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Monitoring and mitigating space weather effects for GNSS applications

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Overview

- Introduction to the Space Weather Services provided at the Bureau of Meteorology
- Space weather impact on precise positioning
- Introduction to PPP-RTK / National Positioning Infrastructure (NPI)
- 3D Tomographic Ionospheric Model
- Model performance / Validation (quiet conditions)
- September 2017 storm
- Comparative PPP-RTK performance through storm conditions
- Summary

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Australian Bureau of Meteorology Space Weather Services

www.sws.bom.gov.au

- Originally Ionospheric Prediction Service (IPS) 1947-2008.
- 2008 Renamed "Space Weather Services" (SWS) section within Bureau of Meteorology Hazards Prediction Branch.
- Contact details changed office@ips.gov.au → sws_office@bom.gov.au

- Australian Space Forecast Centre (ASFC) team consists of
  - 4 Senior Space Weather Forecasters (SSWF's).
  - 7 Space Weather Forecasters (SWF's)
  - Weekly rotation cycle
- Move to 24/7 forecast centre coverage for significant events.

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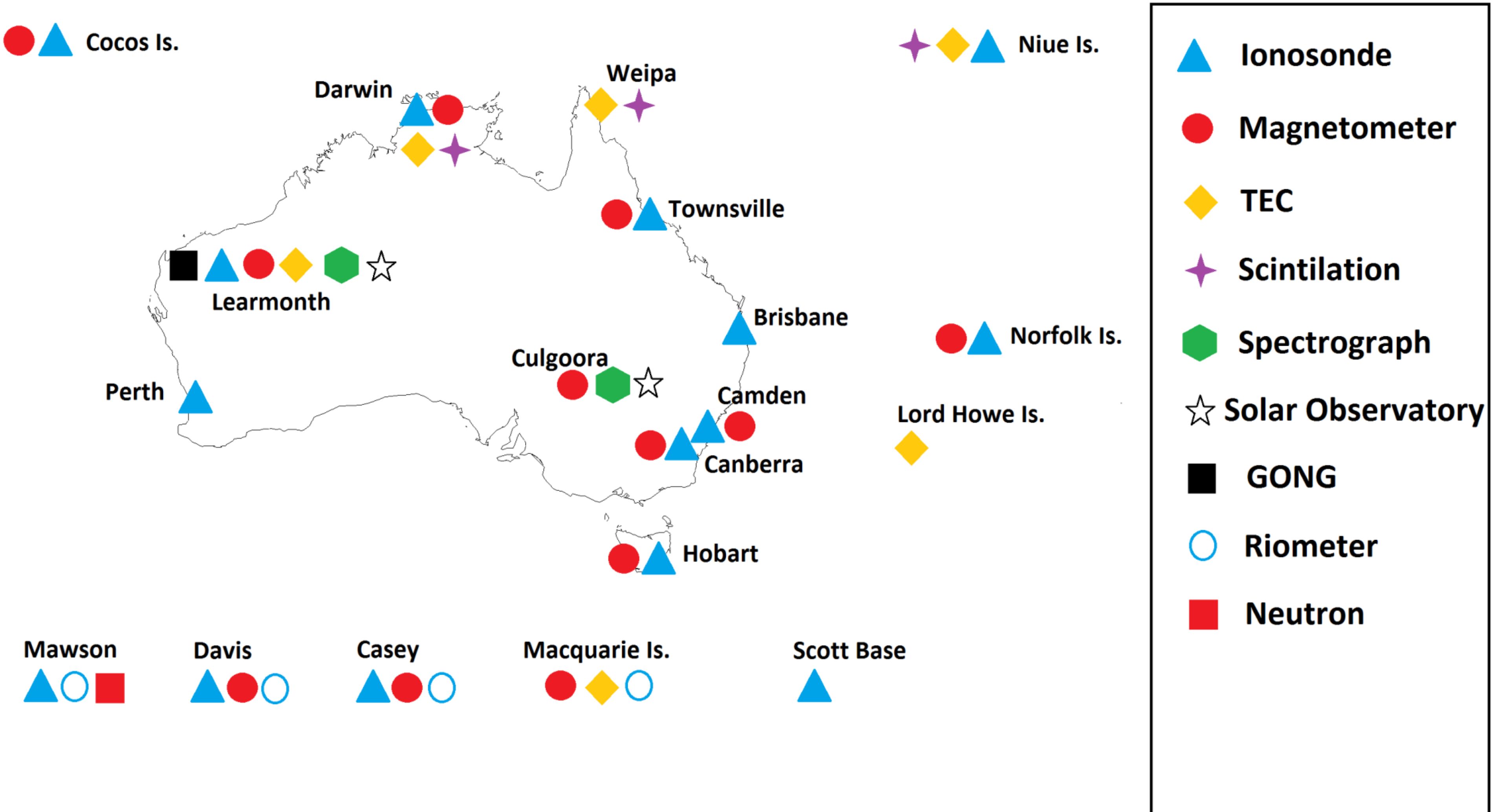
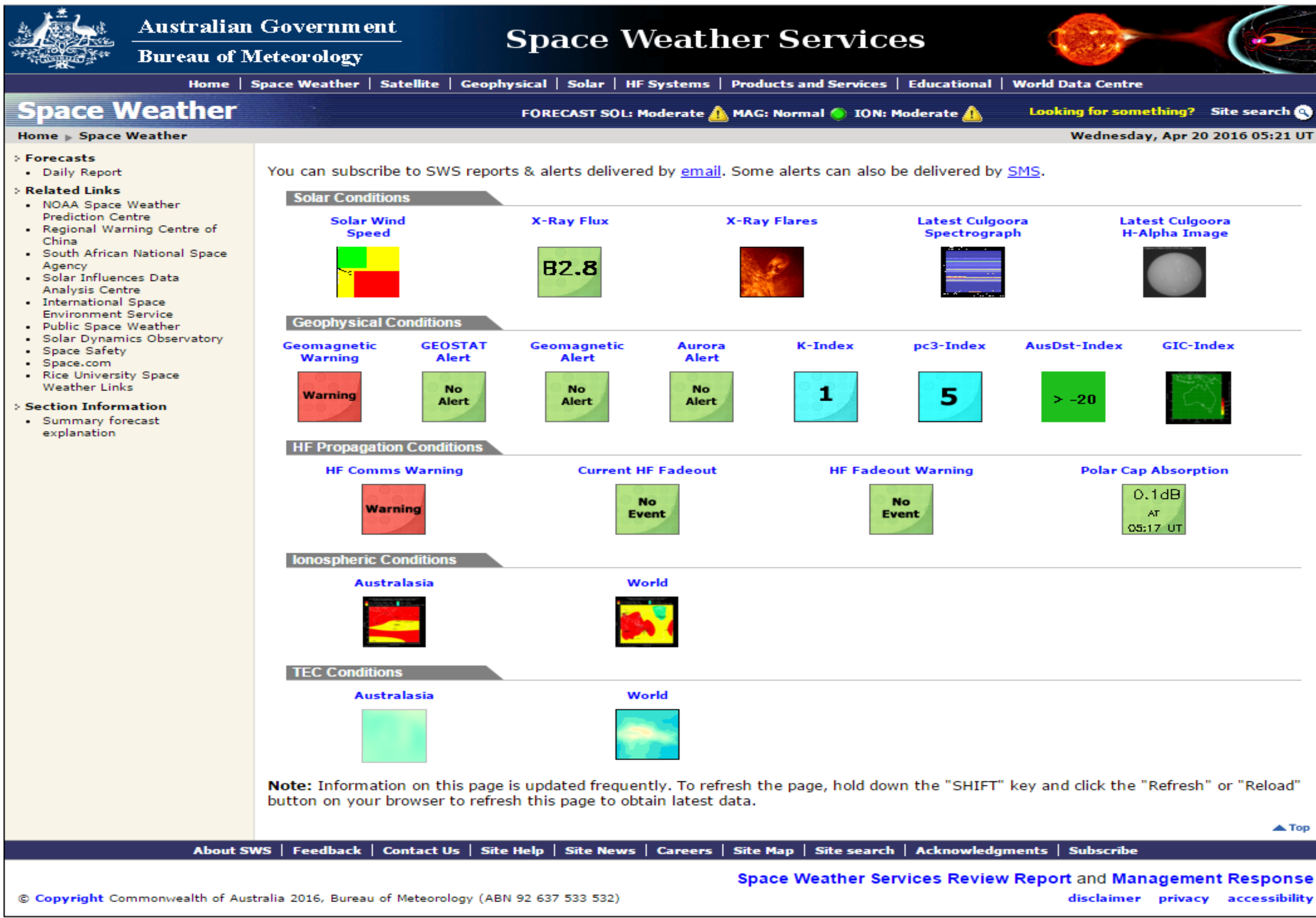
1. SWS Overview: Space Weather Network Sensors and Locations



