The Impact of the Ionosphere on WAAS at Low Latitude

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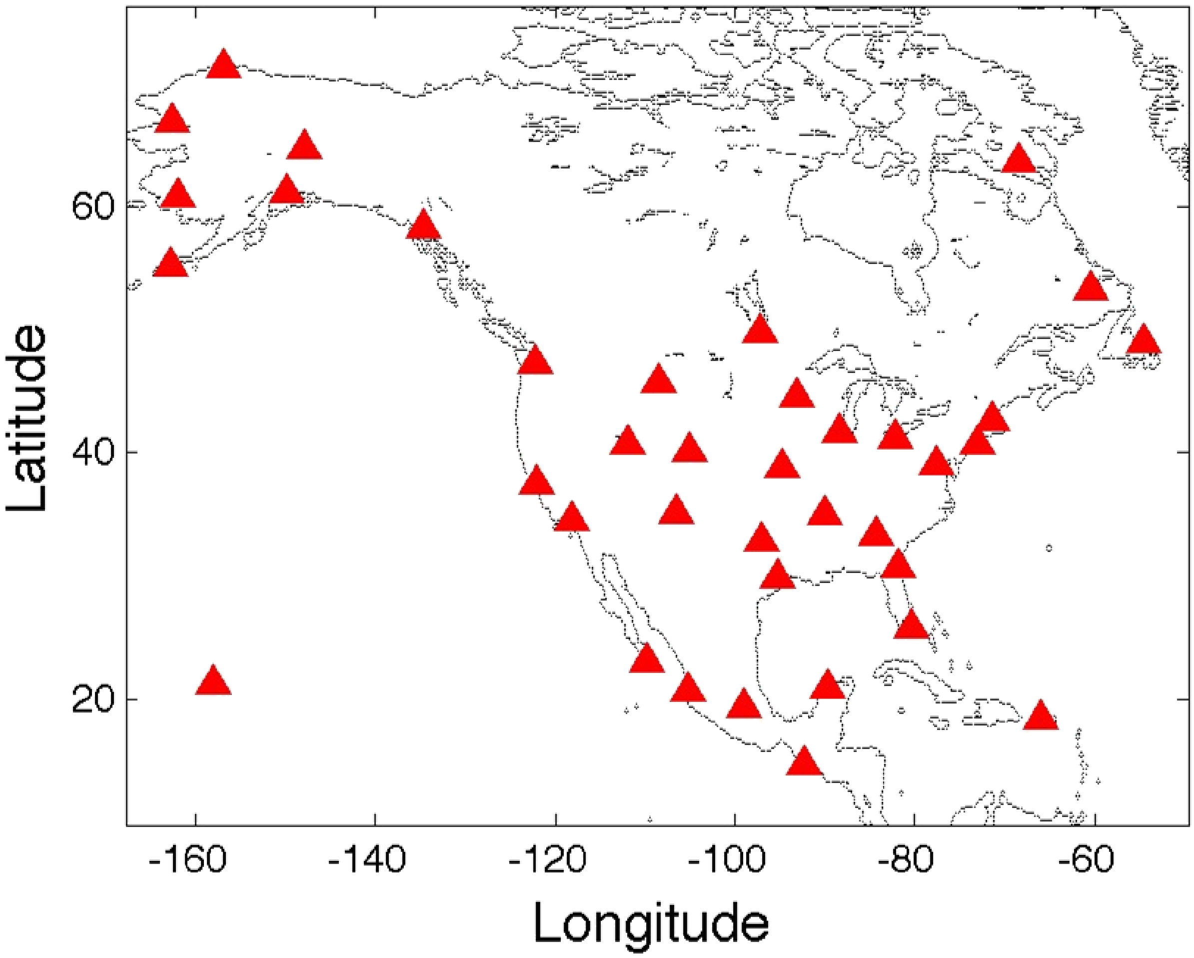
Outline

- *How WAAS protects users from ionospheric threats*
- *How solar cycle 24 data affect the ionospheric threat model*
- *How threat error is distributed geographically*
- *How WAAS availability will be improved in the CY18 upgrade*

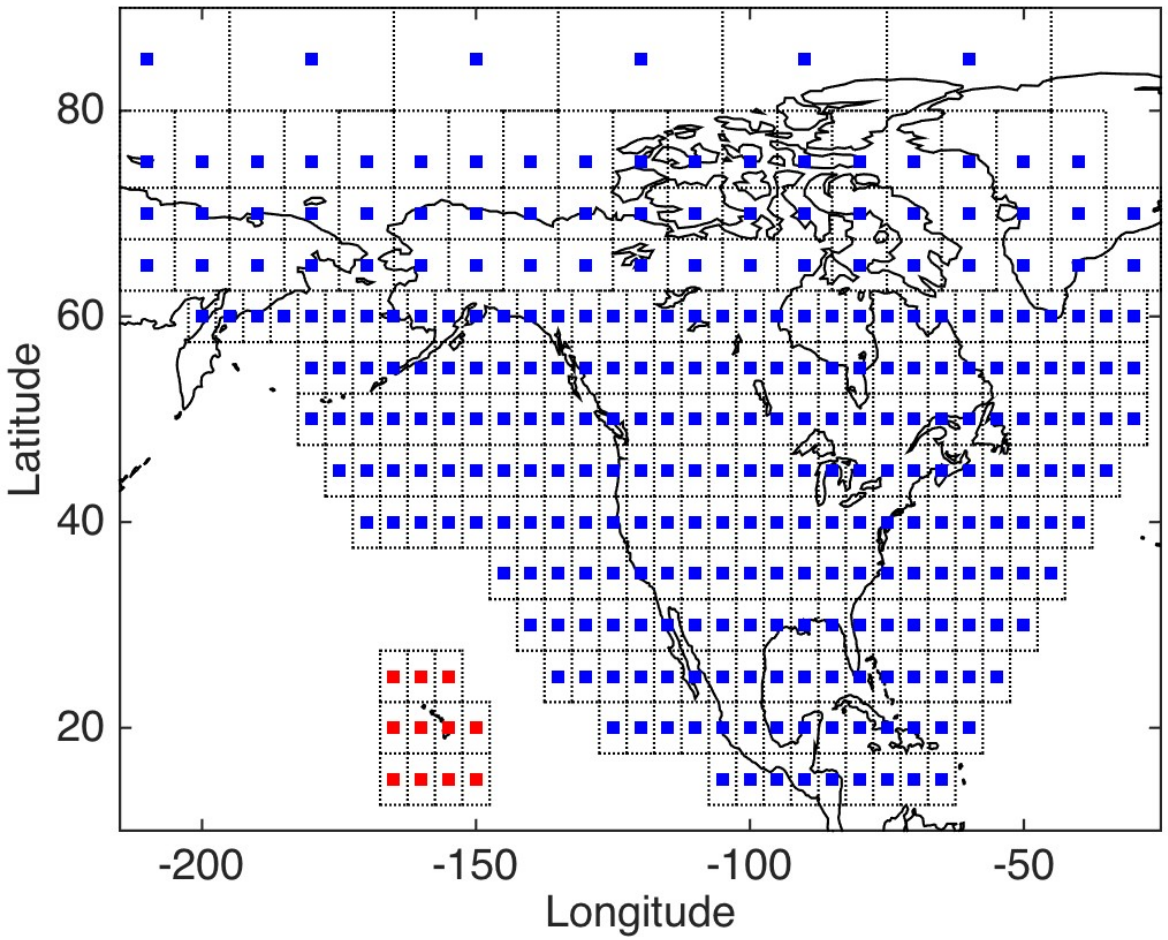
WAAS receiver sites



WAAS receiver network currently consists of 38 sites in North America.

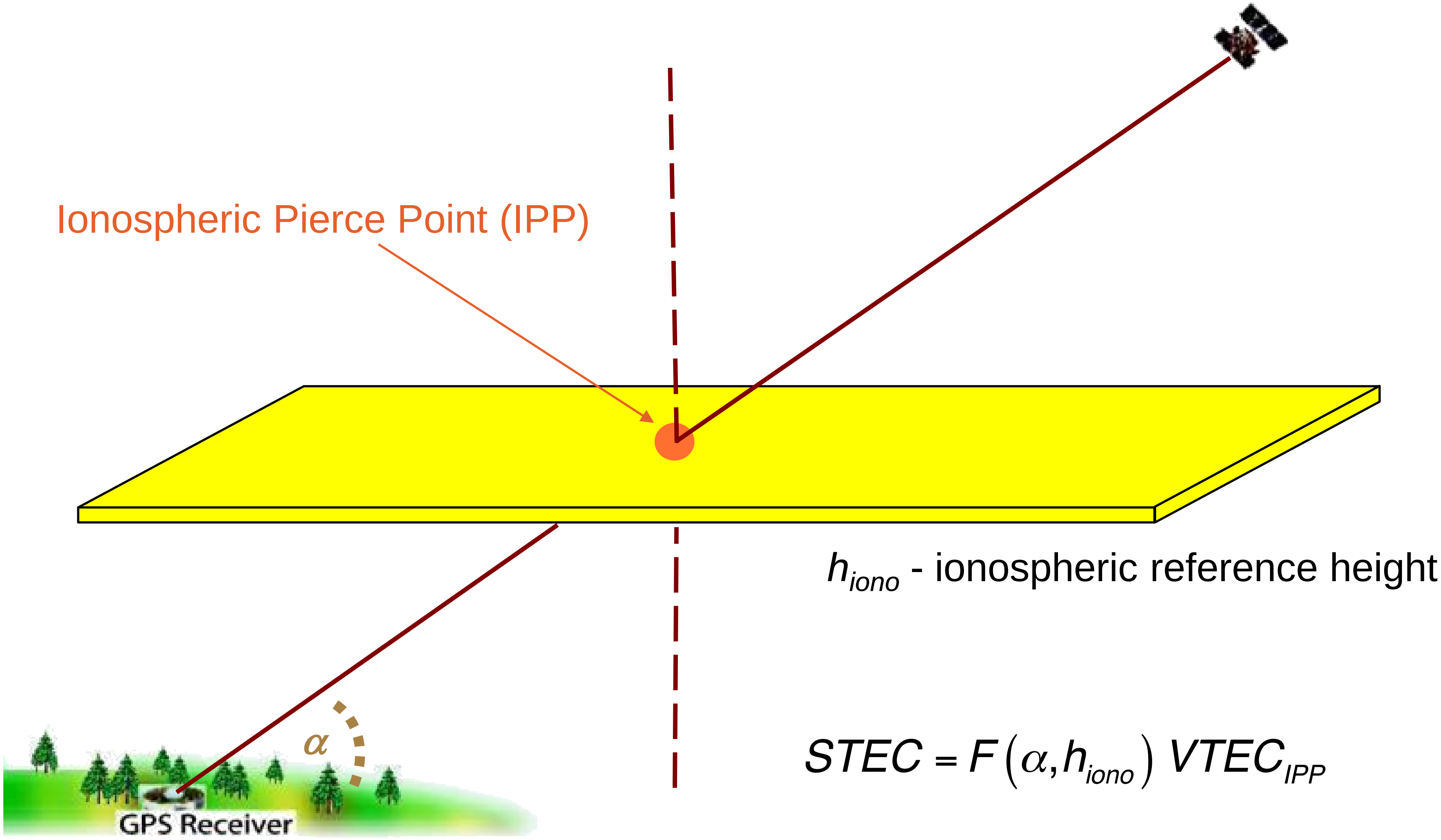
IGP mask

20-Oct-2016 IGPs_mask_006.domains.jpeg



WAAS broadcasts vertical delay estimates and error bounds at ionospheric grid points in *IGP working set* (blue dots).

