Data-Quality Improvements and Applications of Long-Term Monitoring of Ionospheric Anomalies for GBAS

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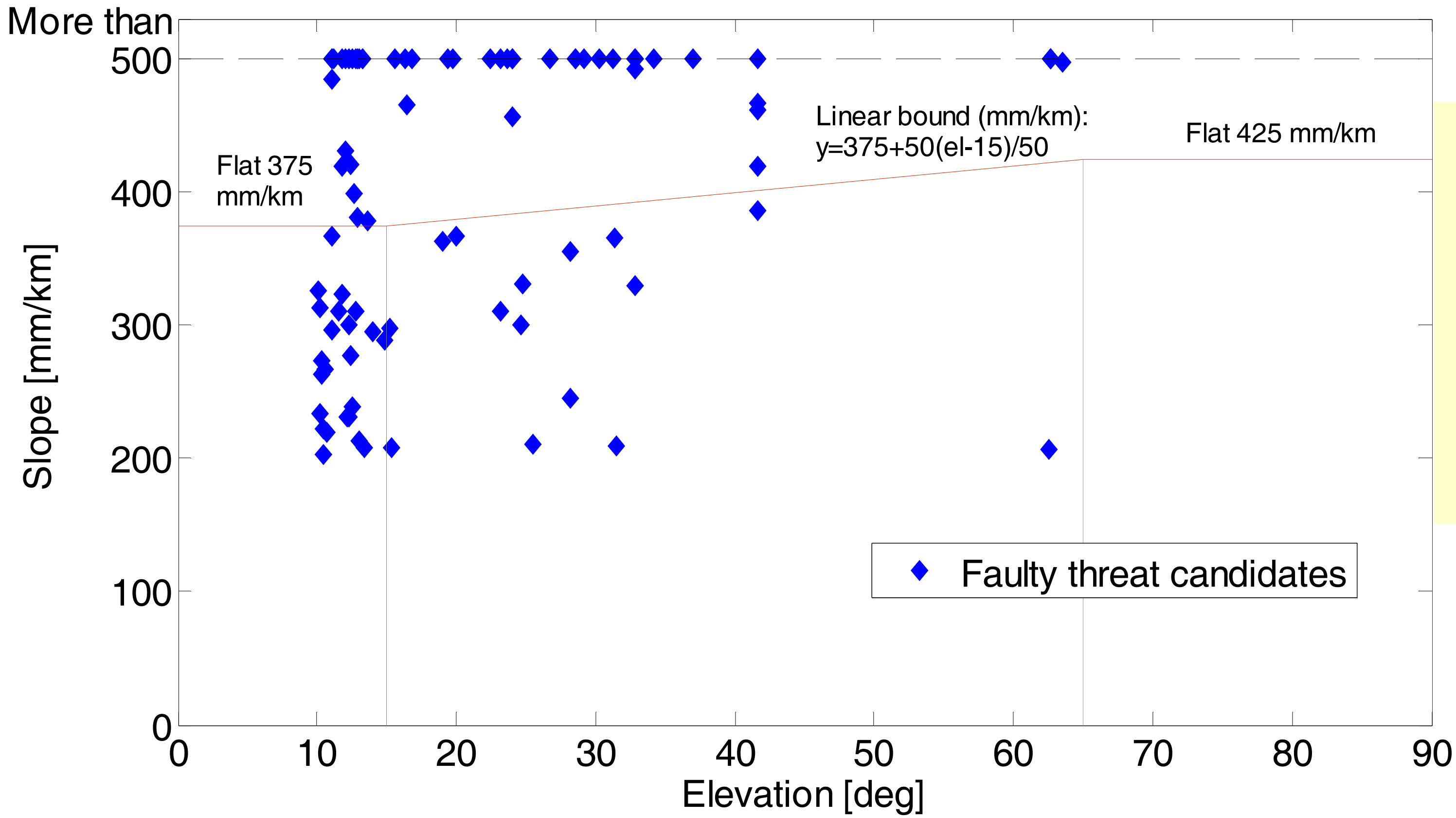
Motivation, Previous Work, and Objective

- **Continued monitoring of the Ionosphere to ensure gradients larger than those included in the threat model are not present**
  - **11 year solar cycle → we are now approaching the next solar maximum (2013 – 2015)**
- **Developed the Long Term Ionospheric Anomaly Monitor (LTIAM) to verify the LAAS CAT I threat model**
  - **Building ionosphere threat models for all regions where GBAS will be fielded in the future**
- **Selection criteria need to be defined to reduce processing time in both the automated procedure and the manual analysis/validation**
  - **The number of stations with poor GPS data quality also increases, as the total number of stations increases**

Faulty Candidates Generated from LTIAM on a Nominal (Quiet) Day (26 May 2012)

Faulty anomaly candidates
before removing stations with poor GPS data quality



92 faulty candidates must be manually validated to confirm these are not real anomalies

Faulty Candidates Generated from LTIAM on a Nominal (Quiet) Day (26 May 2012)