1. SWS overview: Online Products and Services



Precise positioning and space weather

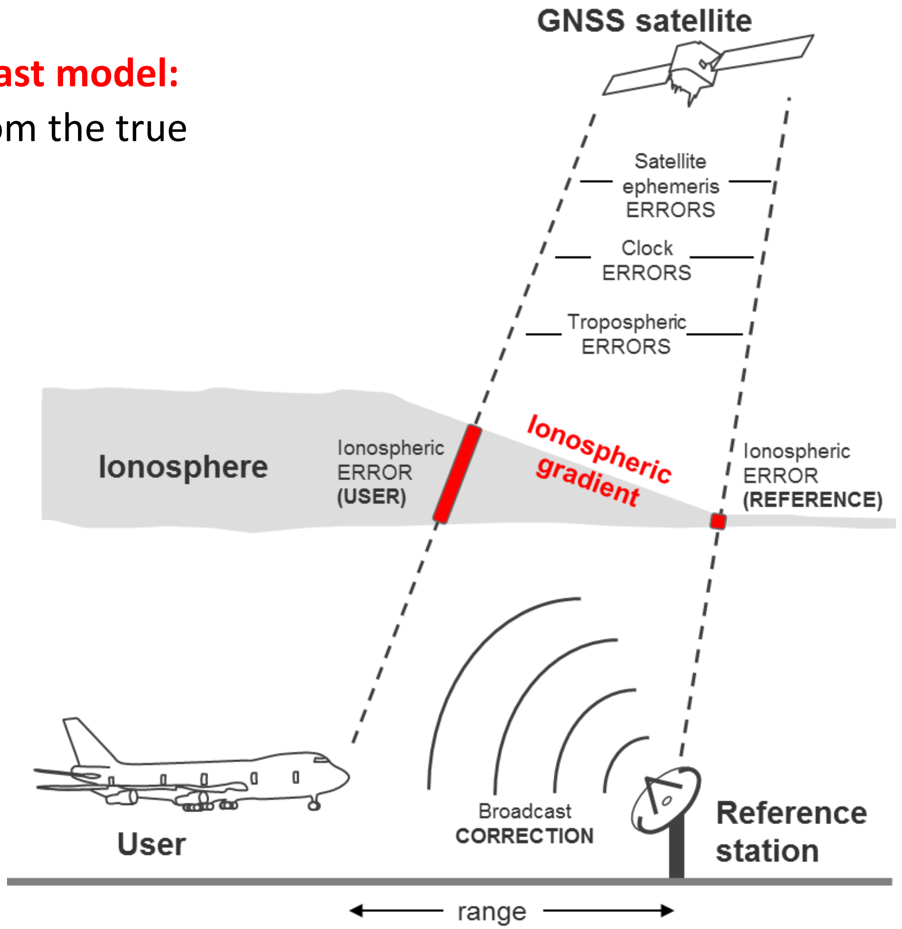
Space weather impacts vary by system:

Single-frequency positioning: Impacted by absolute ionospheric delay

Single frequency positioning utilising broadcast model: impacted by deviation of Klobuchar model from the true ionosphere.

Differential / augmented positioning: Most significantly impacted by spatial gradients in the ionosphere

Network RTK: Impacted by non-linear gradients and ionospheric variability with small spatial scales