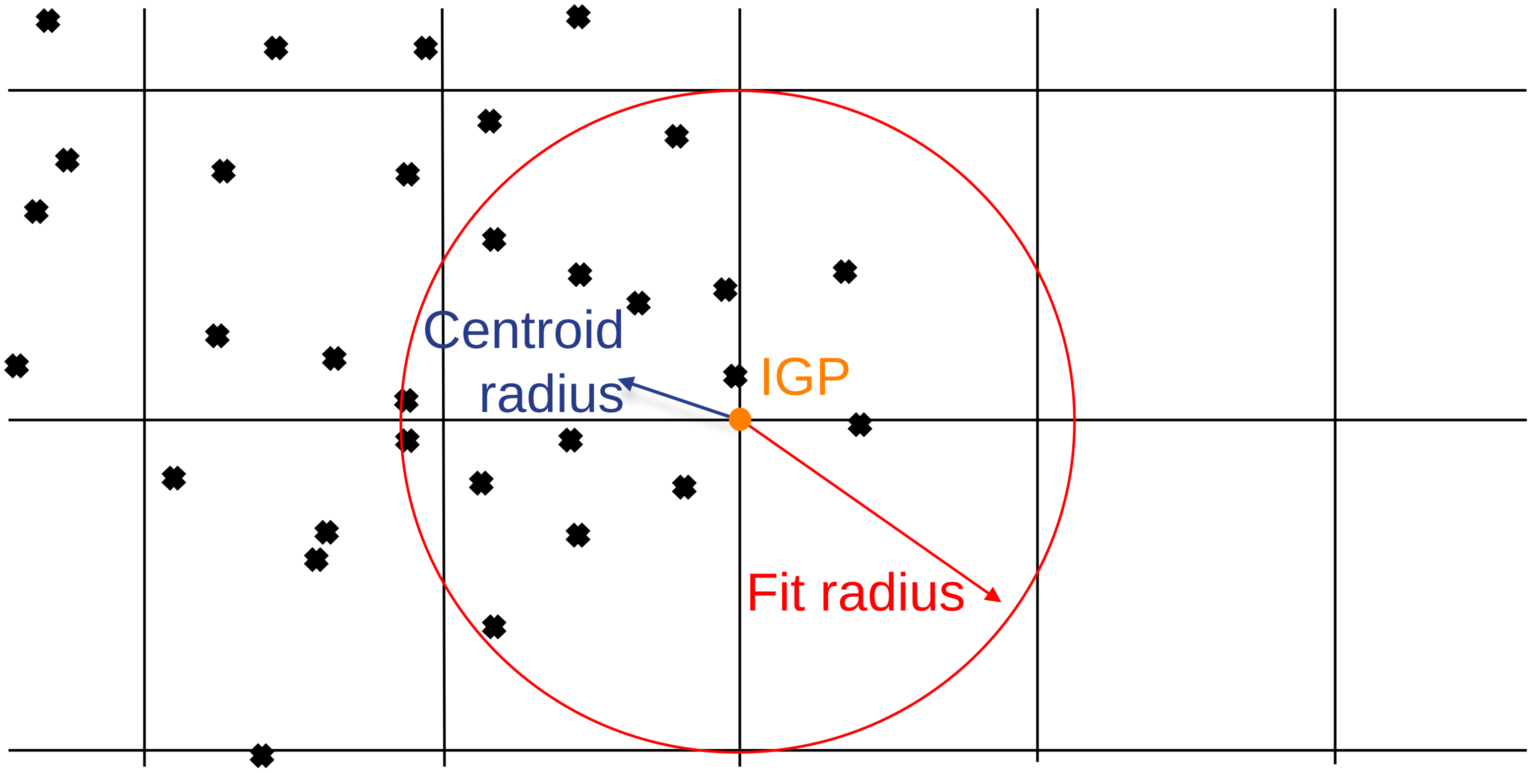
Thin-shell model of ionosphere



$$STEC = F\left(\alpha, h_{iono}\right) VTEC_{IPP}$$

Mapping slant delay to vertical delay assumes the ionosphere occupies a thin shell.

Estimating vertical delay at a specified location



Model: $I_{true}(\Delta \mathbf{x}) = a_0 + a_{east}\, \Delta \mathbf{x}^T \bullet \hat{e}_{east} + a_{north}\, \Delta \mathbf{x}^T \bullet \hat{e}_{north} + r(\Delta \mathbf{x})$

Estimated delay values and error bounds are based upon fits of vertical delay measurements near the ionospheric grid point (IGP).

Grid Ionospheric Vertical Error

GIVE at IGP is a safety critical error bound on the vertical delay:

$$\text{GIVE} \equiv K_{GIVE} \frac{K_{HMI\_GIVE}}{K_{HMI}} \tilde{\sigma}_{GIVE}$$

where

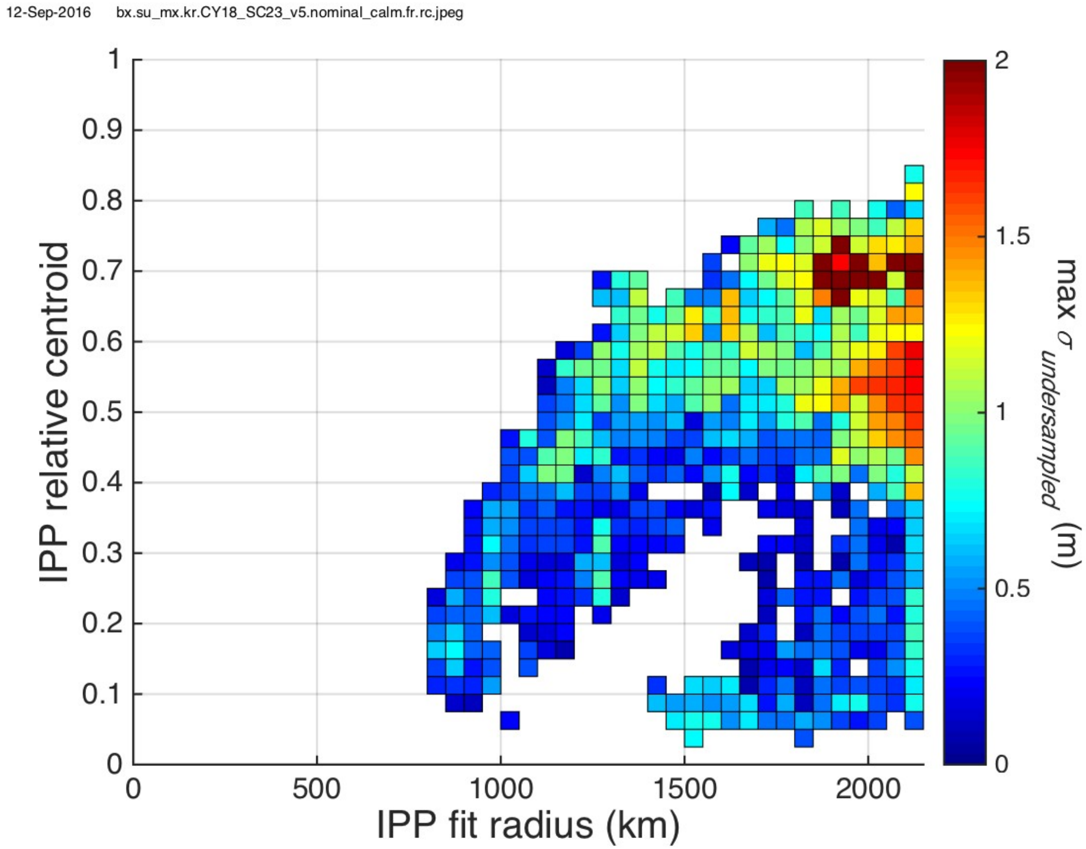
$$\tilde{\sigma}^2_{GIVE} \equiv \tilde{\sigma}^2_{IGP} + \sigma^2_{undersampled}$$

Variance of inflated formal error associated with vertical delay at IPP

Variance to protect against undersampling

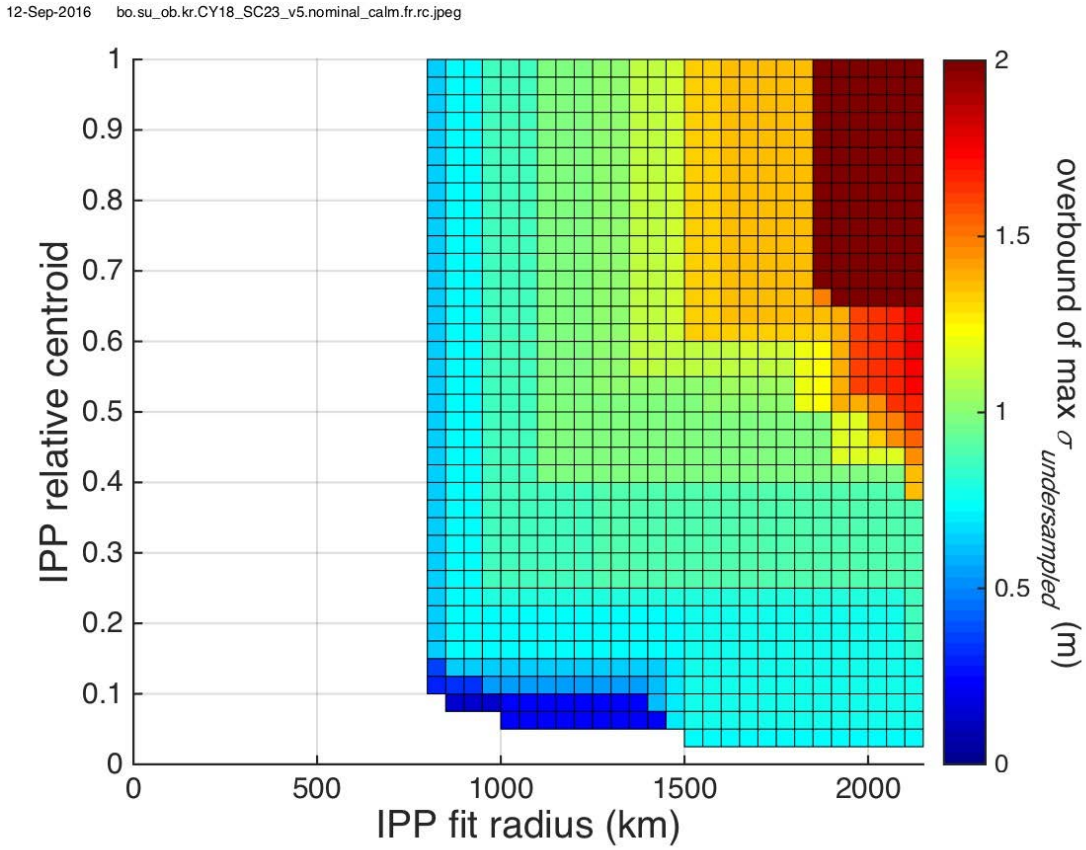
The GIVE provides a very conservative bound on true estimation error.

Current quiet-time threat model: raw data



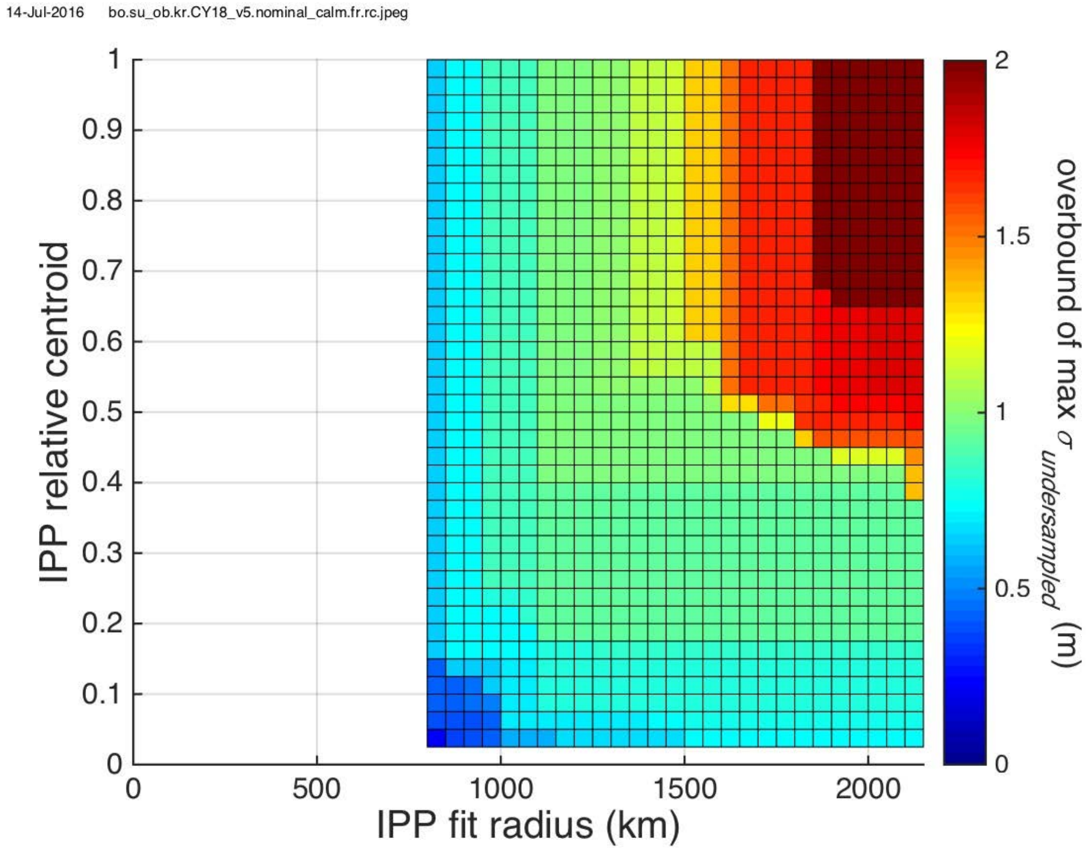
The ionospheric threat model provides $\sigma_{undersampled}$ as a function of fit radius and relative centroid.