Faulty anomaly candidates
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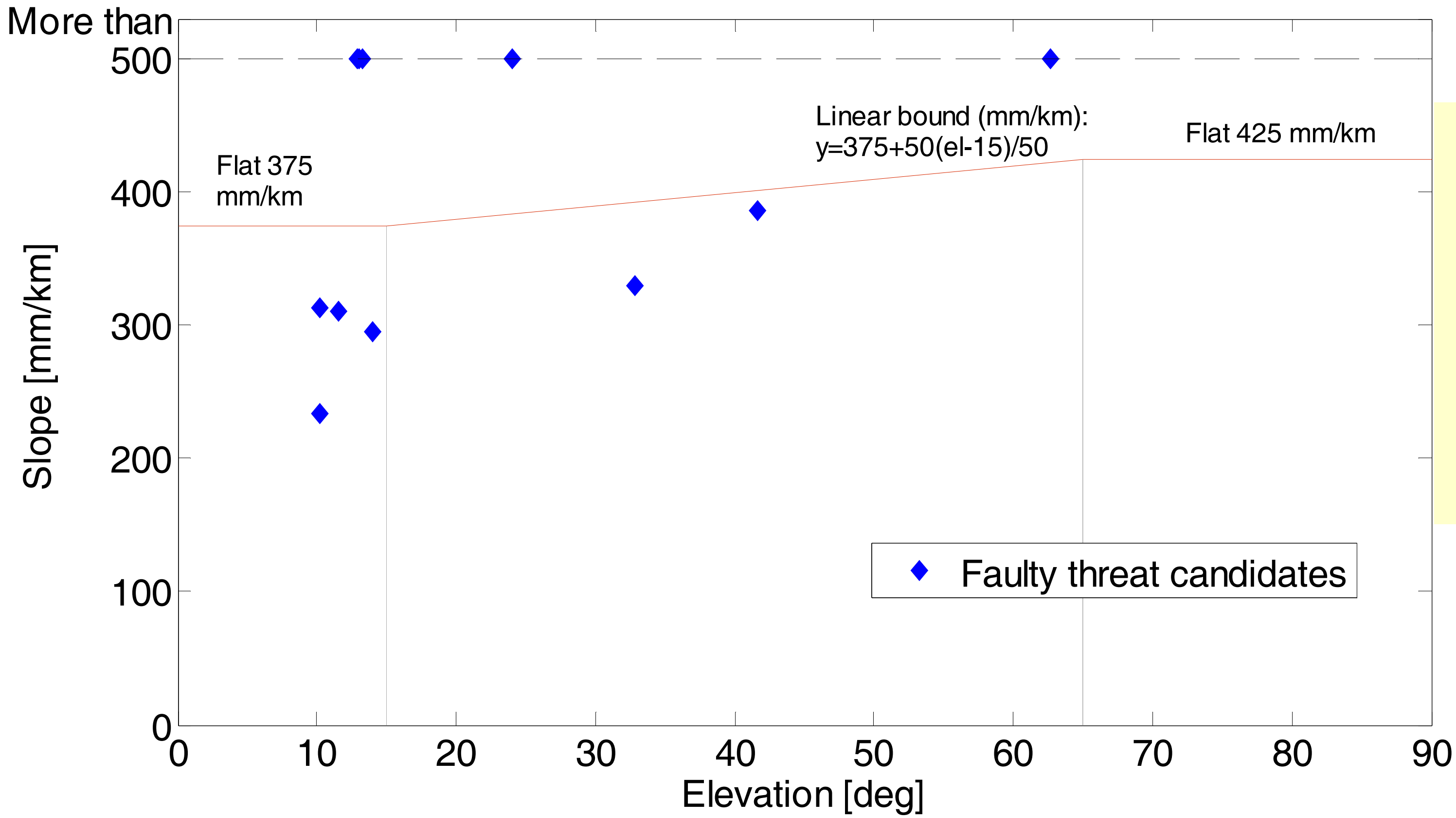


Only 11 faulty candidates must be manually validated to confirm these are not real anomalies

Methodology of GPS Data Quality Determination and CORS Station Selection

Poor data quality causes LTIAM processing errors and generate erroneous estimates of ionospheric delay/gradient

GPS Data Quality Information

Station Selection for LTIAM

Geographical Distribution

The selected stations should cover all of CONUS with short-baselines to the degree possible

Data Sampling Rates

Data with higher sampling rates is preferred

The goal is to select a subset of CORS stations which optimally meet the three criteria

GPS Data-Quality-Measurement Algorithms

Input: RINEX file collected from a Station (Header and Observations)

LTIAM Pre-processing

IOD Cycle Slip Detection
- Data gap
- Large data jump
- LLI (Loss of Lock Indicator)

Outlier Detection
- Polynomial fit method
- Adjacent point difference method

TEQC algorithm

IOD Cycle Slip Detection

Cycle Slip Detection using Multipath Estimates

Percentage of Observations

RMS of Multipath on Code

Adaptive Filter algorithm

Receiver Noise Estimation on Code Measurement
- Least-mean-square adaptive algorithm

Output: GPS Data Quality Measurement

Test Runs of GPS Data-Quality-Measurement Algorithm on Nominal Days

- **Quality parameters which affect the performance of LTIAM most are: Percentage of observations, # of IOD cycle slips, # of MP slips, # of outliers, # of Short arcs, Mean of MP1 & Mean of MP2**

- **Tests conducted on 7 consecutive days during which geomagnetic storm conditions were quiet**

- **Number of stations processed in CONUS: 1578**

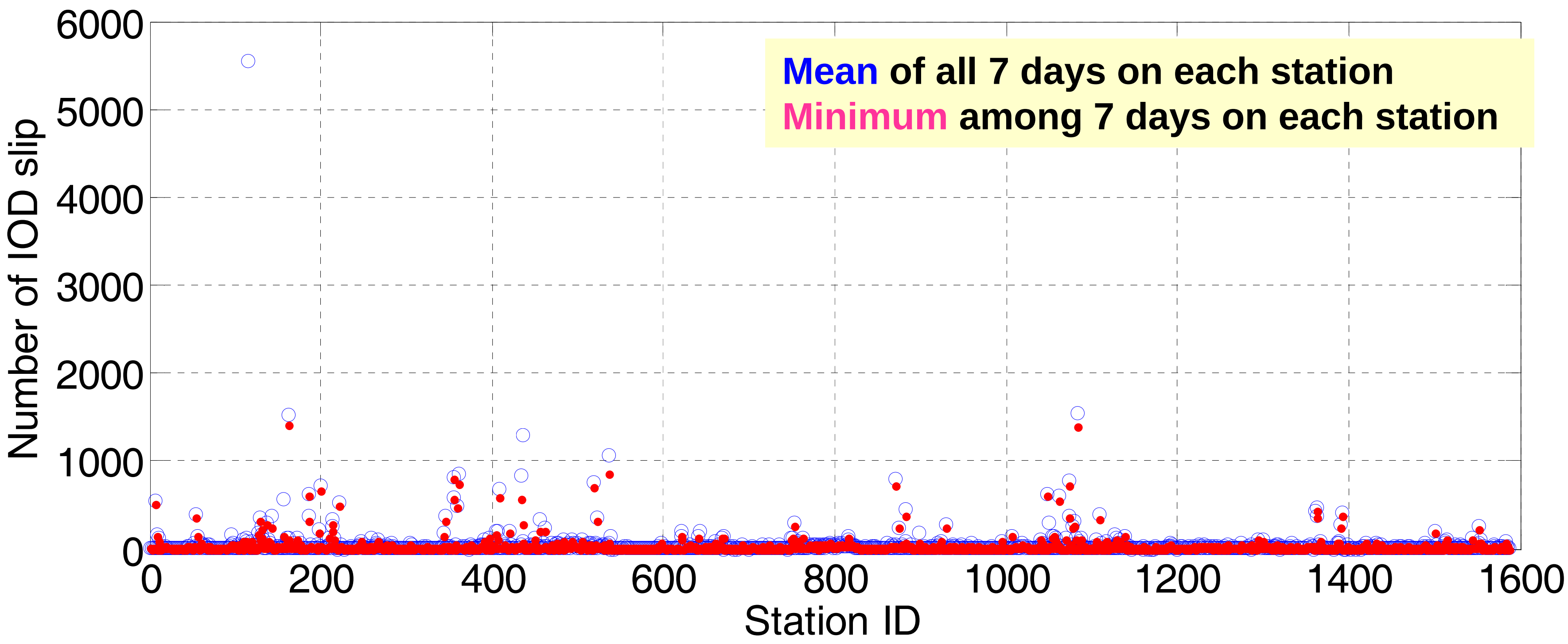
Day (UT)	K_P	D_{ST}
24 May 2012	2.0	-15
25 May 2012	2.3	17
26 May 2012	2.3	-6
27 May 2012	1.3	14
28 May 2012	2.3	23
29 May 2012	2.3	23
30 May 2012	2.3	16