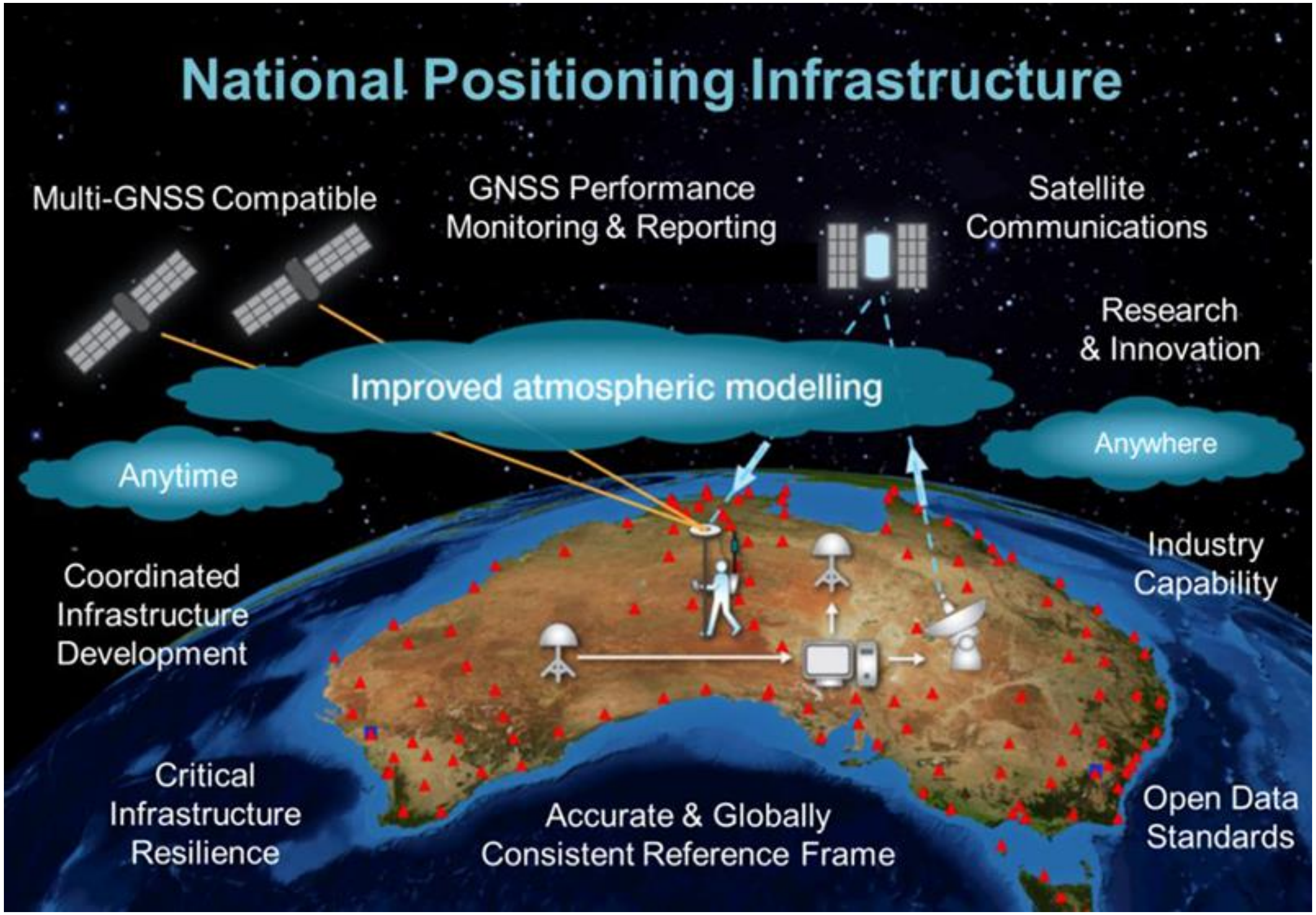


Positioning using <u>pseudorange</u> → ionospheric error directly impacts positioning algorithm

Positioning using <u>carrier phase</u> → ionospheric error impacts ambiguity resolution / positioning

National Positioning Infrastructure

"Instantaneous, reliable and fit-for-purpose access to positioning and timing information anytime and anywhere across the Australian landscape and its maritime jurisdictions"



3D Tomographic ionospheric model: 3DB-tomion

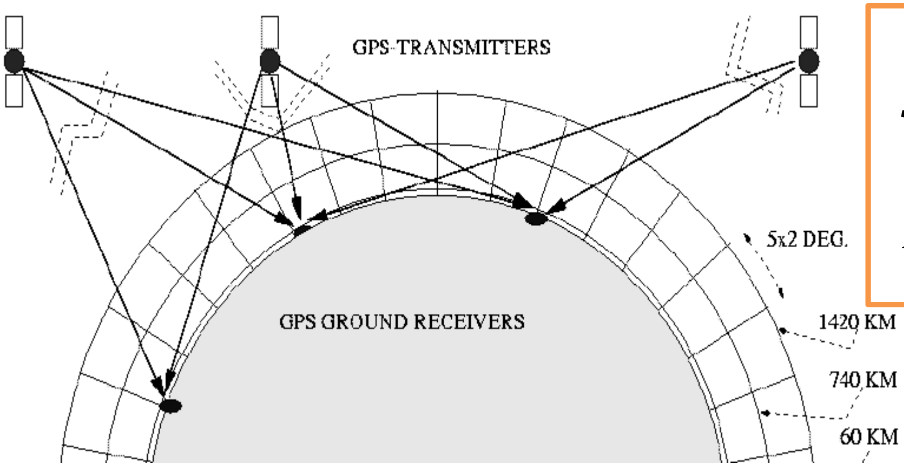


Figure from M. Hernandez-Pajares, J.M. Juan, J. Sanz, O.L. Colombo, Improving the real-time ionospheric determination from GPS sites at very long distances over the equator, J Geo Res, V. 107, No A10, 1296, doi:10.1029/2001JA009203, (2002).

$$\tilde{S}_r^s = \int_{P_r}^{P_s} N_e dl + d_{r,GF} - d^s_{,GF}$$

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

- $\tilde{\boldsymbol{S}}$:Biased Slant Total Electron Content.
- $\boldsymbol{N_e}$: Electron Density.
- $\boldsymbol{d}$: Delay Code Bias.
- $\boldsymbol{\psi_i}$: Basis function (e.g. splines).
- $\boldsymbol{c_{ijk}(t)}$: 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.
- Receiver and satellites DCBs do not depend on geometry, whereas STEC does → geometrically decorrelated from STEC.

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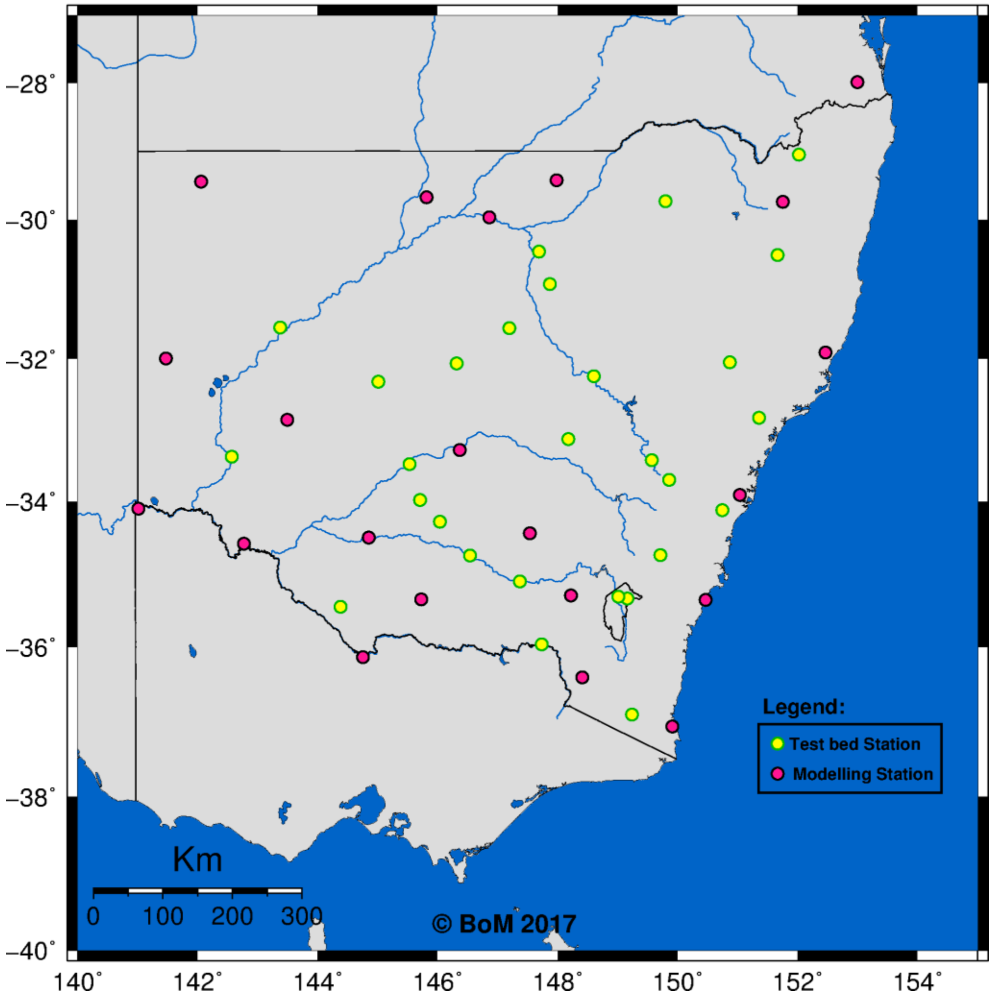
Ionospheric sounding network



- Reference Network (21 GPS receivers; red dots)
- Test sites (28 rovers; yellow dots).