Current quiet-time threat model: overbound



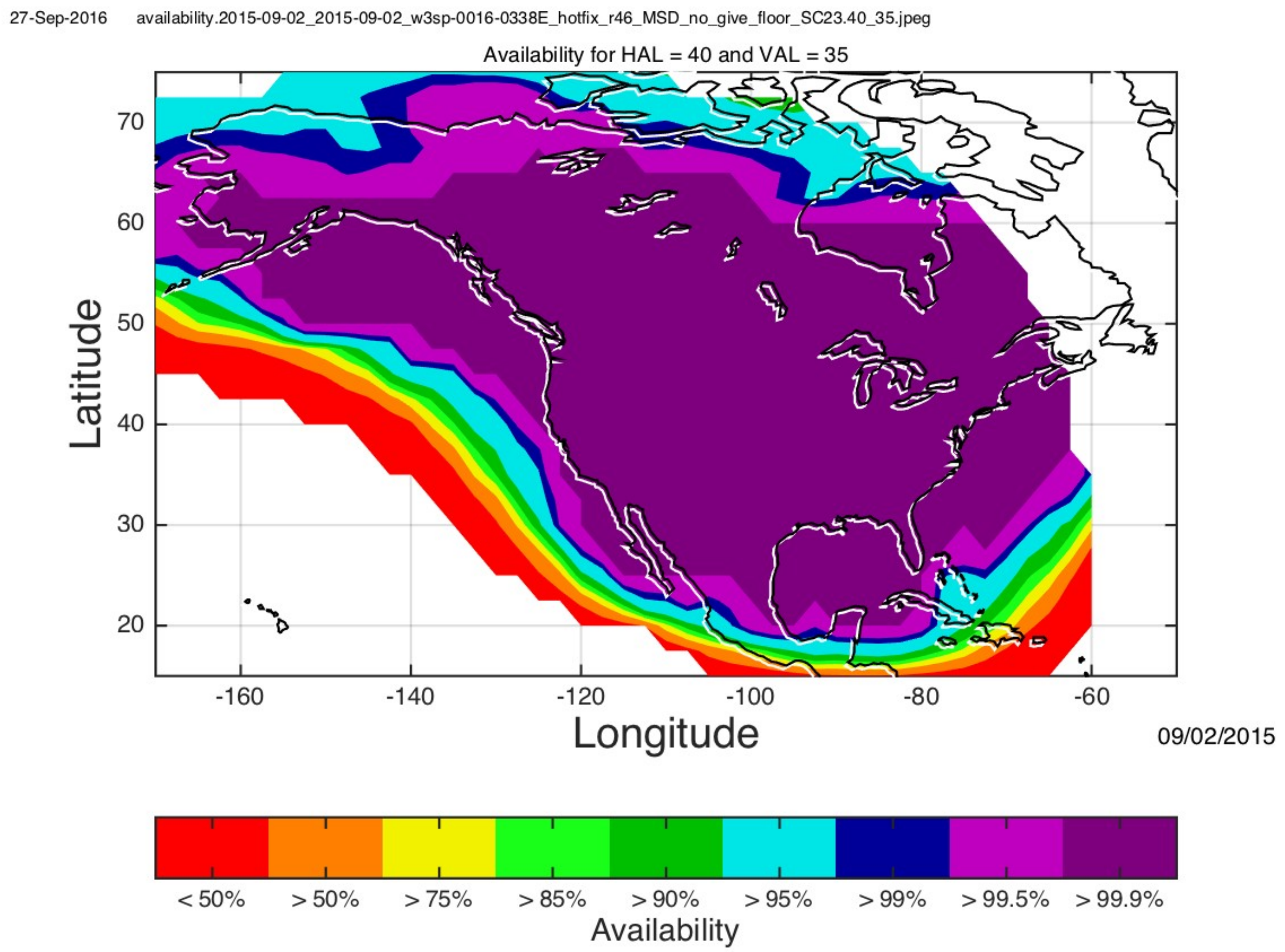
Introducing the Moderate Storm Detector in 2016 has lowered broadcast GIVEs by reducing $\sigma_{undersampled}$ values.

Adding solar cycle 24 data



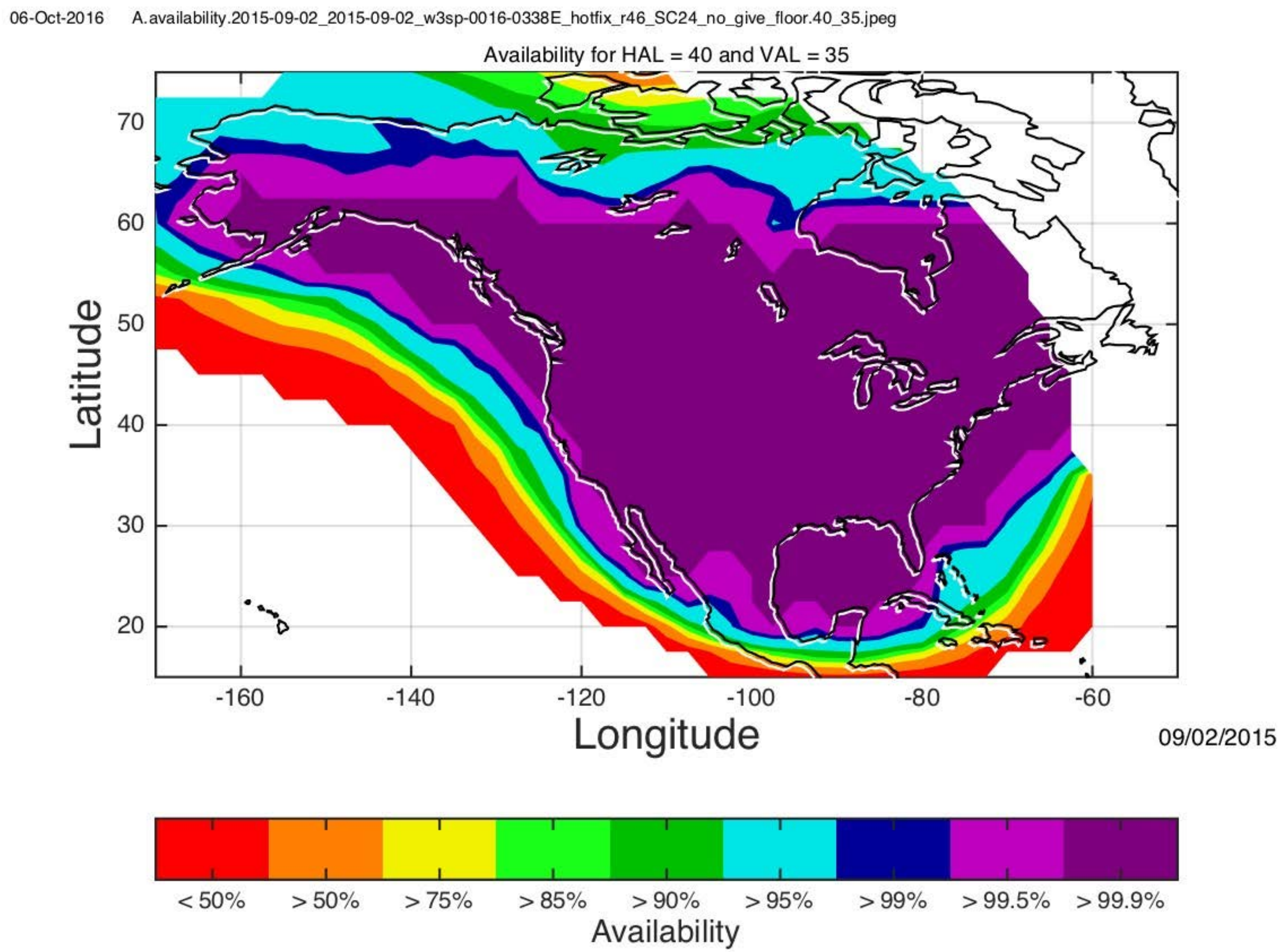
Despite the absence of major storms in solar cycle 24, incorporating solar cycle 24 data degrades the threat model.

Coverage for 9/2/2015 using VAL = 35 m with current threat model



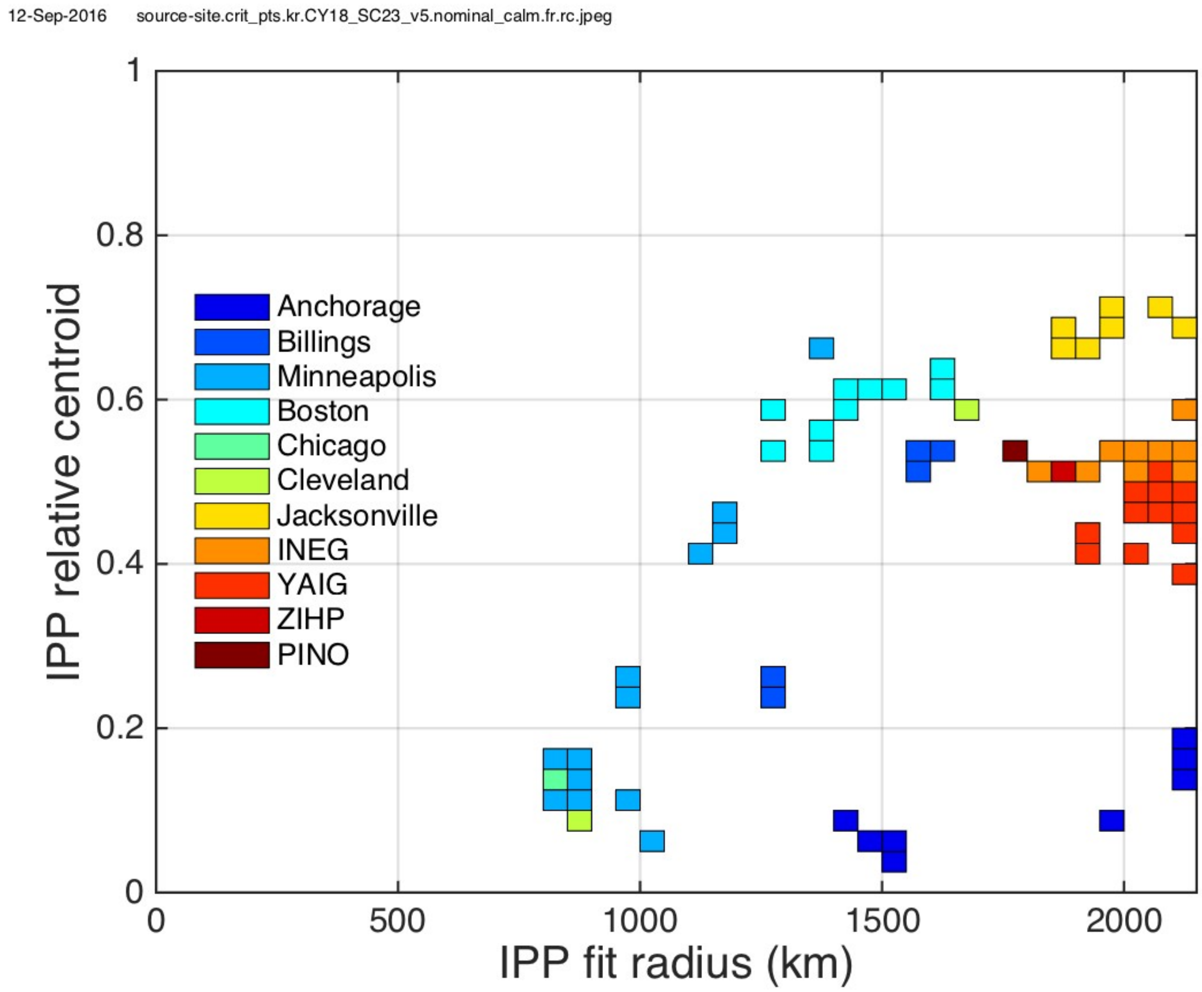
Supertruth:	version 4	Solar Cycle:	23 only
MSD:	on	GIVE floor logic:	off

Coverage for 9/2/2015 using VAL = 35 m
Adding solar cycle 24 data diminishes coverage