- **The statistics of quality measurements obtained from the tests are used to determine station selection criteria**

IOD Cycle Slips (all satellites, per day, per station)

Number of IOD cycle slips occurring on each station per day

Mean number of IOD cycle slips over all 7 days and all stations : 37.98



# of IOD slips per day	> 50	> 100	> 500
# of stations (percentage)	192 (12.1%)	105 (6.1%)	20 (1.2%)

Stations with Poor GPS Data Quality

Bad

IOD cycle slip

	Stn.	#
1	bru5	5552
2	sag5	1544
3	covx	1529.43
4	ls02	1301.5
5	mlf5	1063
6	kns6	862.29
7	loz1	832.29
8	kew6	819.71
9	okee	801.57
10	red6	767.57
11	mion	766.71
12	drv6	715
13	lou6	673.57
14	plo5	625.14
15	det6	621.71
16	prry	598.29

Per. of Obs.

	Stn.	%
1	p702	18
2	p699	38.33
3	ncwj	42.14
4	twhl	50.71
5	okee	59.71
6	barn	61
7	wvbr	61
8	loz1	64.86
9	ohfa	67
10	sag6	67
11	hgis	68.86
12	kysc	68.86
13	arm3	70
14	dqcy	71.14
15	hamm	71.14
16	negi	71.29

Short arc

	Stn.	#
1	bru5	5545
2	covx	1483.71
3	sag5	1466.43
4	ls02	1256.17
5	mlf5	1051
6	kns6	862.14
7	kew6	819.57
8	loz1	792.71
9	okee	763.57
10	red6	760.14
11	drv6	705.86
12	mion	697.57
13	lou6	646.71
14	det6	617.86
15	plo5	615.57
16	kew5	574.57

Outlier

	Stn.	#
1	mion	281.86
2	ls02	100.33
3	frtg	67.71
4	jxvl	65.57
5	okee	59.71
6	cpac	57
7	pltk	55.29
8	mipw	54.57
9	njcm	52
10	mihl	50.86
11	hruf	47.57
12	napl	46.86
13	brig	45.14
14	adri	44.43
15	brtw	43.29
16	p671	41.14

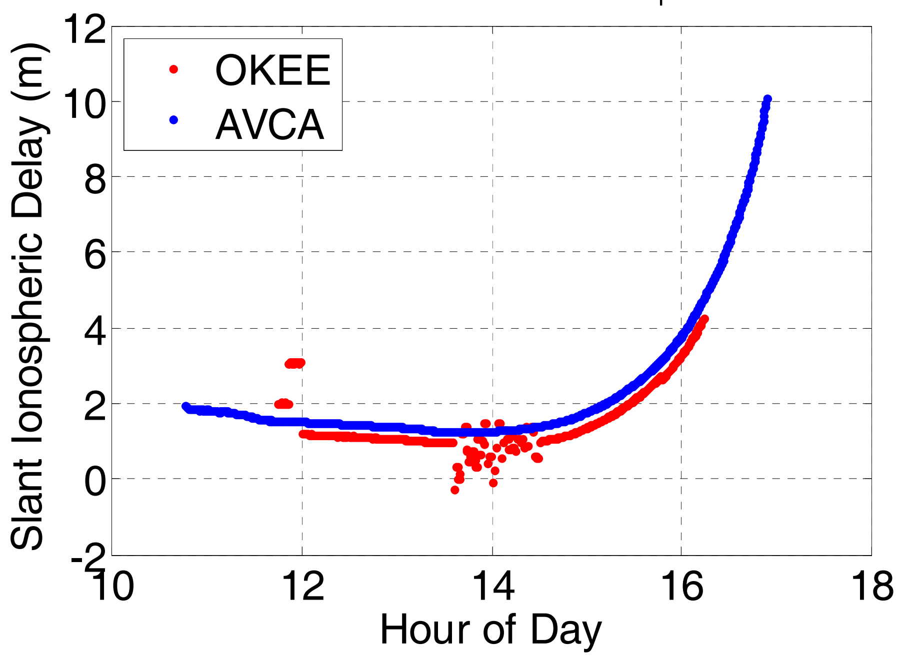
Mean of MP1

	Stn.	meter
1	defi	0.7244
2	wach	0.718
3	ormd	0.7047
4	zoa2	0.696
5	zfw1	0.6852
6	zla1	0.6797
7	zau1	0.6766
8	zob1	0.6461
9	zlc1	0.6346
10	zab1	0.6337
11	zmp1	0.6335
12	zse1	0.6331
13	zoa1	0.6297
14	red6	0.623
15	zma1	0.6226
16	loz1	0.6178

