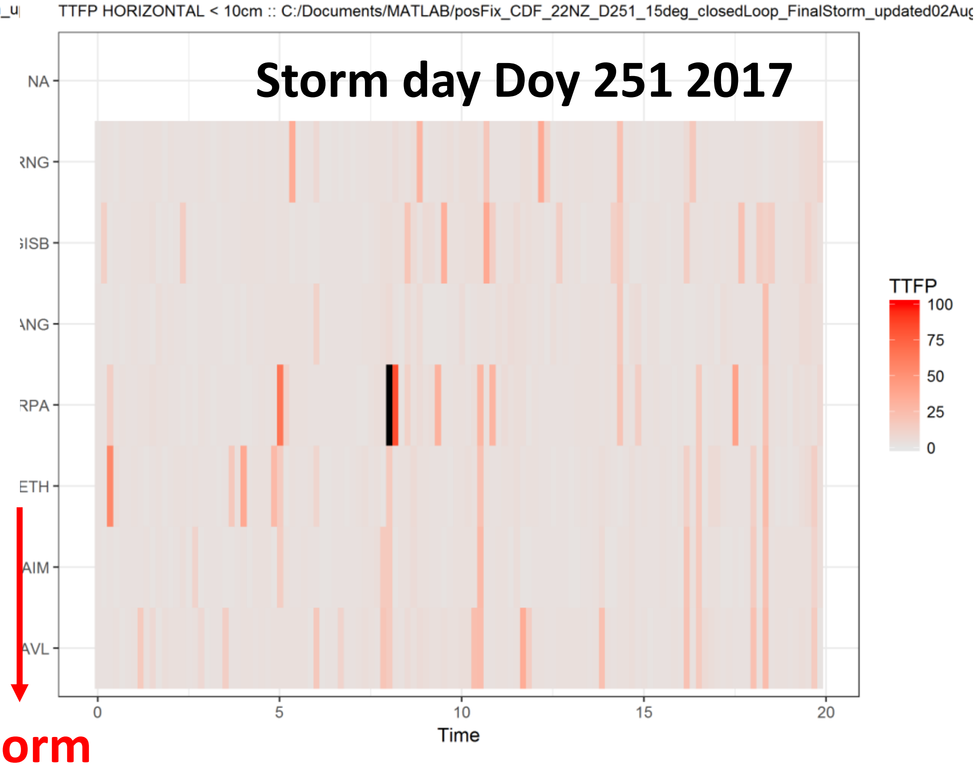


- Baseline ranges from 50 to 230 km.
- 1 epoch = 30 ″
- 15° elevation cutoff

TTFP (epochs) at 90% CDF	Doy 249 (Dst ~0)	Doy 251 (Dst~-240)
Network	~10	~20
Rover	~30	>120
Rover (Float)	~80	~80 (?)