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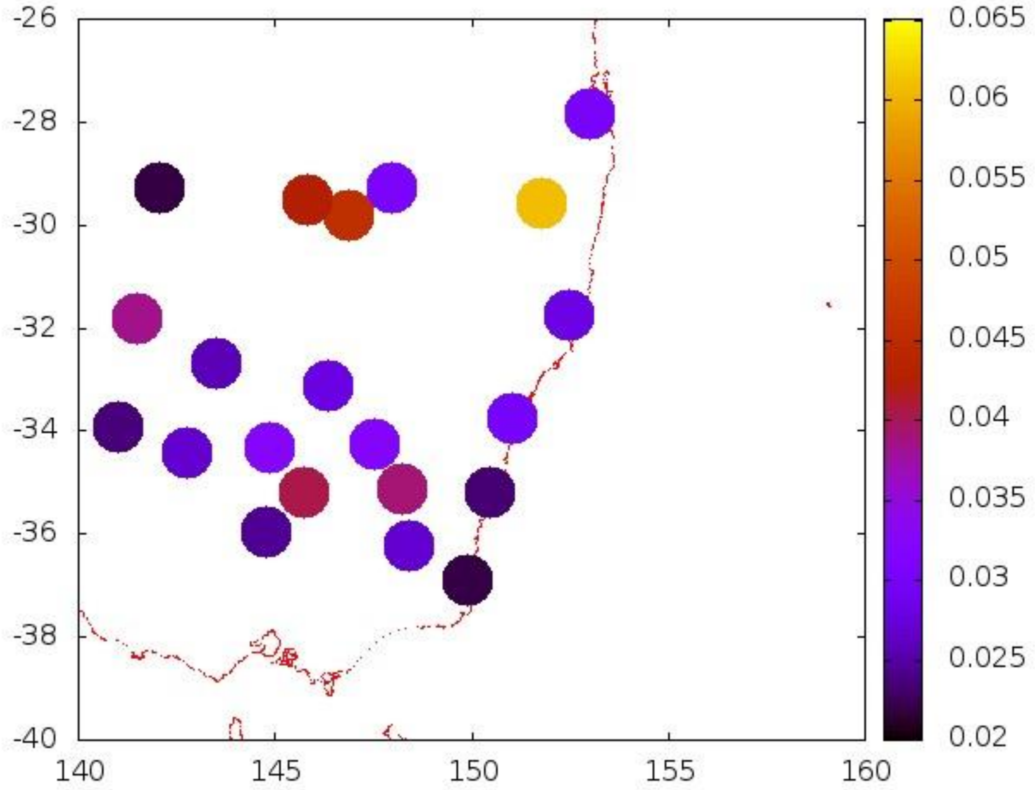
How accurate is the 3D B-splines ionospheric model?

Ionospheric model performance

Post-fit residuals

- Compares the raw input data with the modelled output

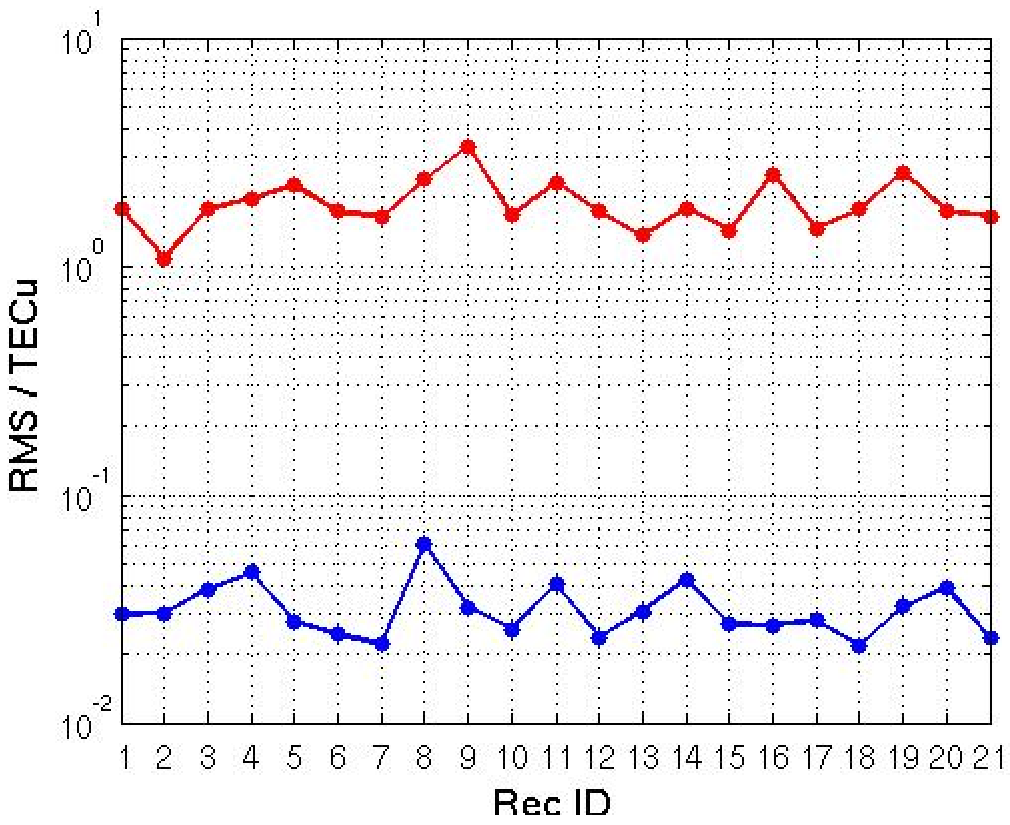


Highly accurate model

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

Ionospheric model performance

3D ionospheric model? Why bother?



- 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.

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By how much does the model improve positioning performance?