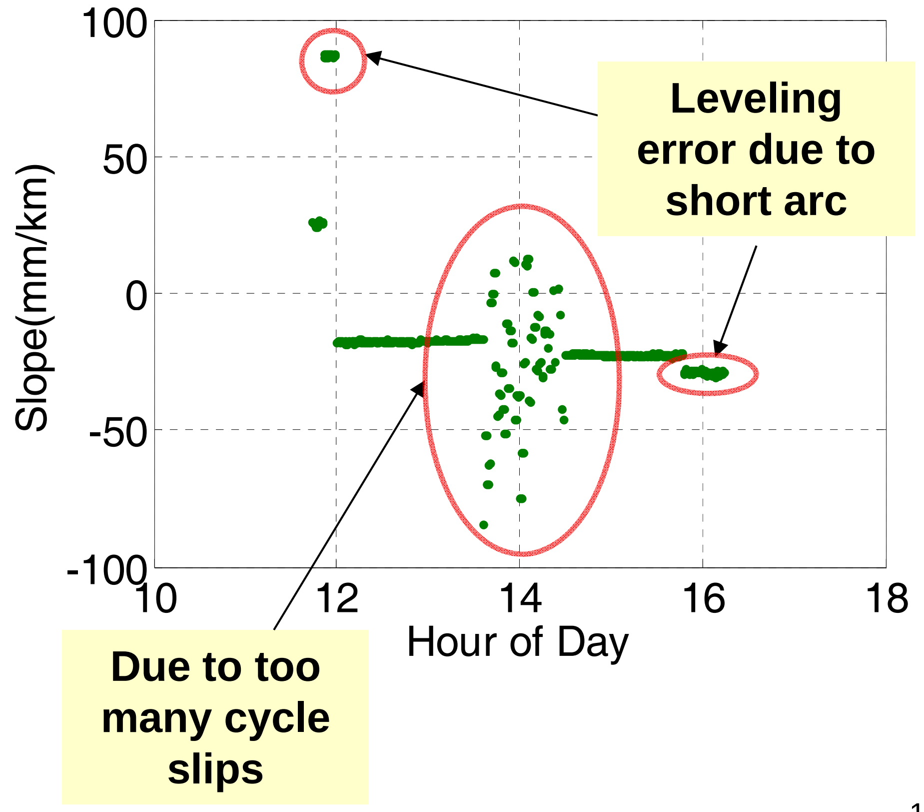
Impact on Ionospheric Delay/Gradient Estimation
Station *OKEE*

OKEE, 5/24/2012					
IOD cycle slip (#)	**Per. of Obs. (%)**	**Short arc (#)**	**Outlier (#)**	**MP1 (m)**	**MP2 (m)**
801.57	**59.71**	**763.57**	**59.71**	**0.4803**	**0.5490**

Slant Ionospheric Delay, I_ϕ, PRN 22

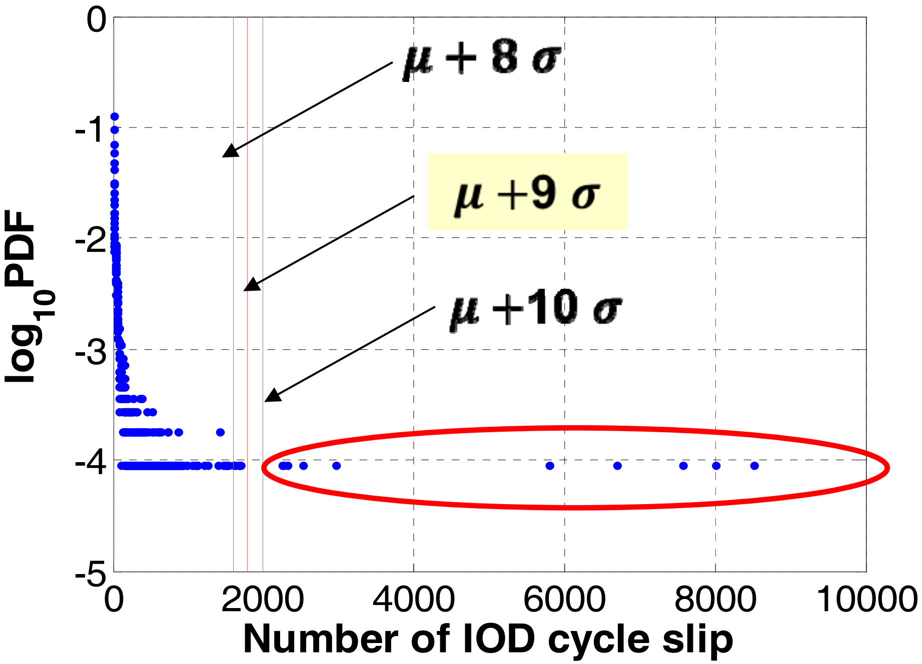


Ionospheric Spatial Gradient

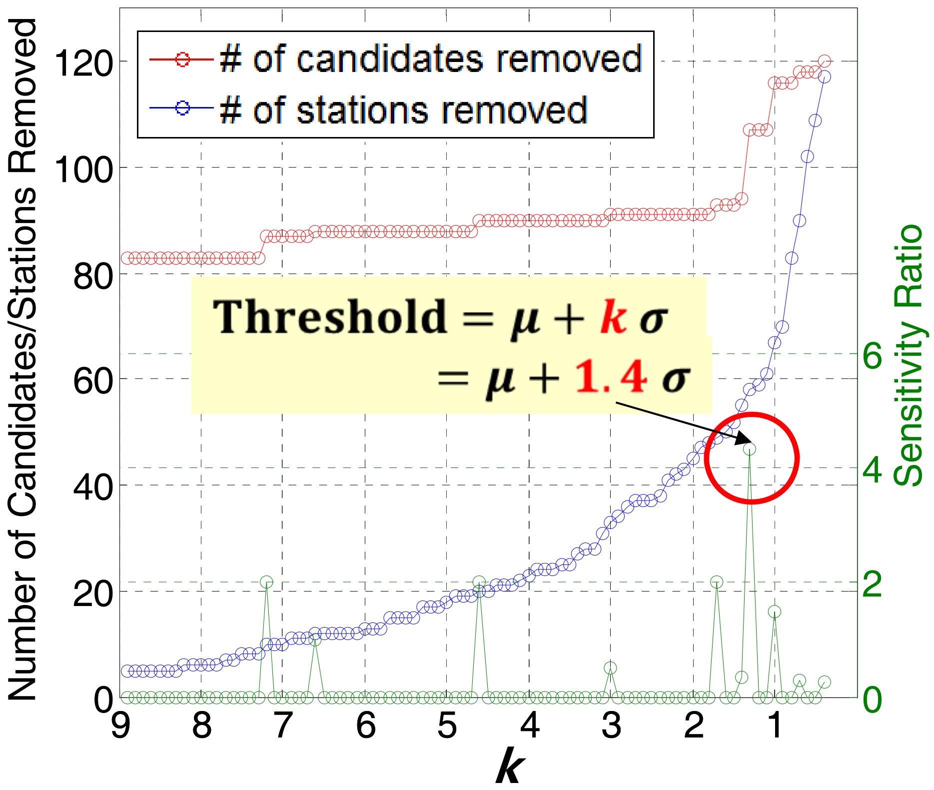


Determining Thresholds of Data Quality Parameters (IOD cycle slip)