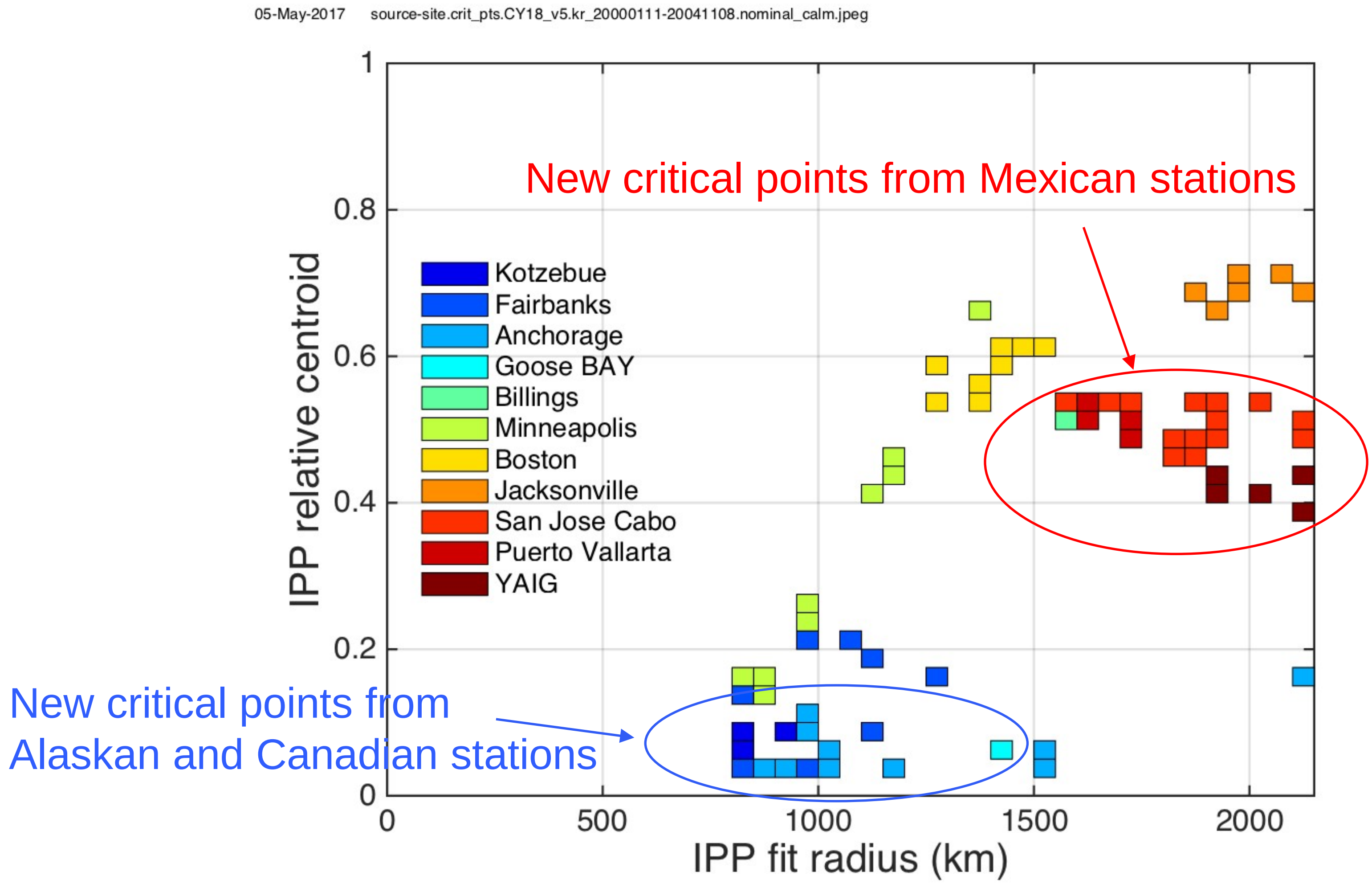


Supertruth:	version 4/5	Solar Cycle:	23 & 24
MSD:	on	GIVE floor logic:	off

Sites that contribute critical points when using only solar cycle 23 data

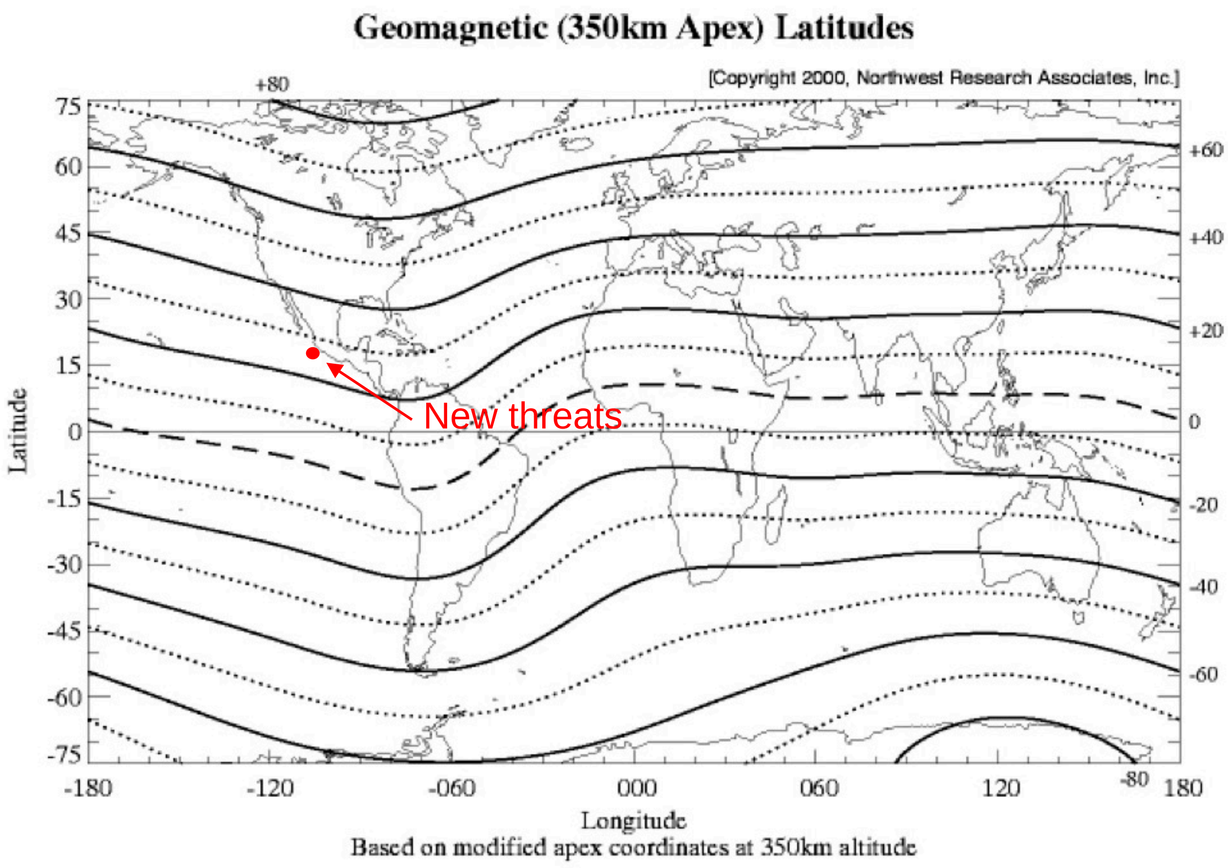


Sites that contribute critical points when using solar cycle 23 and 24 data



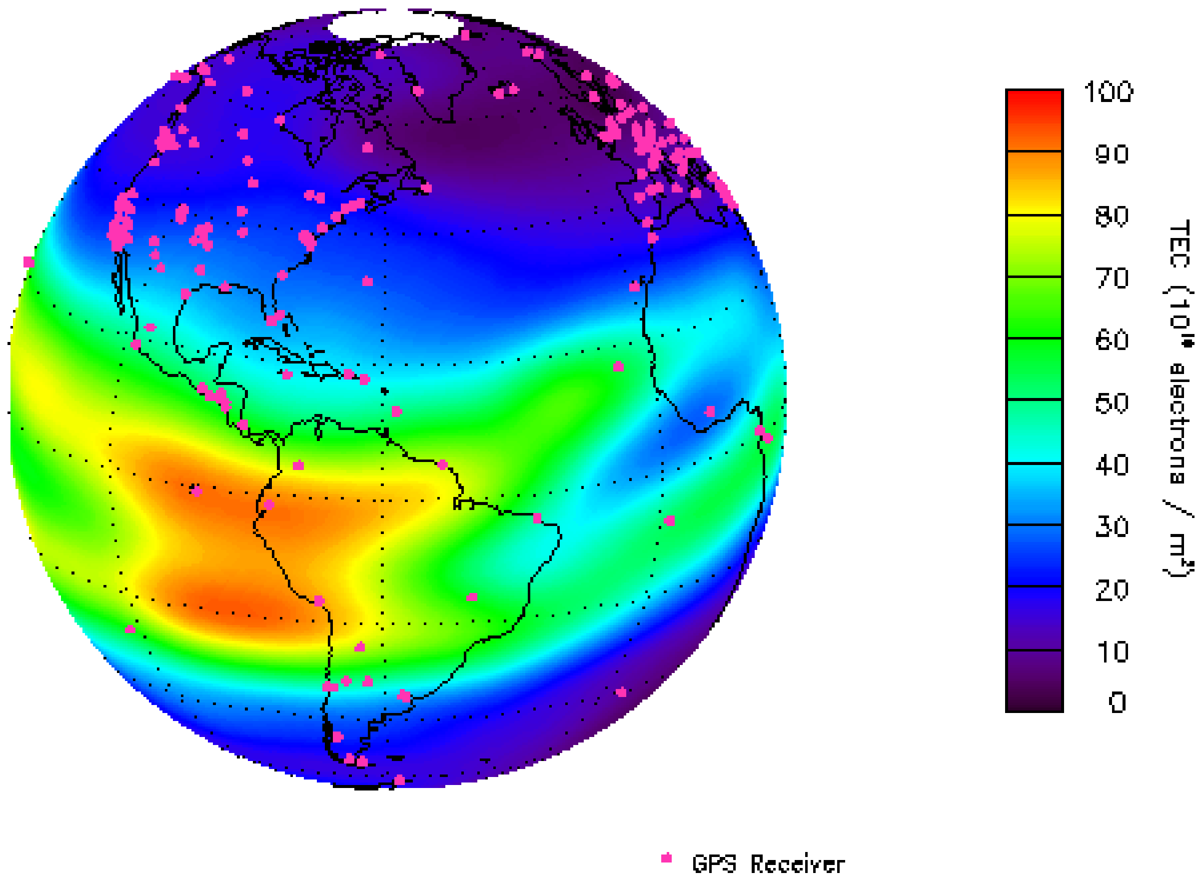
New critical points at low latitude come from fits at [15˚N, 100˚W] and [15˚N, 105˚W].

Geomagnetic coordinates of new threats



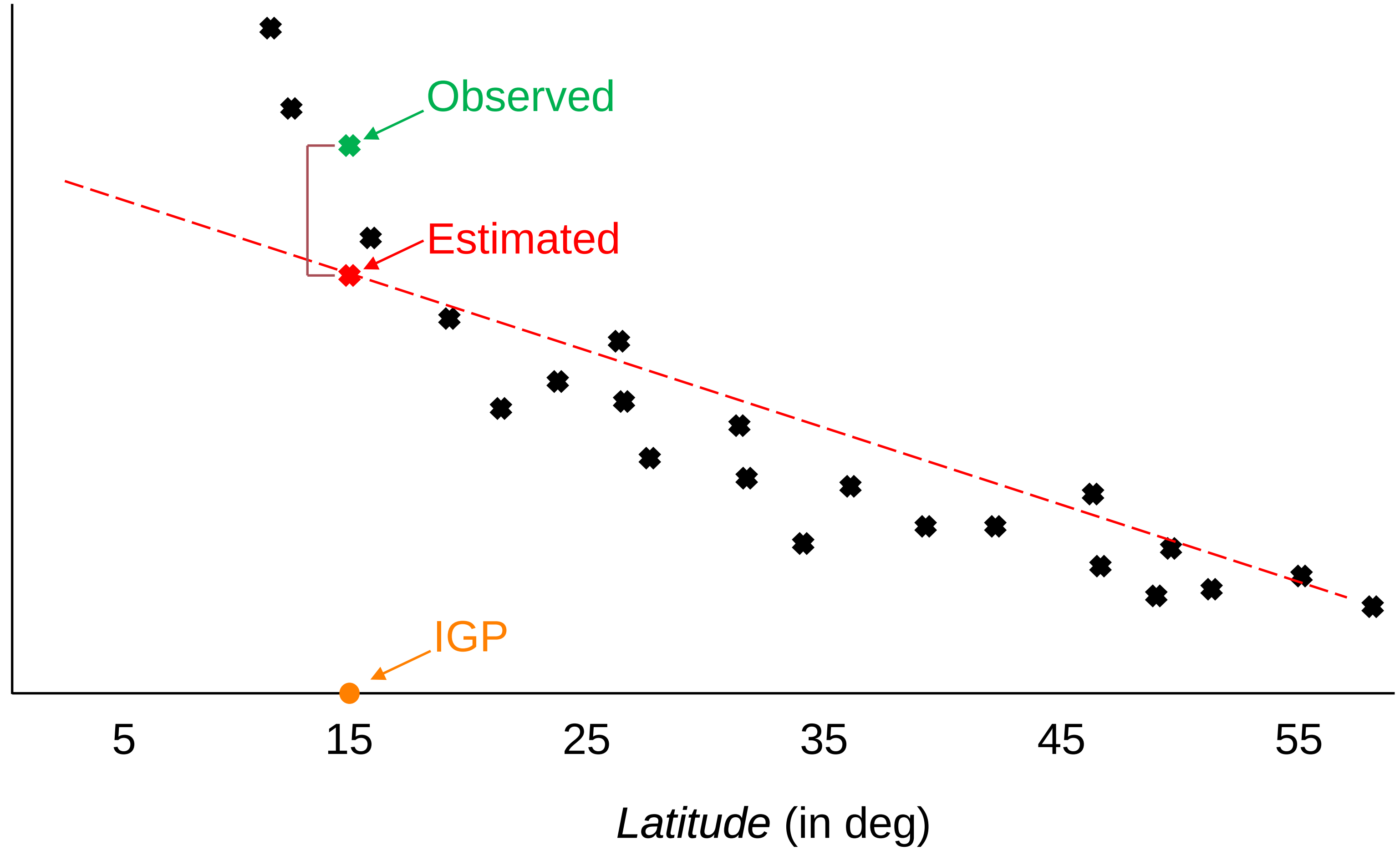
New Mexican threats occur at the lowest geomagnetic latitude.