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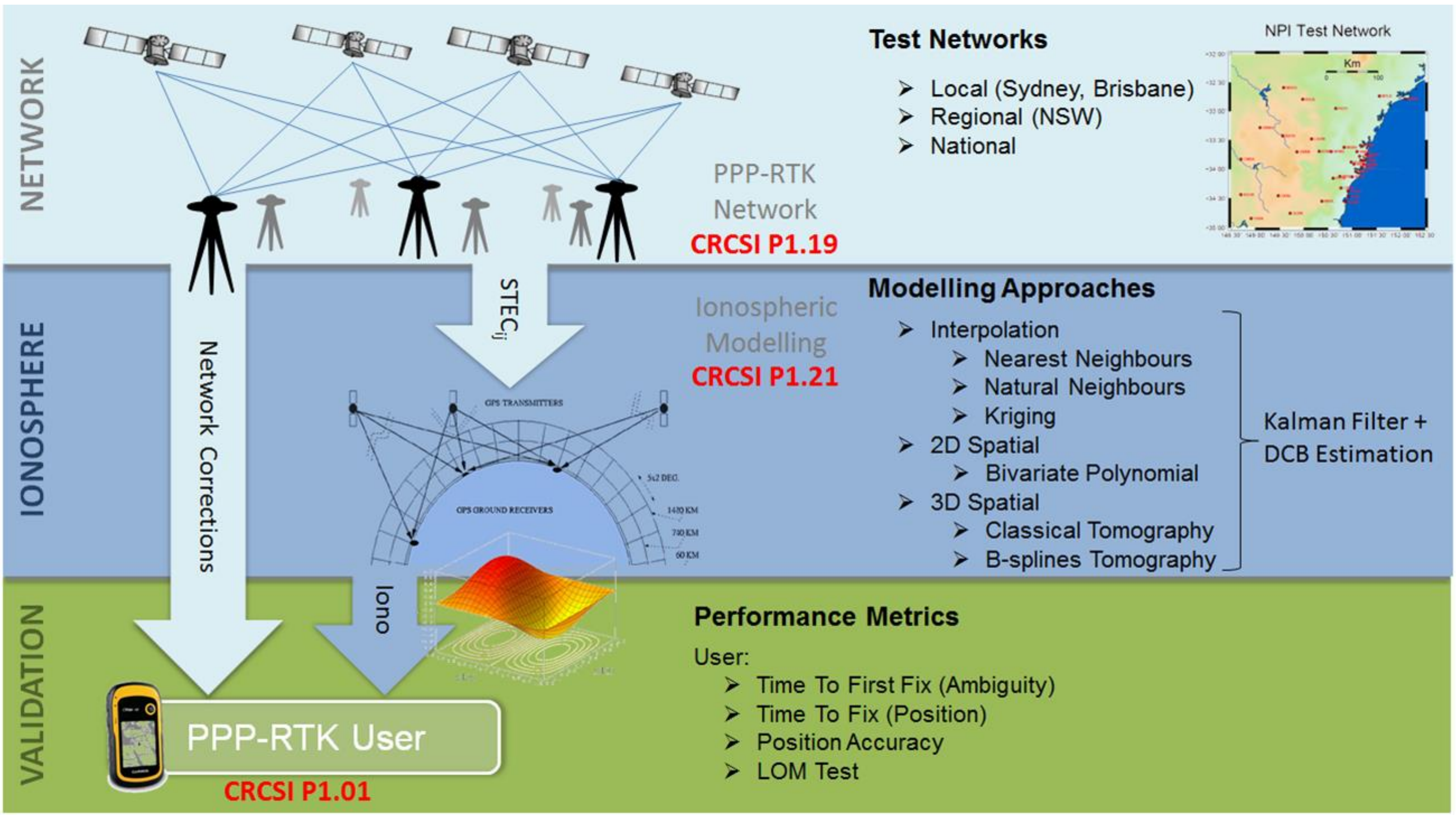
Ionospheric Model Test Bed

Ultimate validation tool → How well does the model improve GNSS positioning?



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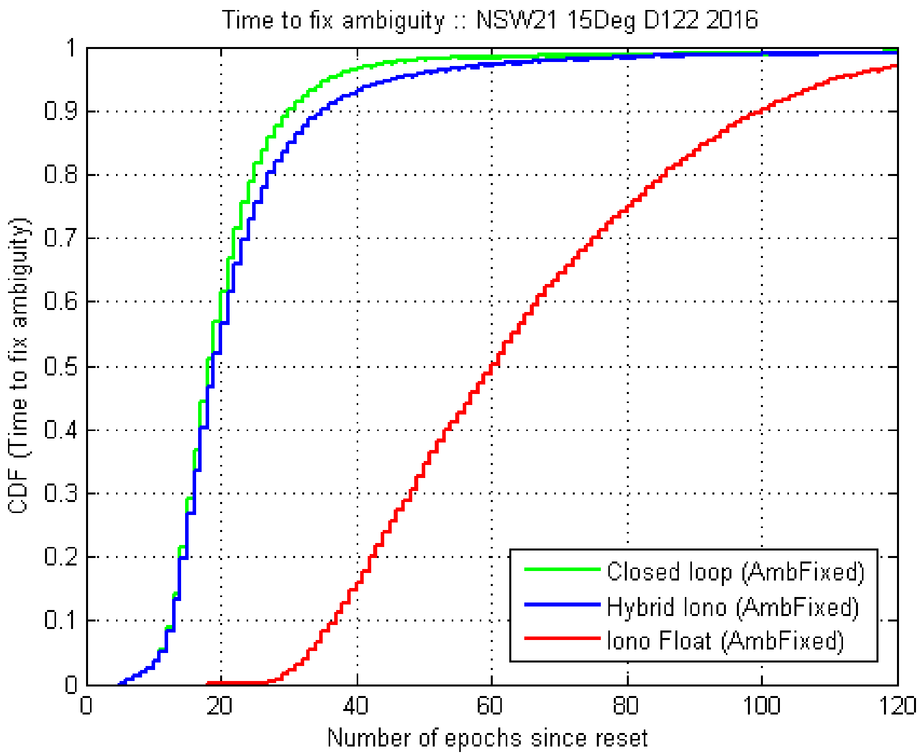
Ionospheric Model Test Bed

Performance Metrics:

- **Time To Fix Ambiguity (TTFA)**
  - Time required to resolve each ambiguity to integer
  - Impacted significantly by the accuracy of the ionospheric model
- **Time To Fix Position (TTFP)**
  - Time required for a user to reach a positioning accuracy better than 10cm
- TTFA / TTFP analysed across all sites
- Results analysed in terms of Cumulative Distribution Functions (CDFs) of TTFA and TTFP

Results – Quiet Conditions
Time to Fix Ambiguity (TTFA)



- Baselines range from 50 to 230 km.
- 1 epoch = 30 ''
- 15° elevation mask

CDF	# epochs / Closed-loop	# epochs / Iono model	# epochs / Float
68%	~22	~22	~74
90%	~30	~34	~100

- **Closed loop**: Observed STEC at reference sites used as ionospheric corrections in fictitious rover located at reference sites → **Baseline network performance**
- **Ionospheric hybrid model**: 3D B-splines ionospheric model with interpolation to rover sites
- **Float solution**: No ionospheric correction provided to rovers.