# of IOD cycle slips on each station per day, data collected for 7 days

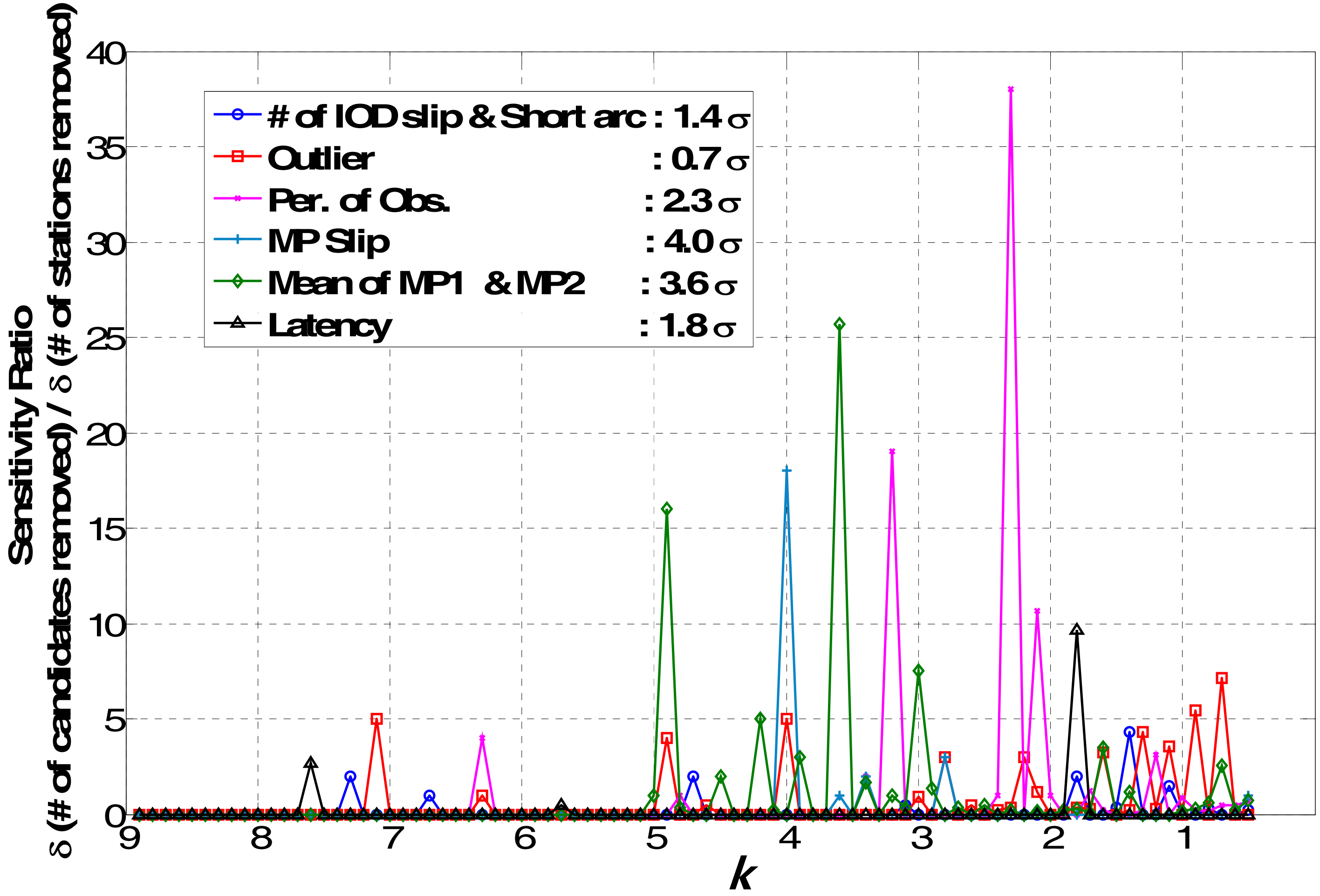


1. Remove outliers and obtain a new (nominal) distribution



2. Determine threshold of data quality parameter through sensitivity analysis

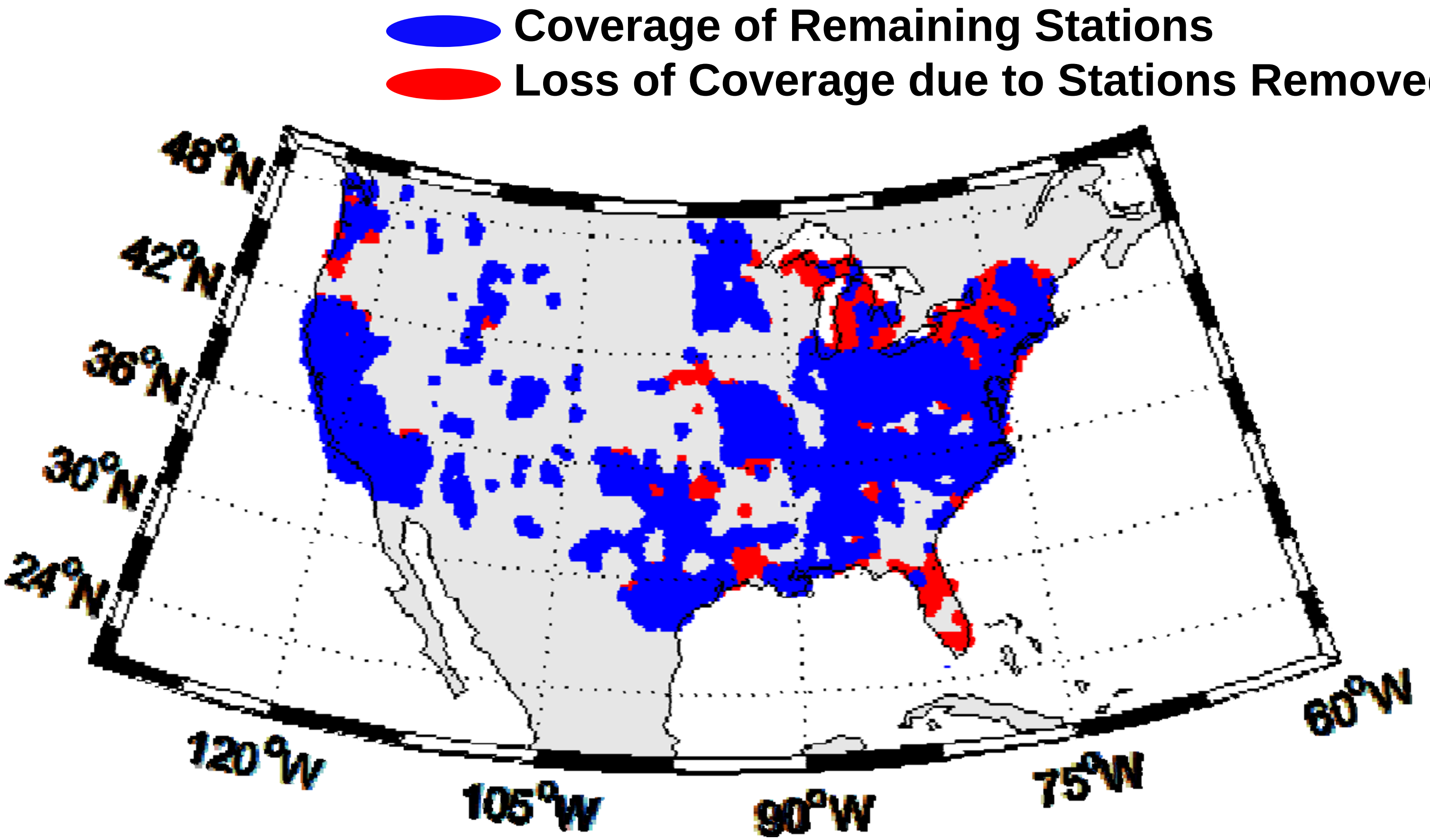
Thresholds of Data Quality Parameters



# of stations removed in CONUS (out of 1587)	308 (19.4%)
# of faulty