Total electron content (TEC)



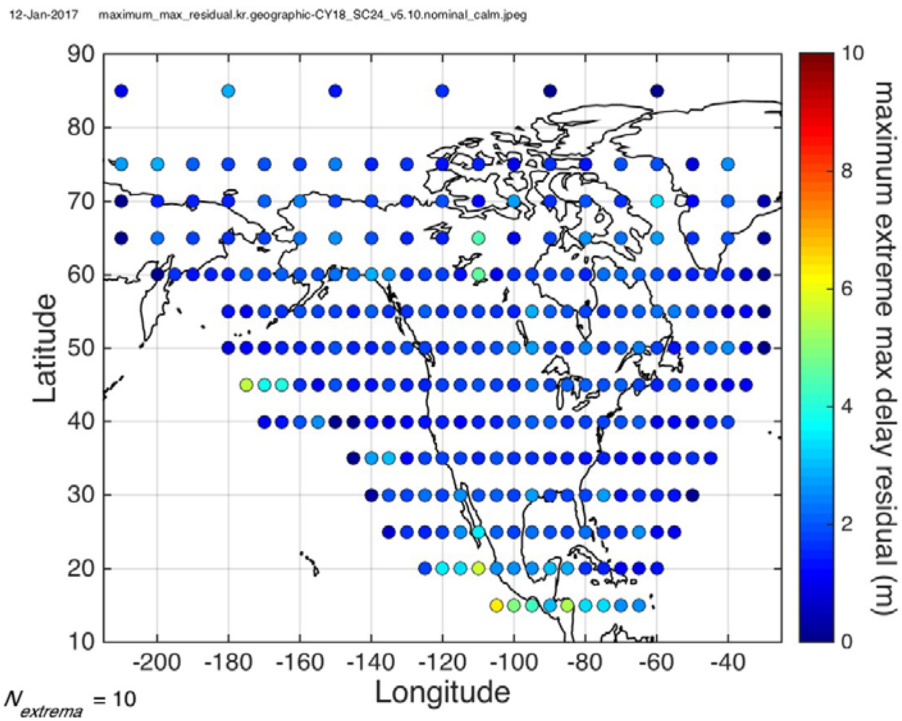
TEC is highly structured at low-latitudes: note the equatorial anomaly.

Residual fit error at low latitude IGPs

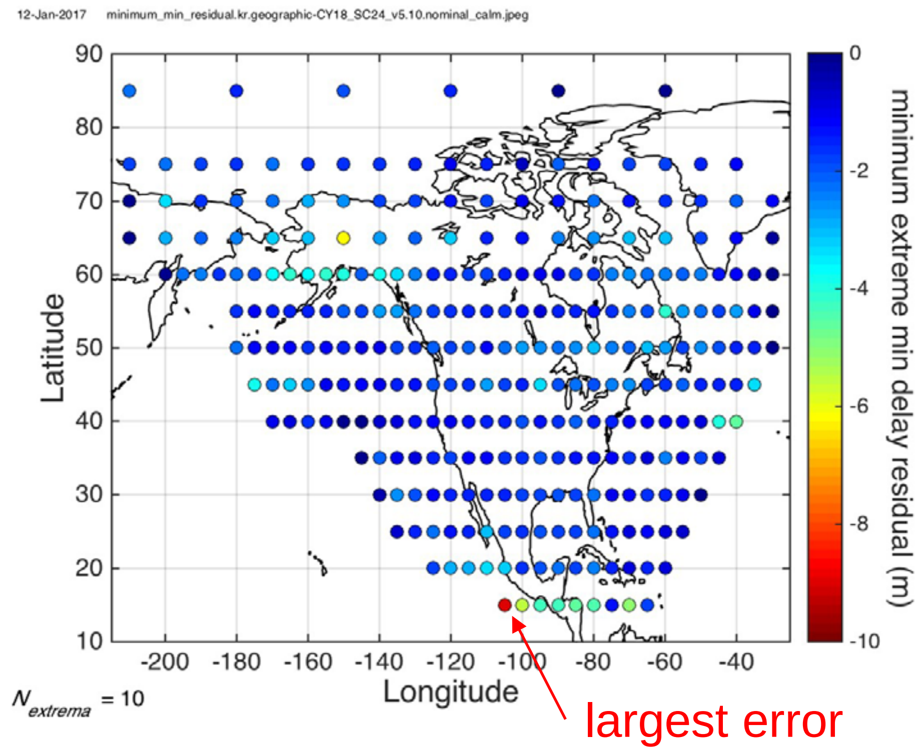


At low magnetic latitude, the planar fit algorithm will tend to *underestimate* the vertical delay due to the equatorial anomaly.

Extreme threat delay residuals for solar cycle 24



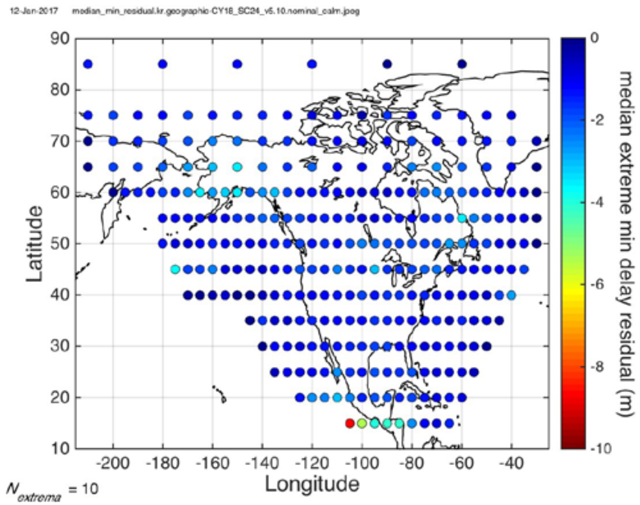
Positive residuals



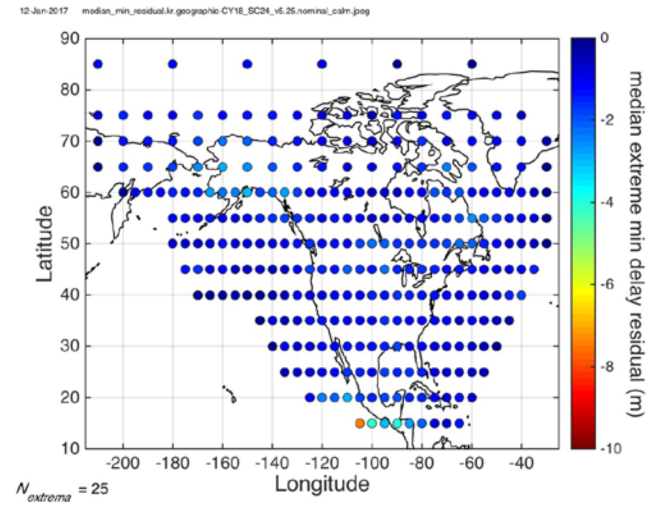
Negative residuals

Threat error = $VTEC_{estimated} - VTEC_{observed}$

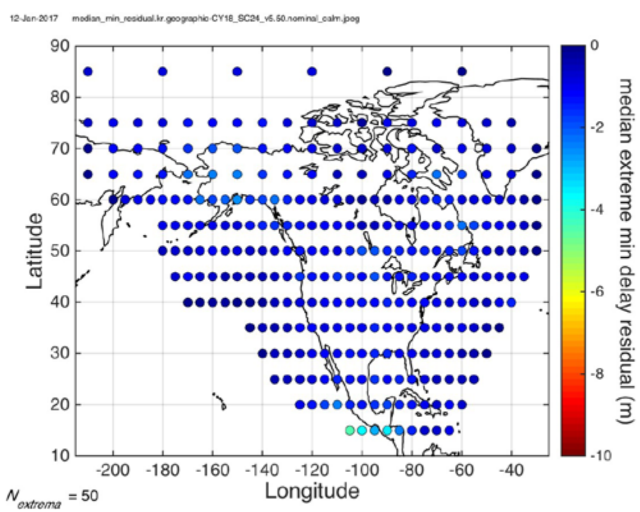
Statistical analysis for solar cycle 24: median of largest *negative* residuals



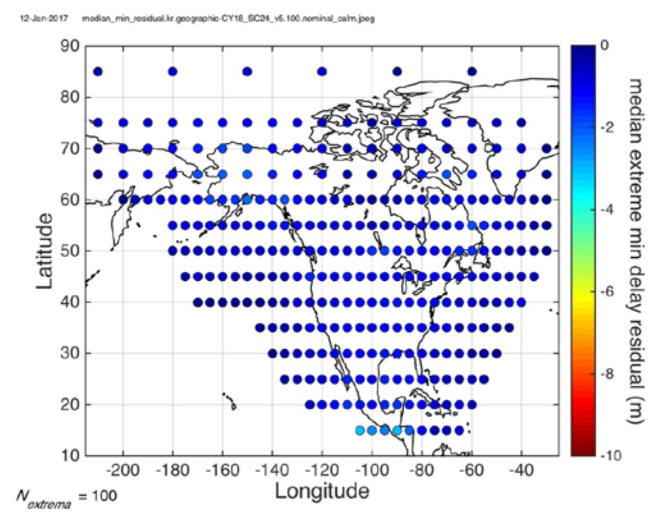
$N_{extrema}$ = 10



$N_{extrema}$ = 25

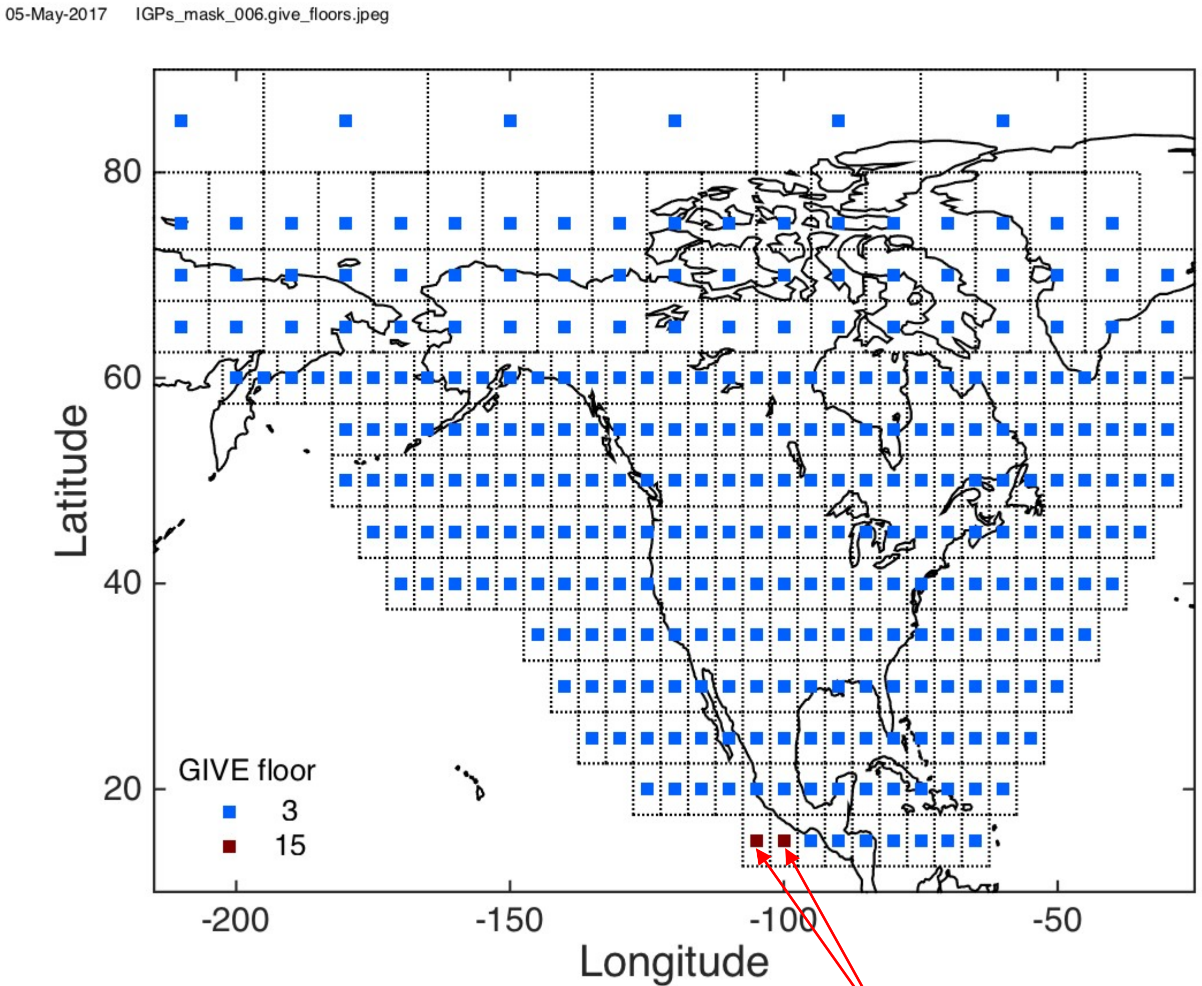


$N_{extrema}$ = 50



$N_{extrema}$ = 100

WAAS ionospheric grid point (IGP) mask



IGPs where new threats occur

Culling threats using the UIVE floor

Conditions to tabulate a threat in the raw data of a threat model:

Current condition to tabulate a threat :

$$\bar{\sigma}^2_{undersampled,\,\kappa} > 0$$

$$\Rightarrow$$

$$\left| \bar{I}_{IPP_\kappa} - \tilde{I}_{IPP_\kappa} \right|^2 > K^2_{undersampled} \tilde{\sigma}^2_{IPP_\kappa}$$

Condition to tabulate a threat not covered by the UIVE floor:

$$\tilde{\sigma}^2_{IPP_\kappa} + \bar{\sigma}^2_{undersampled\,,\kappa} > \tilde{\sigma}^2_{UIVE\,,\,floor}$$

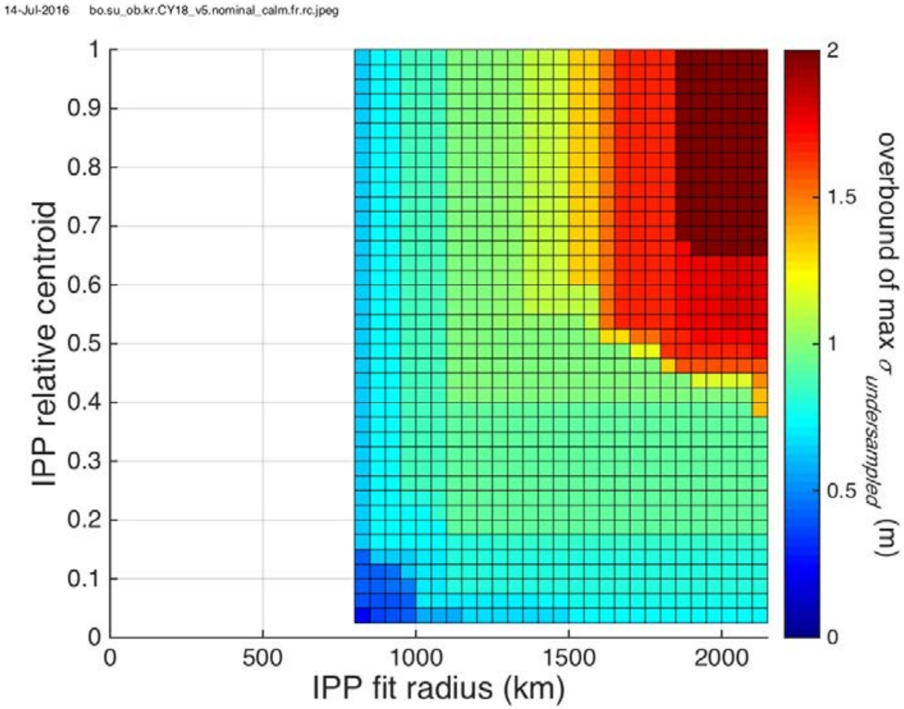
$$\Rightarrow$$

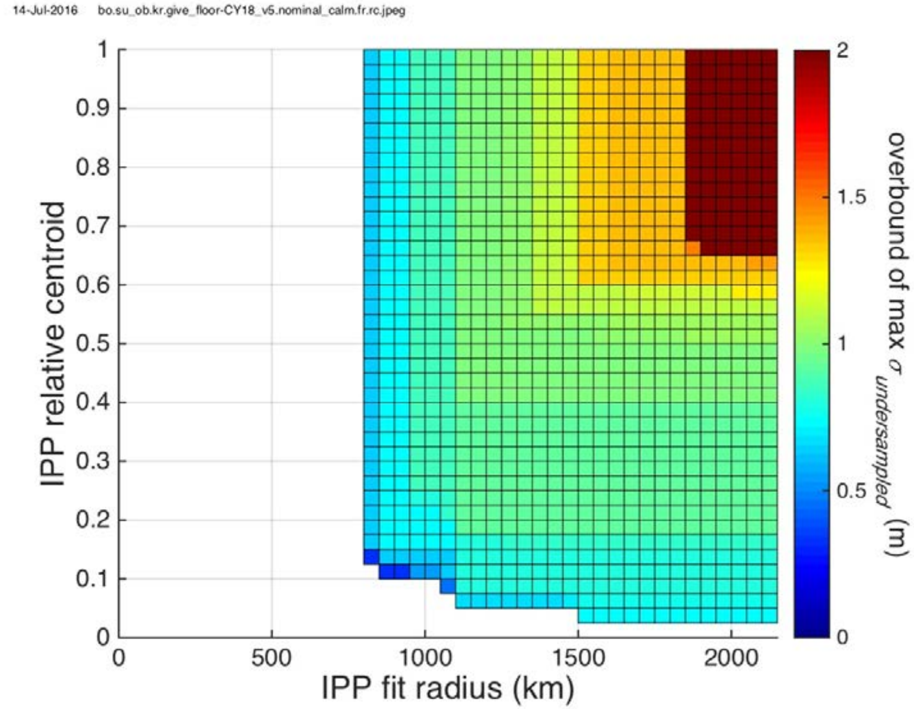
$$\tilde{\sigma}^2_{IPP_\kappa} + \bar{\sigma}^2_{undersampled\,,\kappa} > \tilde{\sigma}^2_{UIVE\,,\,floor}$$

Conditions combined:

$$\left| \bar{I}_{IPP_\kappa} - \tilde{I}_{IPP_\kappa} \right|^2 > K^2_{undersampled} \max\left(\tilde{\sigma}^2_{UIVE\,,\,floor}, \tilde{\sigma}^2_{IPP_\kappa} \right)$$

Implementing removal of threats using UIVE floor



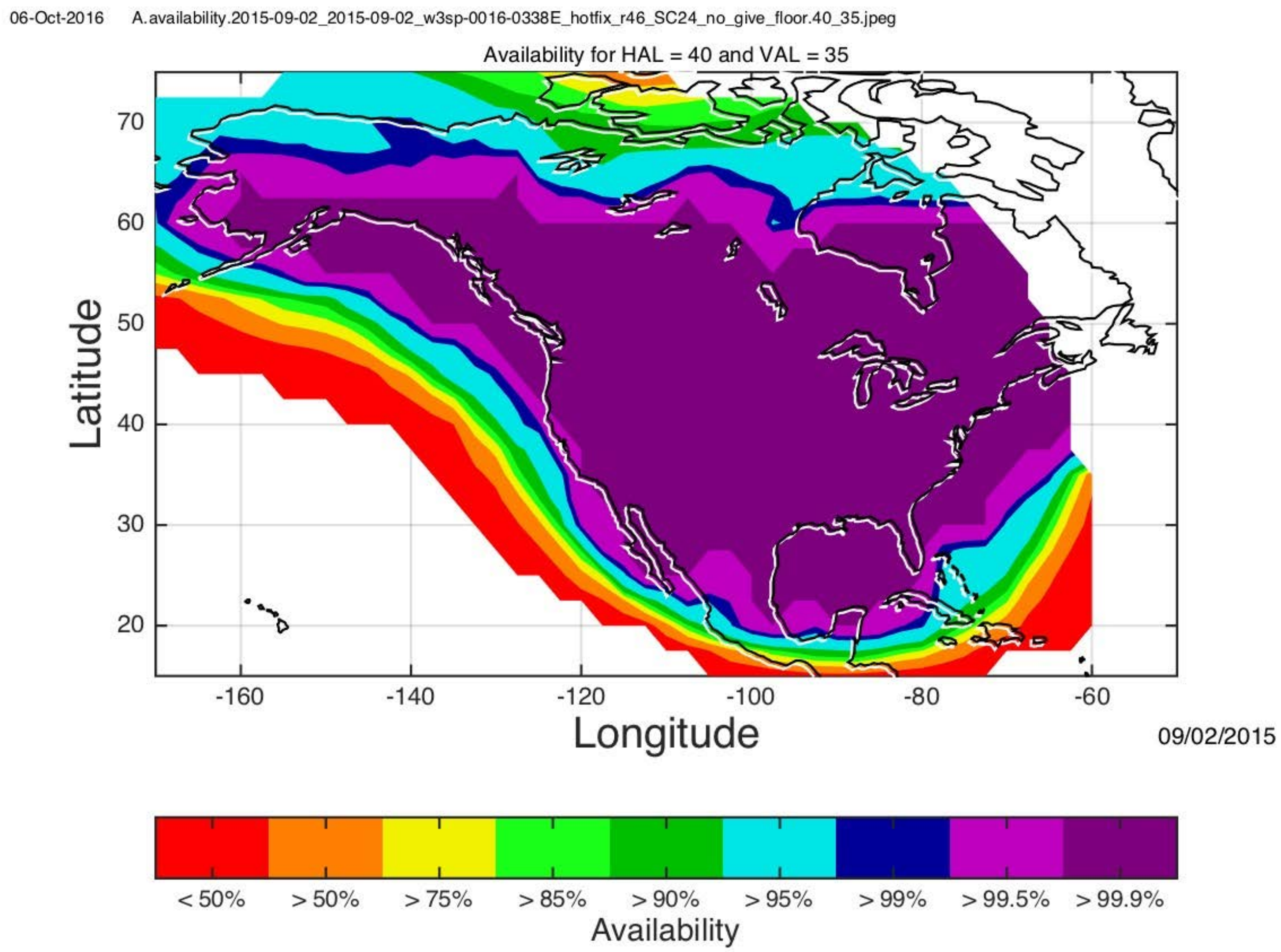


Without UIVE floor culling

With UIVE floor culling

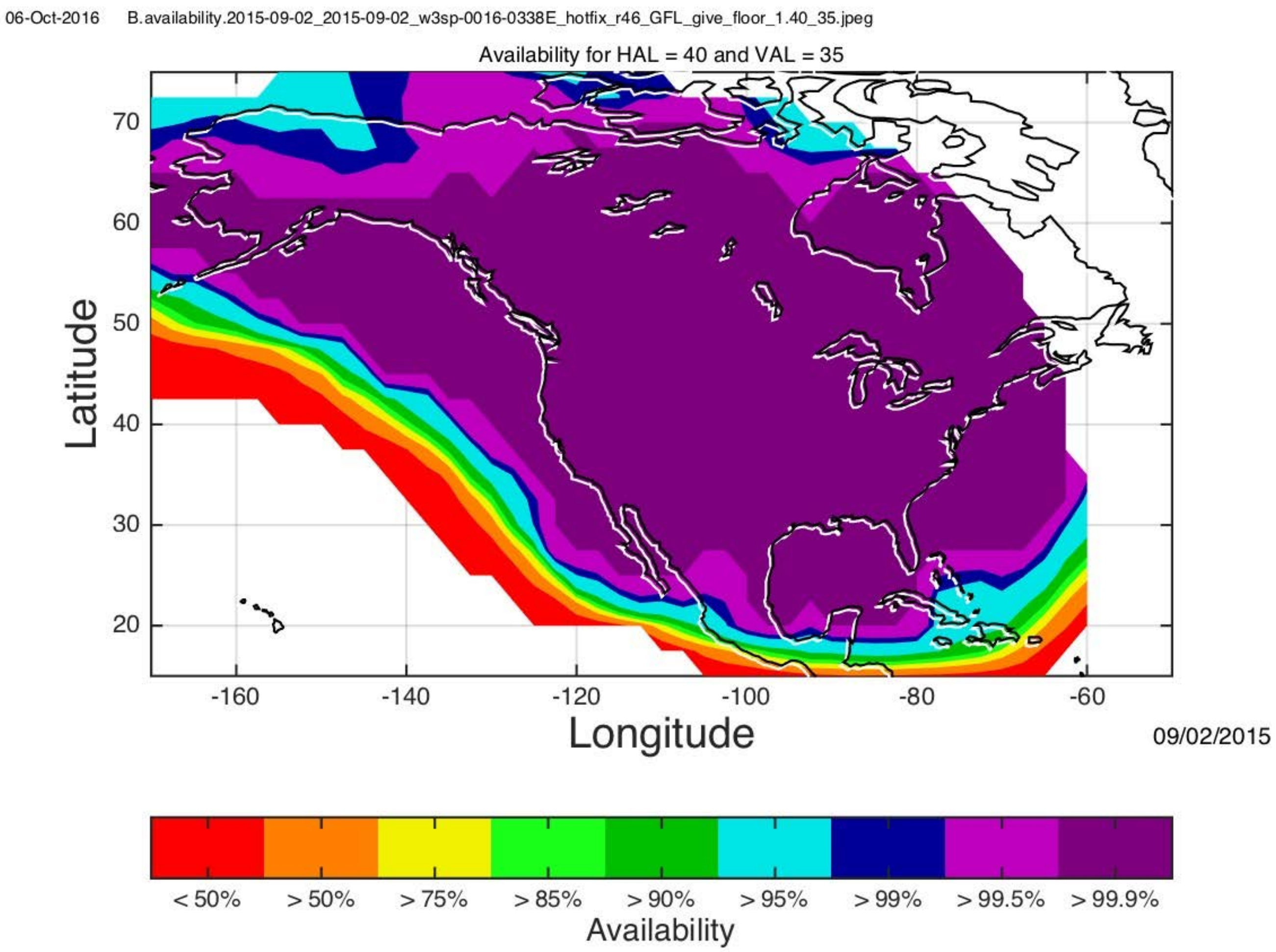
Removing threats using the UIVE floor eliminates critical points that reduce availability.