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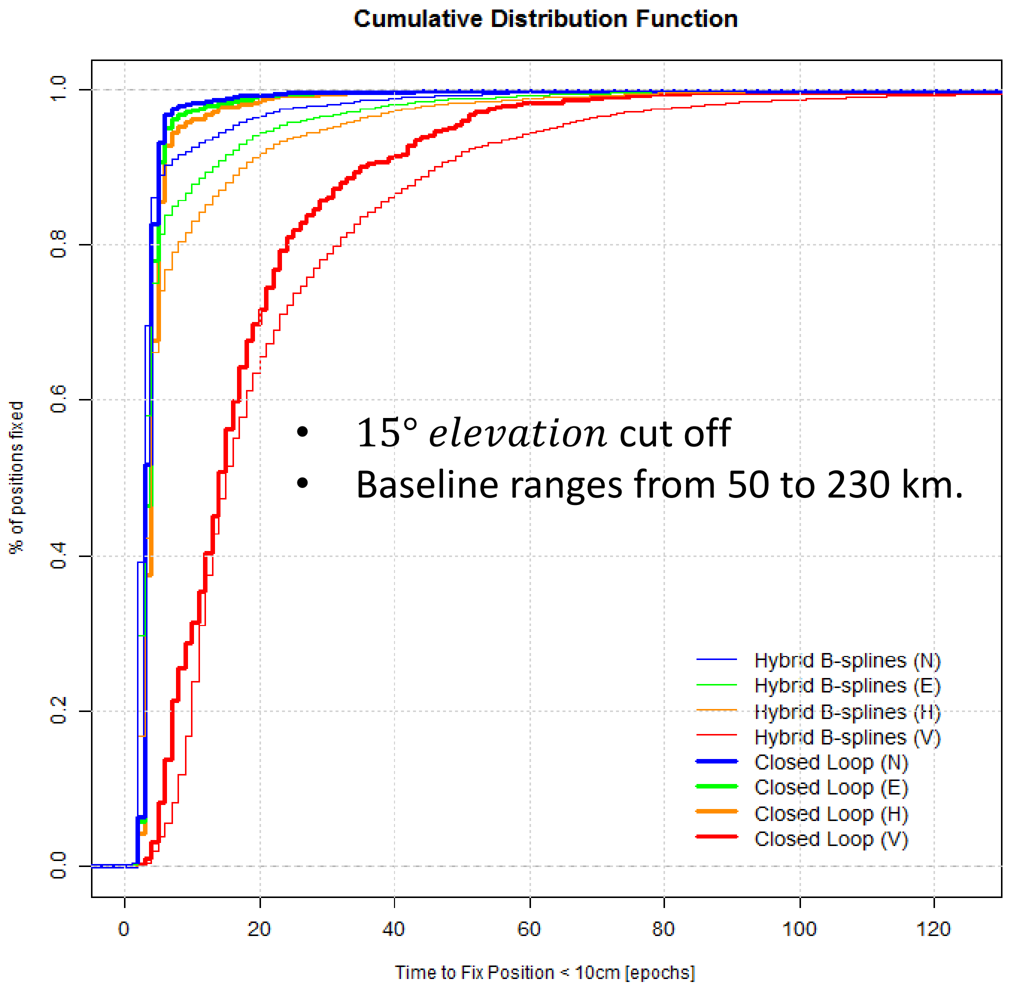
Results – Quiet Conditions Time to Fix Position (TTFP)



1. Closed-loop:
   - **H**: Uncertainty for 90% of computed positions is below 10cm in less than 10 epochs.
   - **V**: Uncertainty for 90% of computed positions are below 10cm in less than 40 epochs.

2. Hybrid model:
   - **H**: Uncertainty for 90% of computed positions are below 10cm in less than 20 epochs.
   - **V**: Uncertainty for 90% of computed positions are below 10cm in less than 50 epochs.

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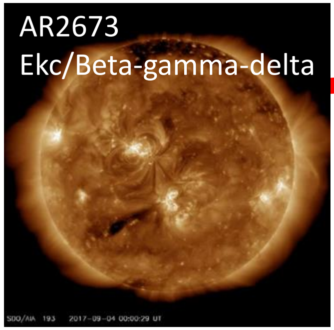
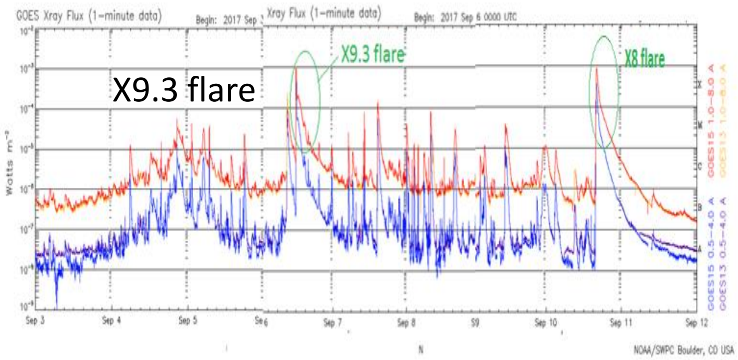
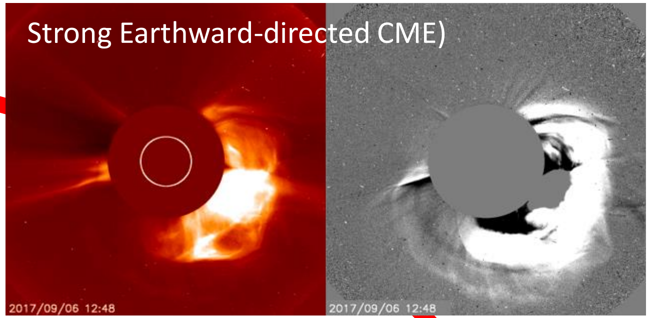
What happens during an ionospheric storm?

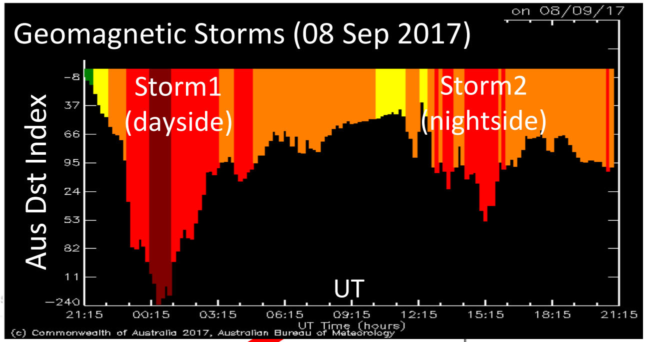
September 2017 Space Weather Event





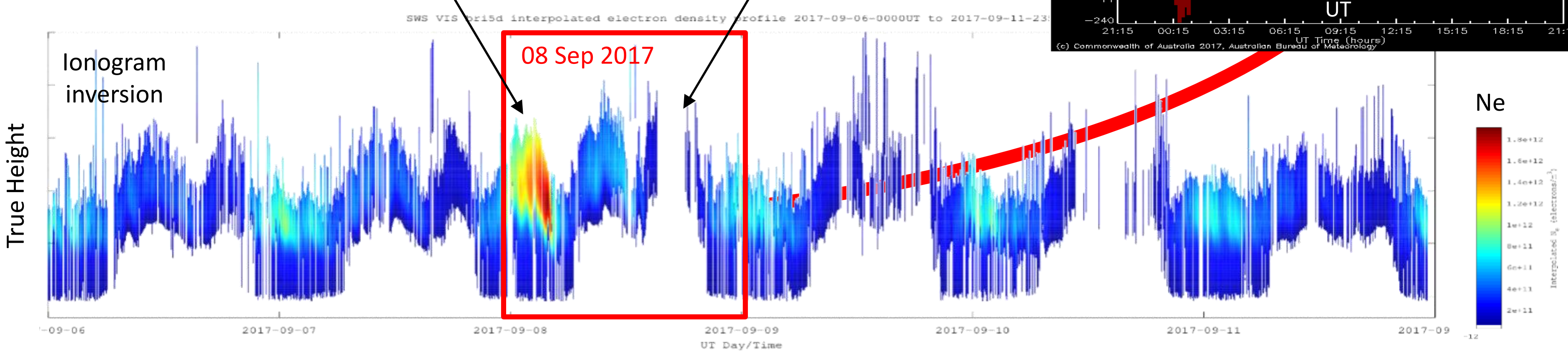


Impact on Precise GNSS??