candidates removed on 05/26/2012 (out of 92)	81 (88.0%)

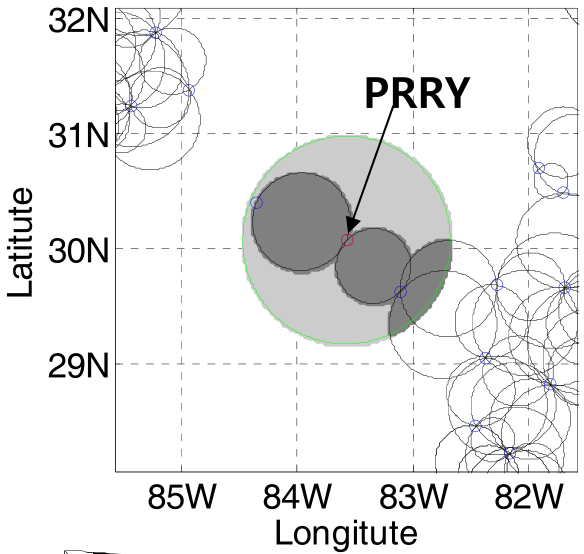
Need for Geometry Check on Each Station

Stations that significantly increase geometric observability of ionospheric anomalies should be retained despite poor data quaity

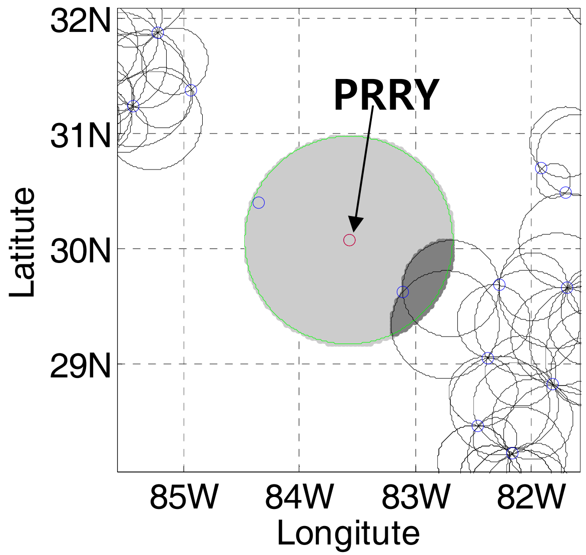


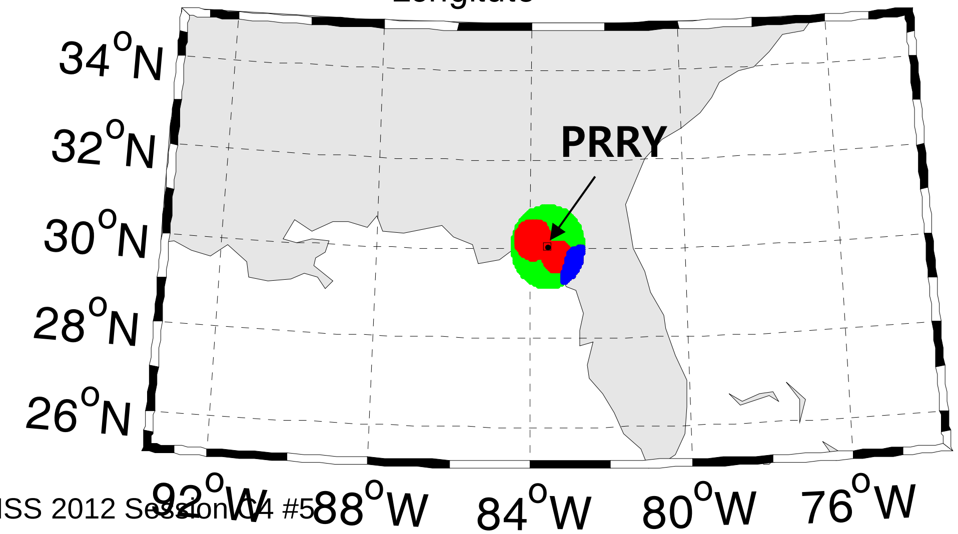
Criteria to Restore Stations Discarded by Data Quality Check