Coverage for 9/2/2015 using VAL = 35 m without UIVE floor culling



Supertruth:	version 4/5	Solar Cycle:	23 & 24
MSD:	on	GIVE floor logic:	off

Coverage for 9/2/2015 using VAL = 35 m with UIVE floor culling



Supertruth:	version 4/5	Solar Cycle:	23 & 24
MSD:	on	GIVE floor logic:	on

Summary

- The largest threat error occurs at the lowest geomagnetic latitude represented in the WAAS grid.
- Solar cycle 24 storm data cause a degradation of the ionospheric threat model that would cause significant loss of WAAS availability, especially in Alaska and along the California coast, if implemented with current threat model algorithms.
- Statistical results are consistent with the assumption that the large fit residuals at low geomagnetic latitude are caused by ionospheric curvature rather than ionospheric irregularities.
- Using the UIVE floor to remove threats from the threat model provides improved availability without compromising safety.
- The next upgrade of the WAAS threat model should enhance both system integrity and availability, especially off the coast of California and Alaska.

Acknowledgment:

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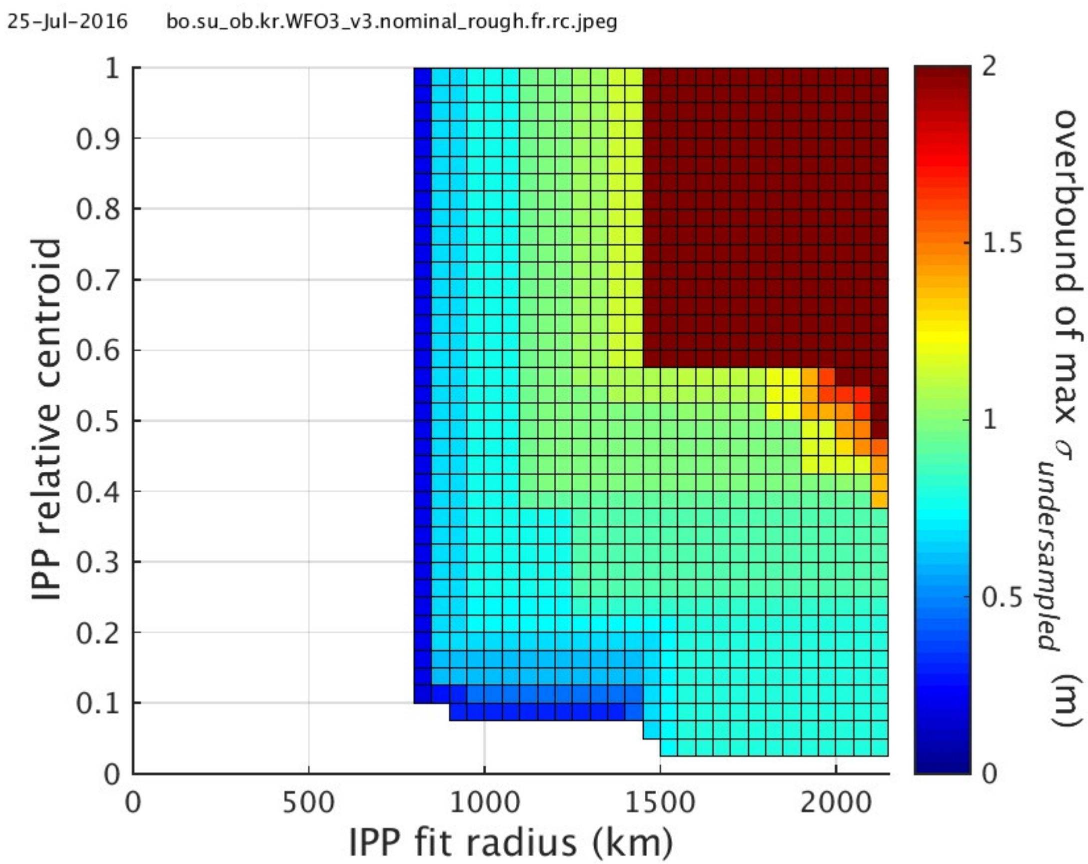
Appendix

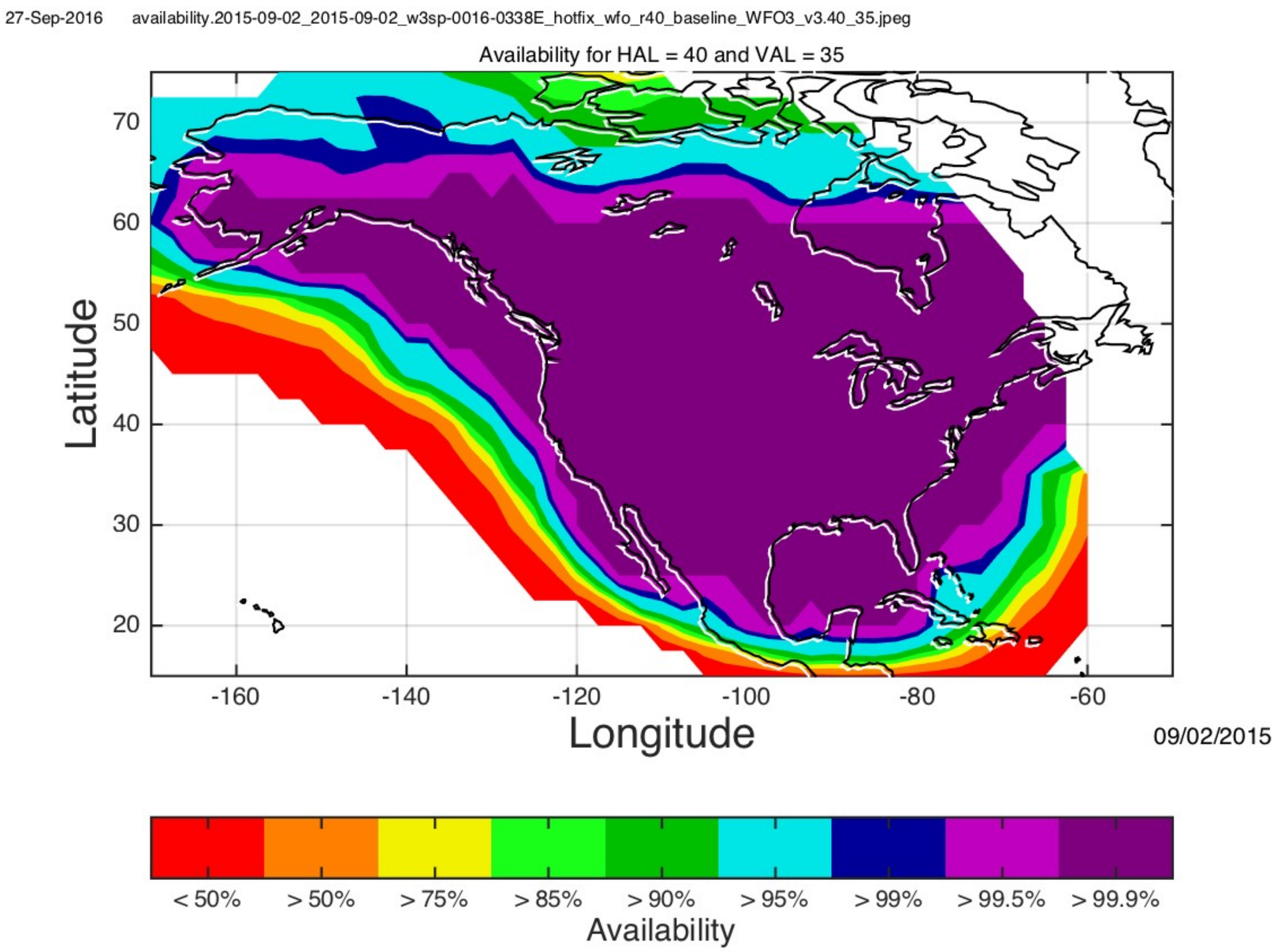
WFO 3 baseline threat model



The ionospheric threat model provides $\sigma_{undersampled}$ as a function of fit radius and relative centroid.

Coverage for 9/2/2015 using VAL = 35 m

WFO 3 baseline

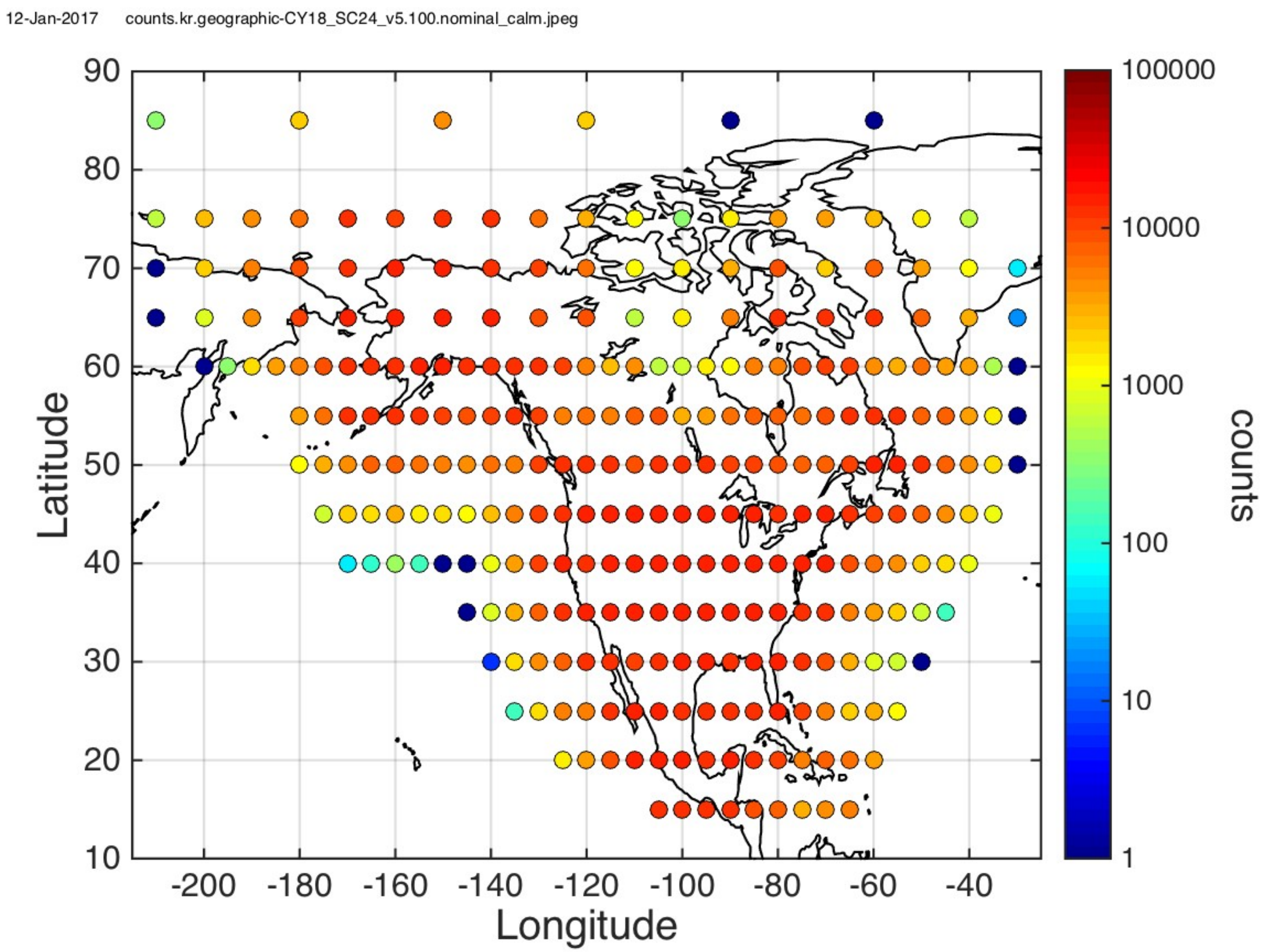


Supertruth:	version 3	Solar Cycle:	23 only
MSD:	off	GIVE floor logic:	off

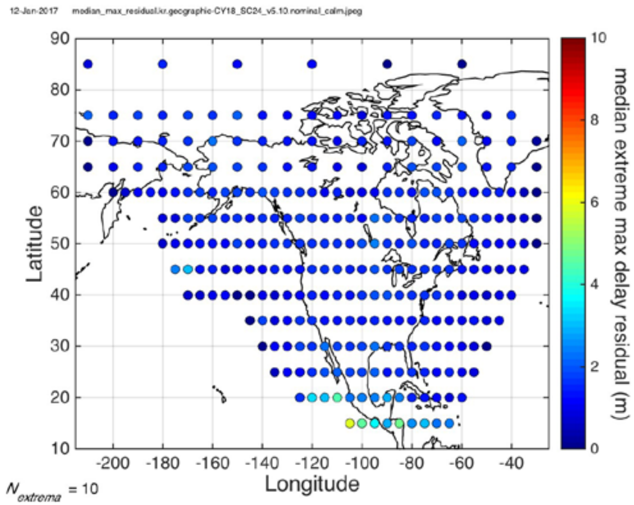
Analysis of the geographic distribution of threat residual error