Strong positive phase ionospheric storm (dayside)

Weak bottom-side ionospheric signature (nightside)



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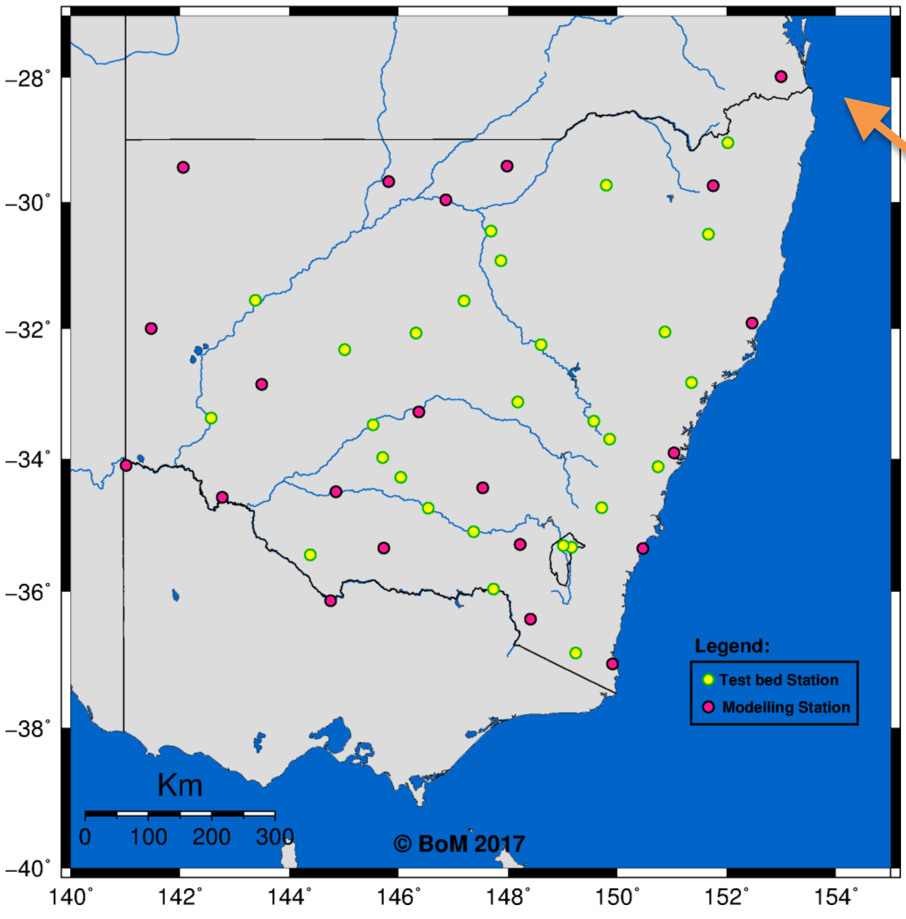
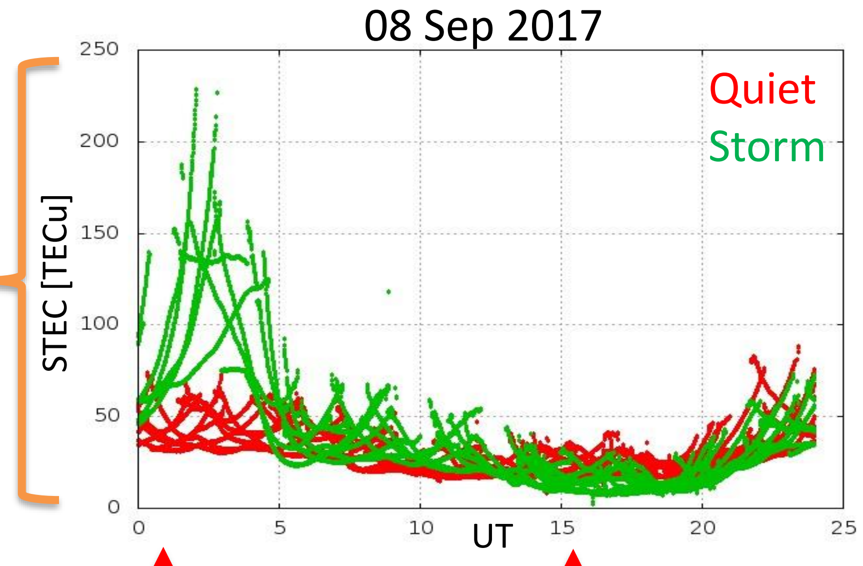
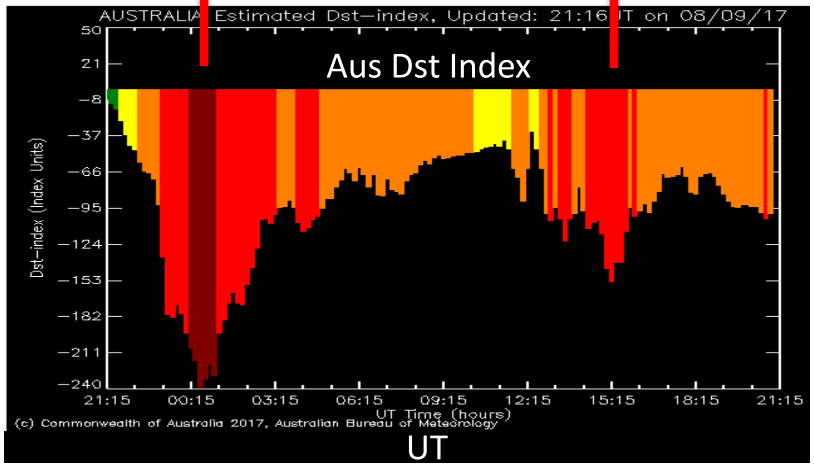
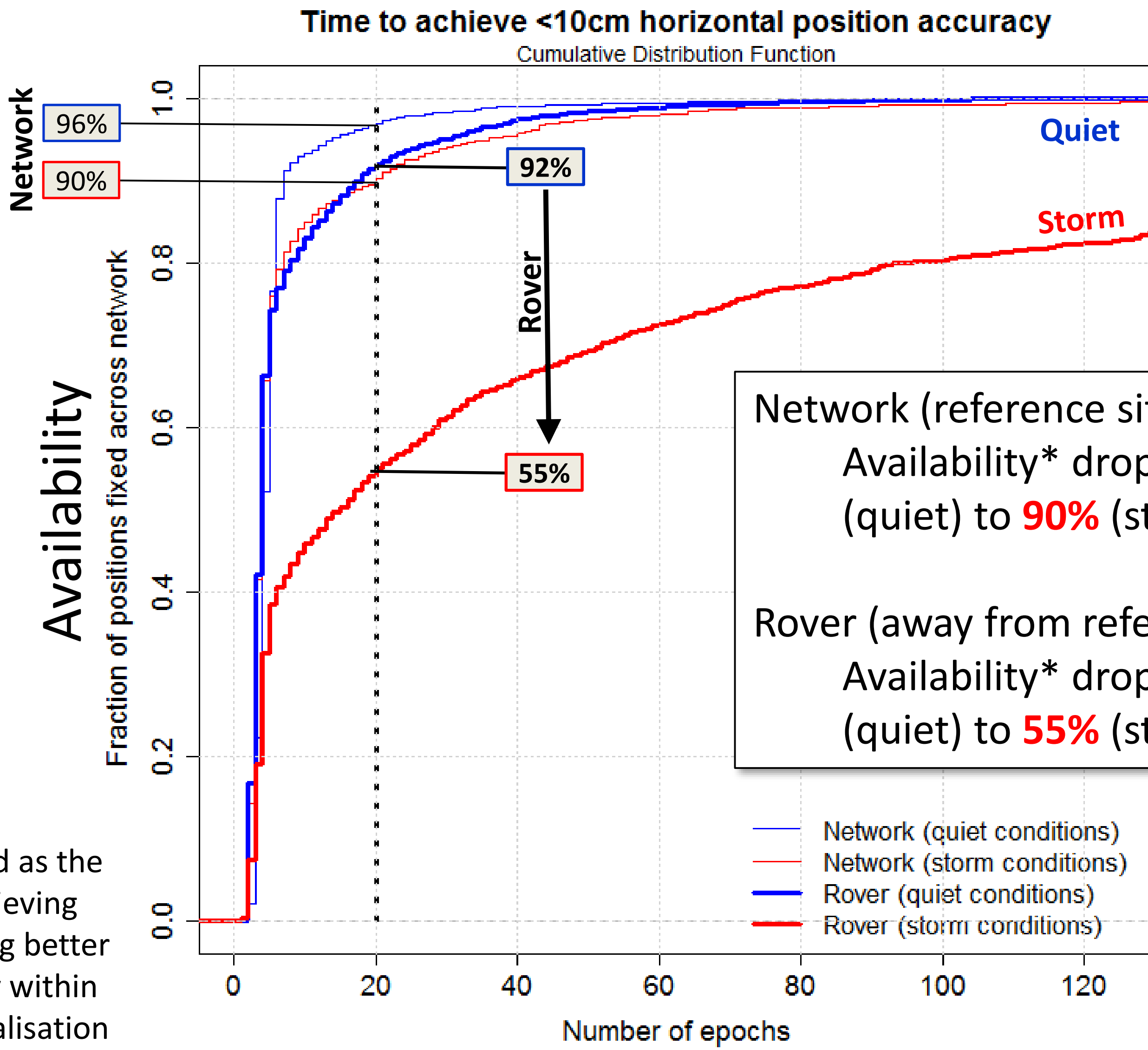
Results
Ionospheric Storm STECs