Coverage of stations before removing PRRY station



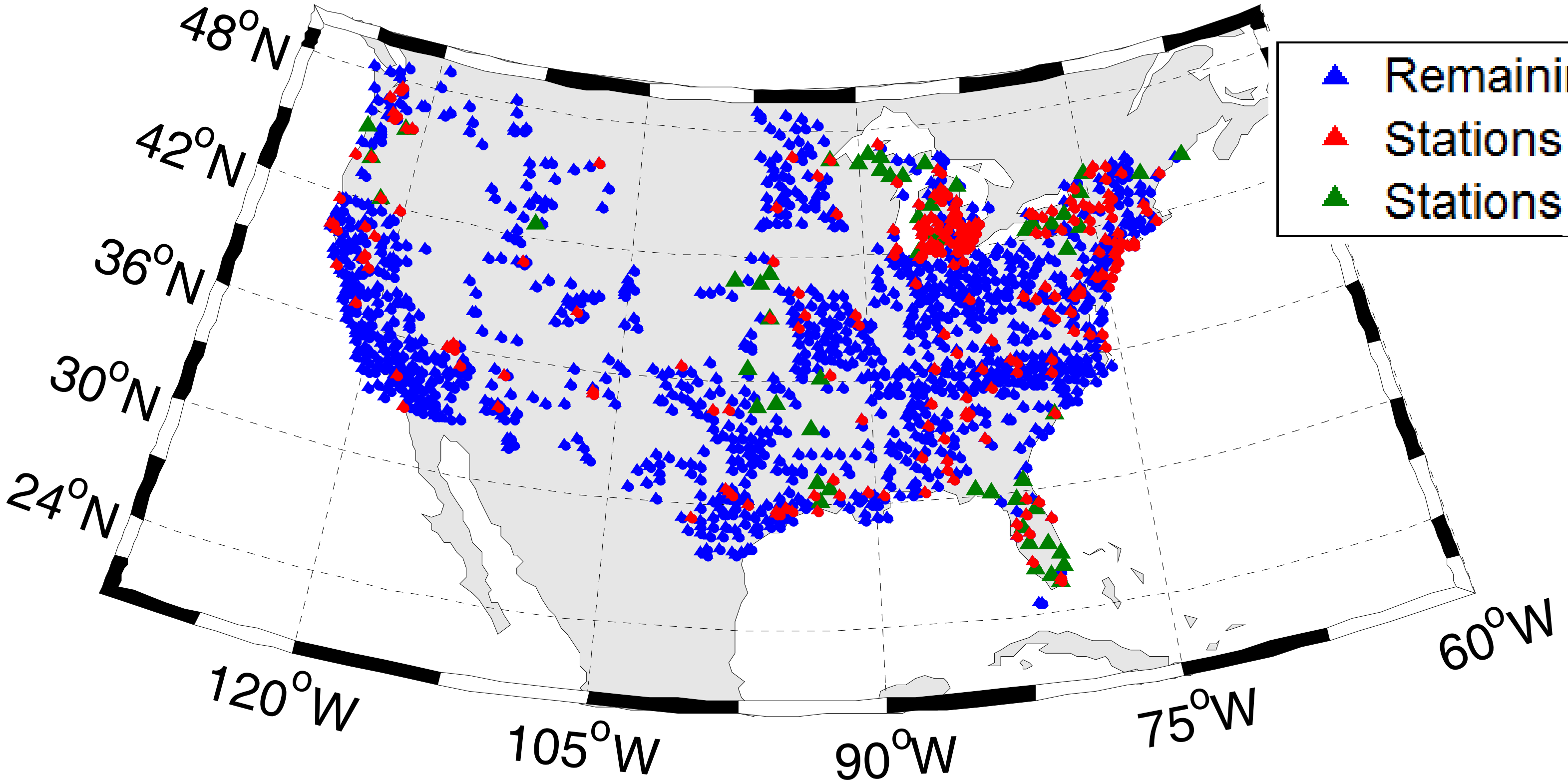
Coverage of stations after removing PRRY station





If the loss of coverage after discarding a station is more than 30% of original coverage, it is restored despite poor data quality