- Tabulate at each IGP the top 100 fit residuals for IPPs in the threat domain
- Tabulate negative residuals separately from positive residuals
- Tabulate residuals separately for storms belonging to different solar cycles:
  - solar cycle 24 (16 storm days; 38 stations)
  - solar cycle 23 (18 storm days; 25 WAAS stations + Mexican stations)
- Exclude residuals when irregularity detector has tripped and when:
  - both MSD and ESD have tripped, or
  - only ESD has tripped
- Tabulate residuals separately for distinct data deprivation:
  - none
  - single station

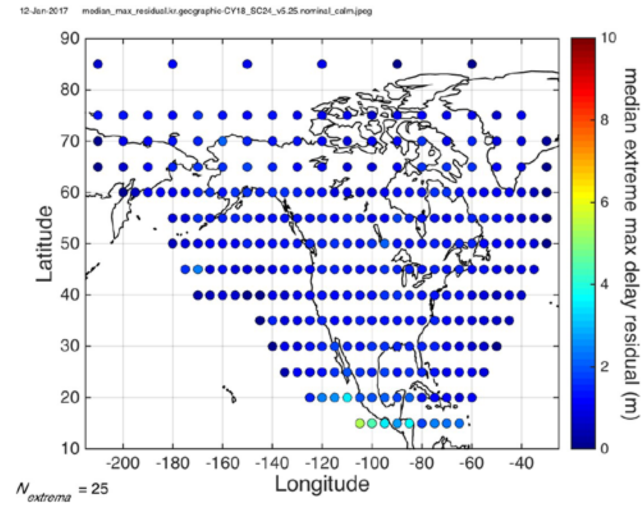
Threat residuals examined at each IGP: solar cycle 24



Statistical analysis for solar cycle 24: median of largest *positive* residuals



$N_{extrema}$ = 10



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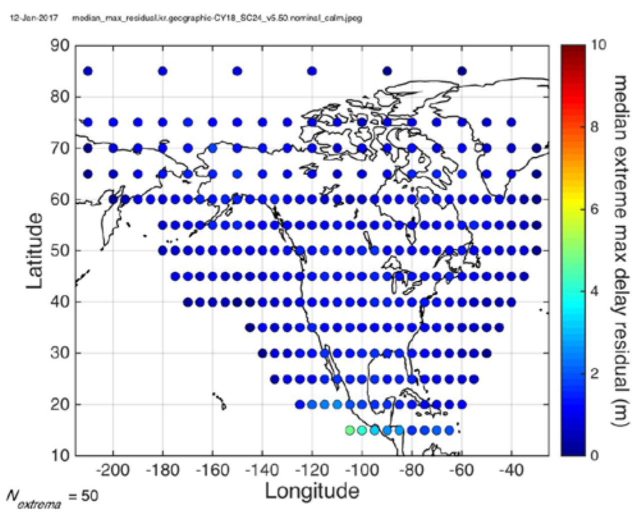

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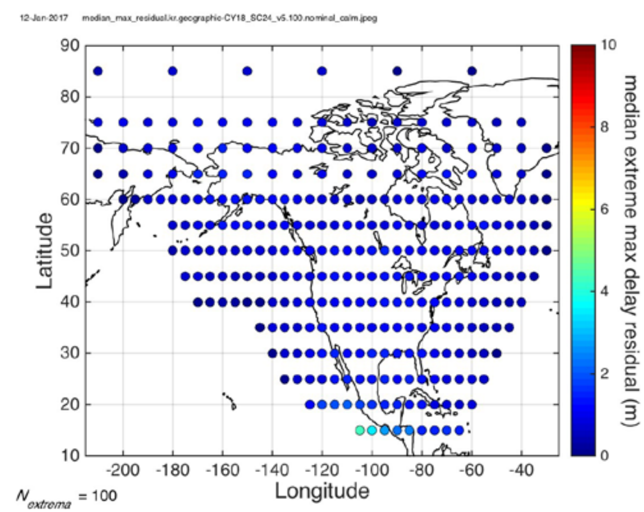
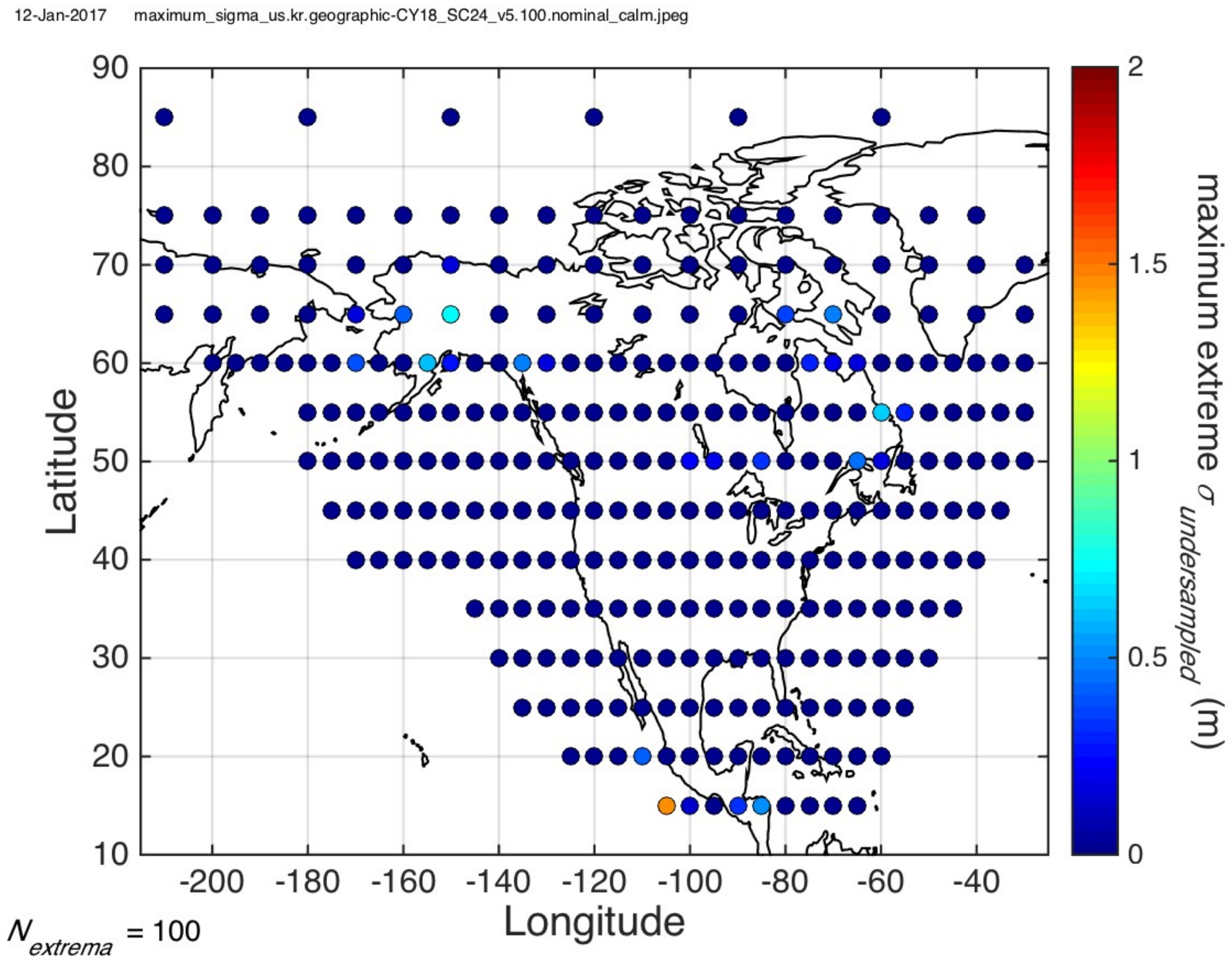
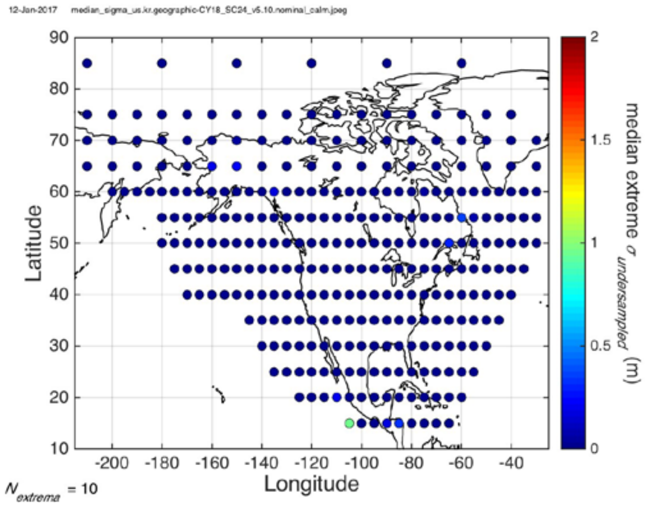


$N_{extrema}$ = 100

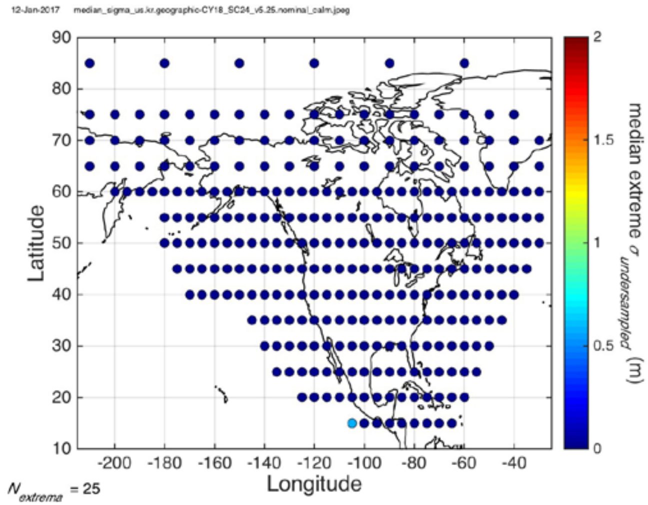
Extreme $\sigma_{undersampled}$ solar cycle 24



Median of $\sigma_{undersampled}$: solar cycle 24



$N_{extrema}$ = 10



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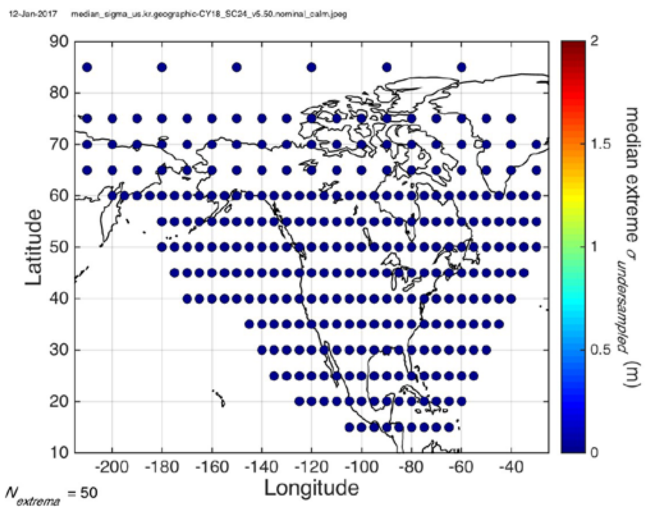

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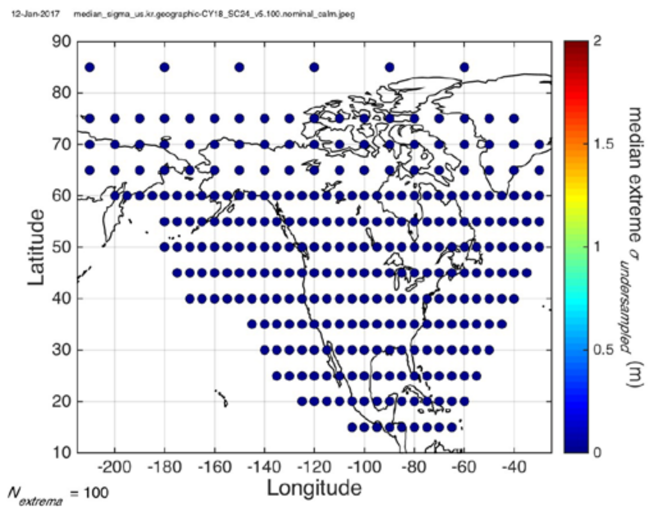

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