PPP-RTK performance
Quiet versus Storm (CDFs)



Network (reference sites):

Availability* dropped from **96%** (quiet) to **90%** (storm)

Rover (away from reference sites):

Availability* dropped from **92%** (quiet) to **55%** (storm)

* Availability defined as the % of locations achieving horizontal positioning better than 10cm accuracy within 20 epochs from initialisation

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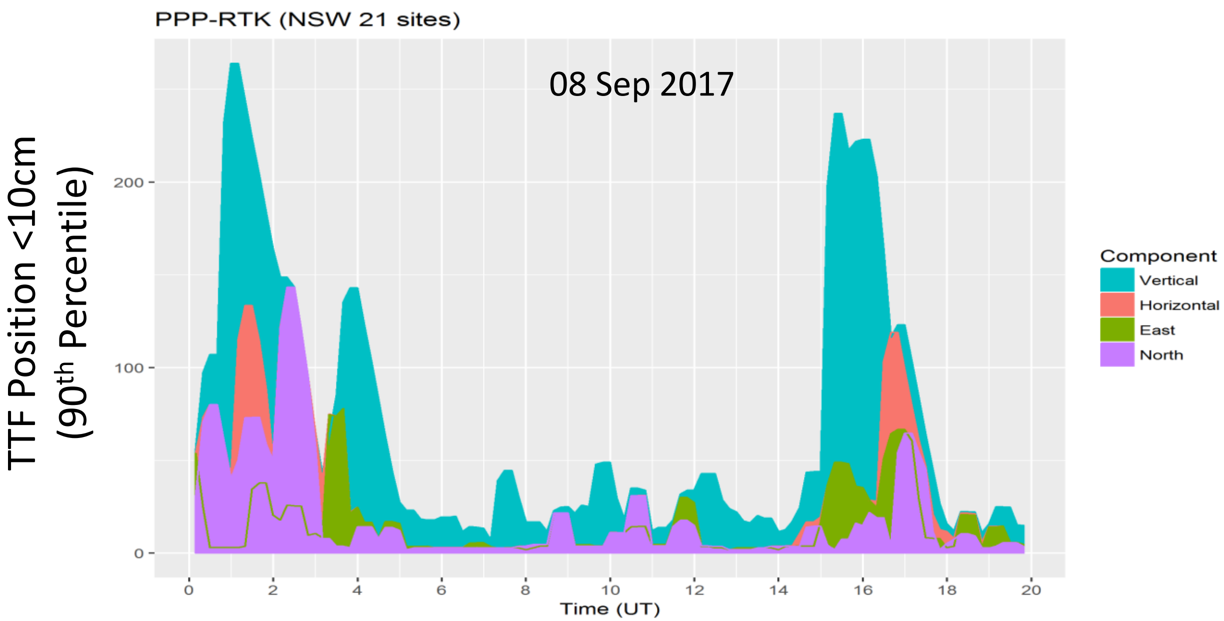
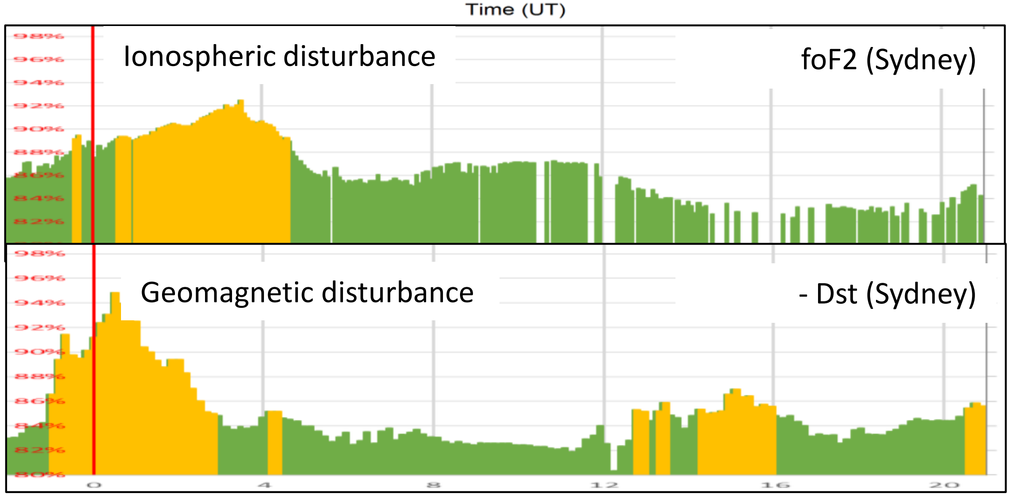
The previous CDFs showed averaged performance over a day…

How does the time evolution of the storm impact the positioning application?

Can the temporal variation in positioning performance help identify an appropriate proxy for space weather impact to GNSS?

Results
Time evolution of CDF summary measure (90th percentile TTFP)





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 appears to be related to a topside disturbance (not seen by ionosonde)

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Summary

- **Quiet conditions**: 3D Ionospheric model corrections → TTFA and TTFP similar to closed-loop (baseline/network performance) with >80% availability (of positioning to <10cm within 10 epochs) across the network in the horizontal component.
- **Storm conditions:** 3D Ionospheric model corrections → TTFF increases across the network around 2 hours after the geomagnetic storm at day time (~03:00-04:00 UT).
- Correlation and delay between DsT and Ambiguity Success Rate.
- No clear correlation between DsT and STEC, TTFF.
- Influence of the plasmasphere on the PPP-RTK platform → lower Ambiguity Success Rate at local night time (~16:00-17:00 UT).

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Thank you!
Questions?

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