PPP-RTK Network. NZ. TTFHP

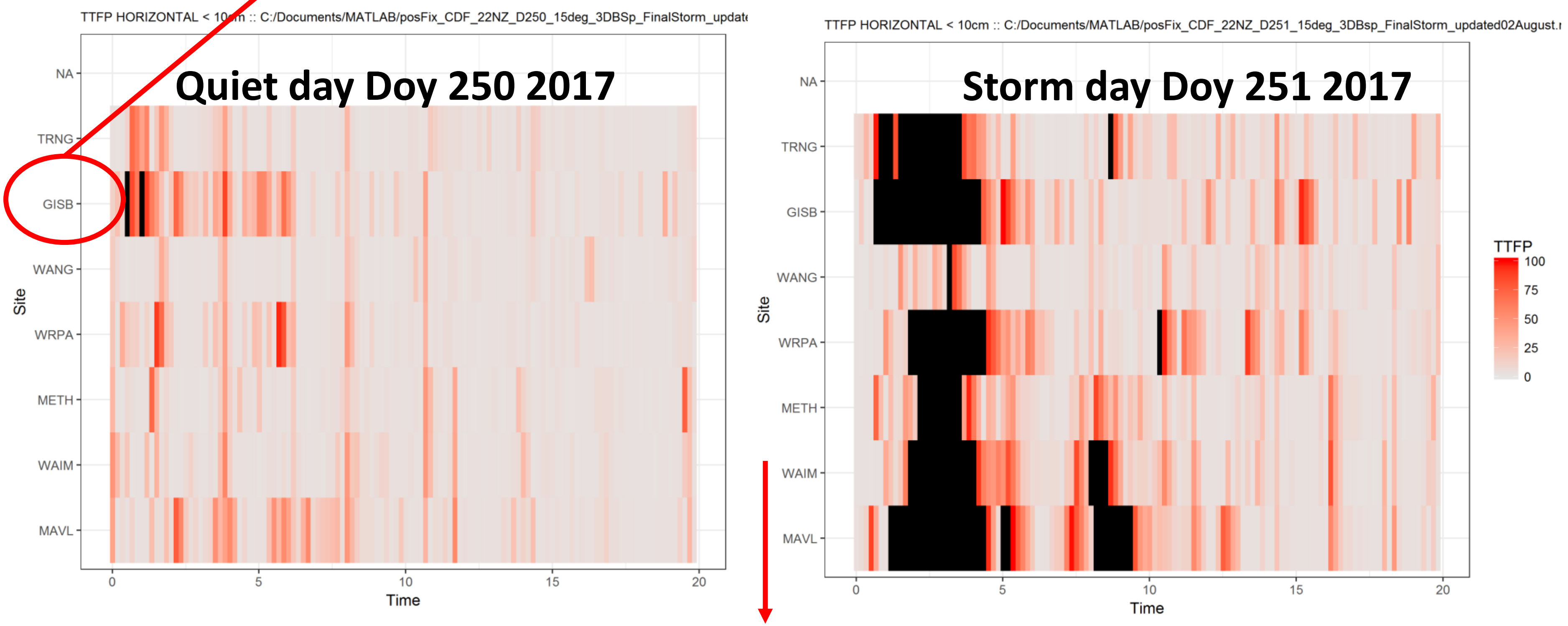




Storm onset

Ionospheric model for PPP-RTK. NZ. TTFHP

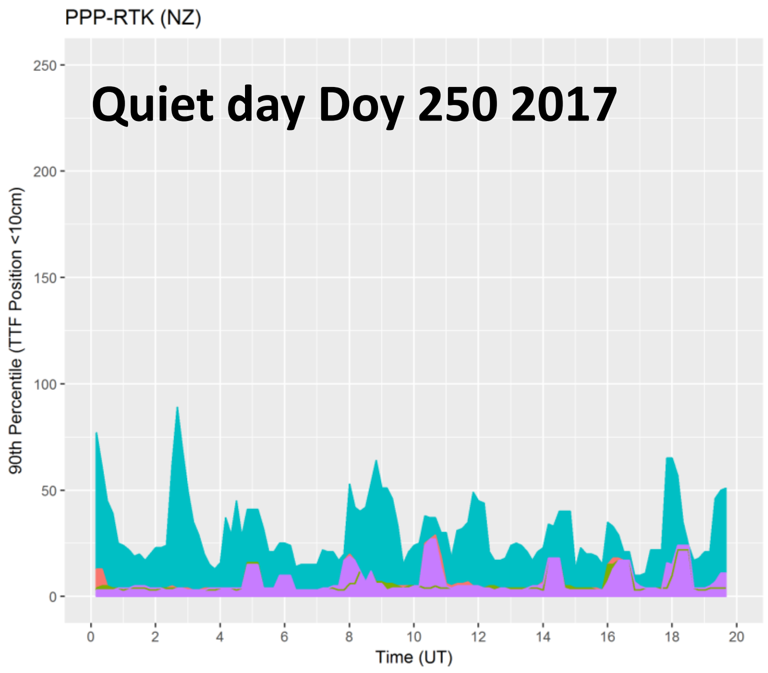
Edge of network



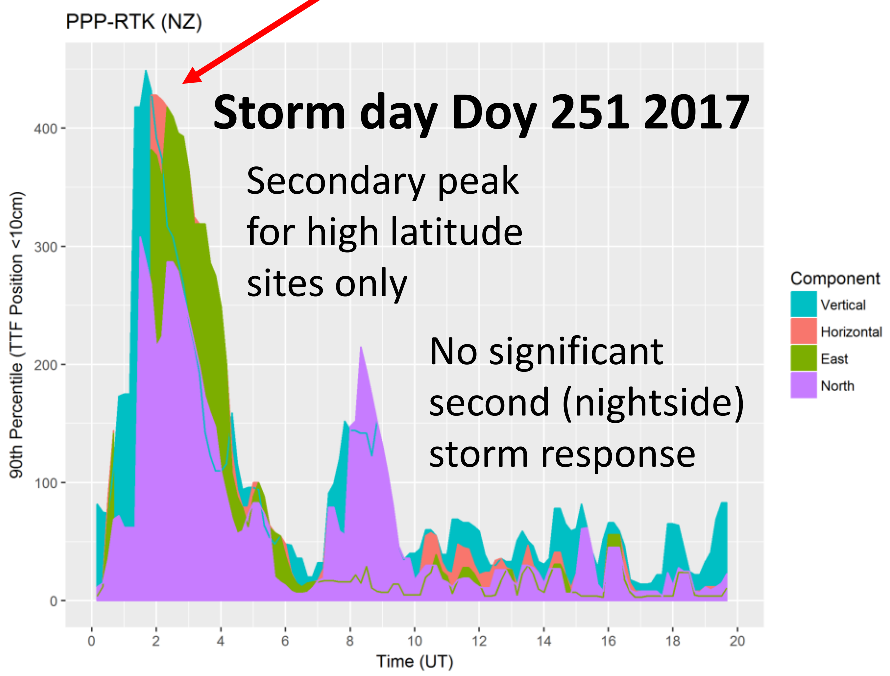
Storm onset

Ionospheric model for PPP-RTK. NZ. Time evolution 90th CDF TTFP. Ionospheric model

Main positive phase ionospheric storm
(evident across all sites)



Quiet day Doy 250 2017



Storm day Doy 251 2017

Secondary peak
for high latitude
sites only

No significant
second (nightside)
storm response

Storm onset