Results from CORS Station Selection

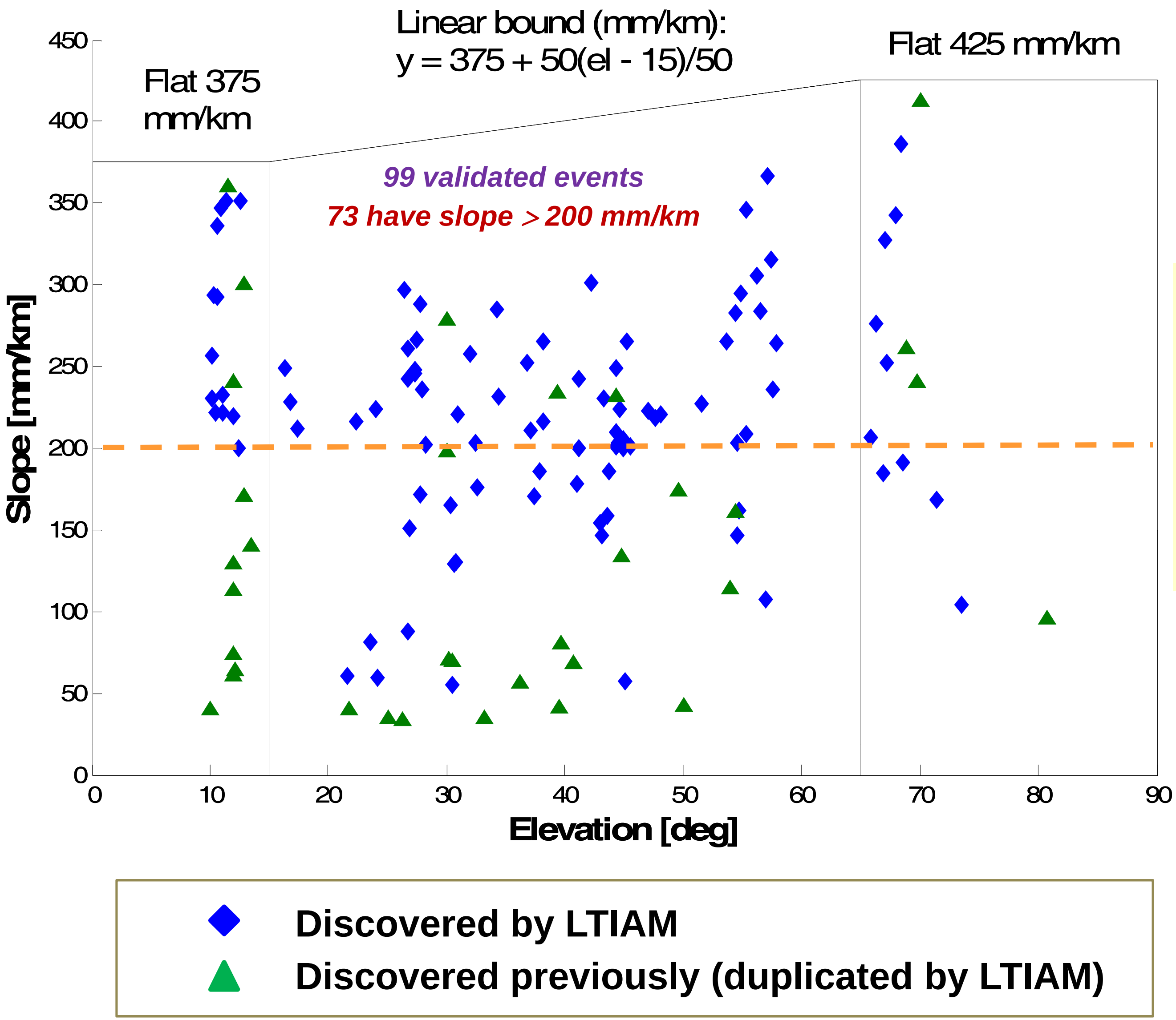


	Before the geometry check	After the geometry check
# of stations removed in CONUS (out of 1587)	308 (19.4%)	252 (15.9%)
# of faulty ionospheric anomaly candidates removed on 05/26/2012 (out of 92)	81 (88.0%)	81 (88.0%)

Historical Storm Database (2000 – 2005)

Day (UT)	K_P	D_{ST}	Geo. Storm Class	WAAS Coverage	Focus Region
4/6/2000	8.3	– 287	Severe	None (pre-IOC)	NE Corridor
4/7/2000	8.7	– 288	Extreme	None (pre-IOC)	NE Corridor
7/15/2000	9.0	– 289	Extreme	None (pre-IOC)	N/A
7/16/2000	7.7	– 301	Strong	None (pre-IOC)	N/A
9/7/2002	7.3	–163	Strong	None (pre-IOC)	N/A
10/29/2003	9.0	– 345	Extreme	~ 0%	N/A
10/30/2003	9.0	– 401	Extreme	~ 0%	TX-OK-LA-AR
10/31/2003	8.3	– 320	Severe	~ 0%	FL-GA
11/20/2003	8.7	– 472	Extreme	~ 0%	OH-MI
7/17/2004	6.0	– 80	Moderate	~ 68.8%	TX-OK-LA-AR

Ionospheric Threat Space with Validated Ionospheric Anomalies



All 10 storm days were processed

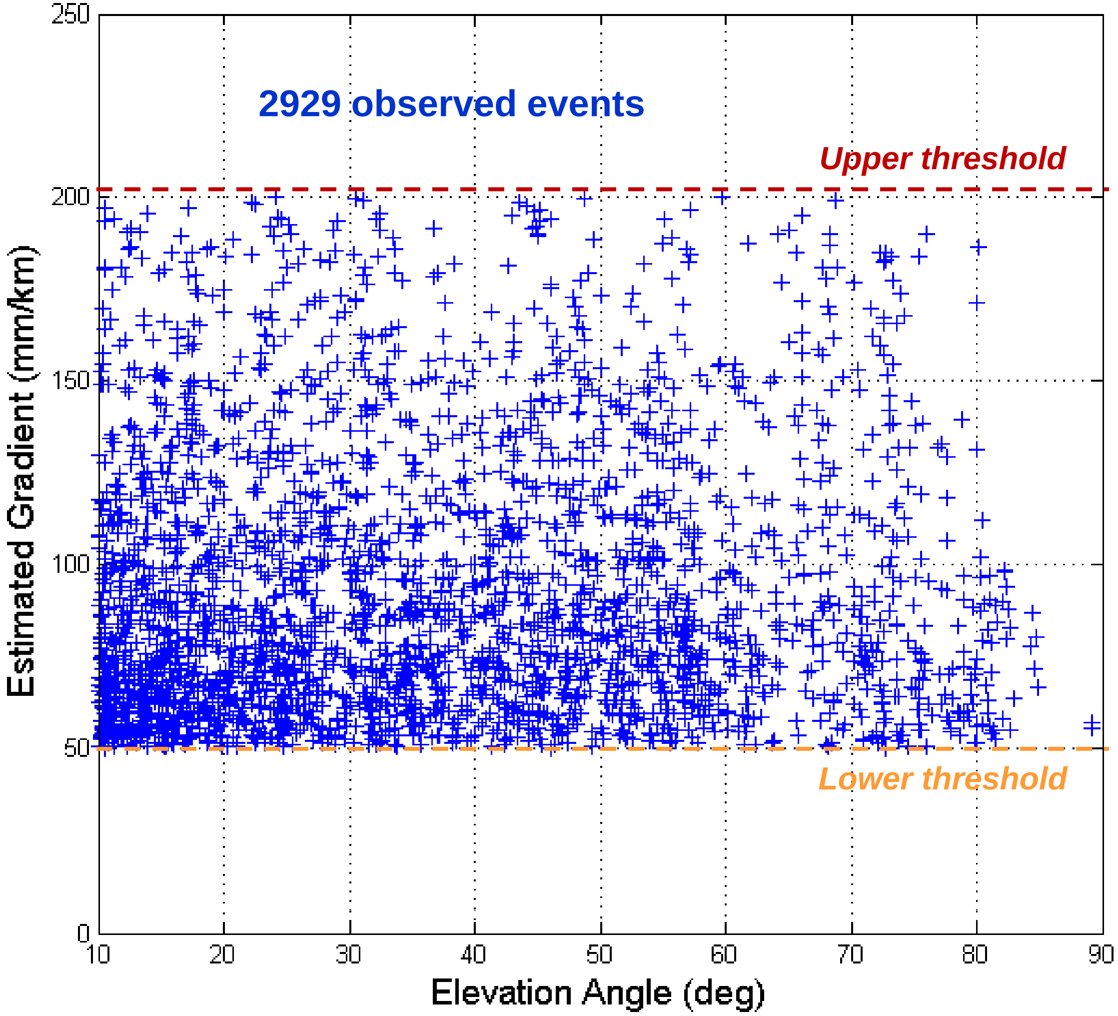
4 of these days included events on this plot

Ratios of Validated Events to Automated Candidates

- **When threshold is set to 300 mm/km**
  - **13 validated events out of 53 candidates (on 1 day)**
  - **13/53 = 0.2453 (24.5%)**
- **When threshold is set to 200 mm/km**
  - **73 validated events out of 243 candidates (on 4 days)**
  - **73/243 = 0.3004 (30.0%)**
- **Ratios are similar but generally increase as threshold is lowered**
  - **Receiver or data errors can be of any size**
  - **Reducing threshold includes more actual events**

Automated Candidates from 50 – 200 mm/km (1)

Estimated Gradient vs. SV Elevation Angle



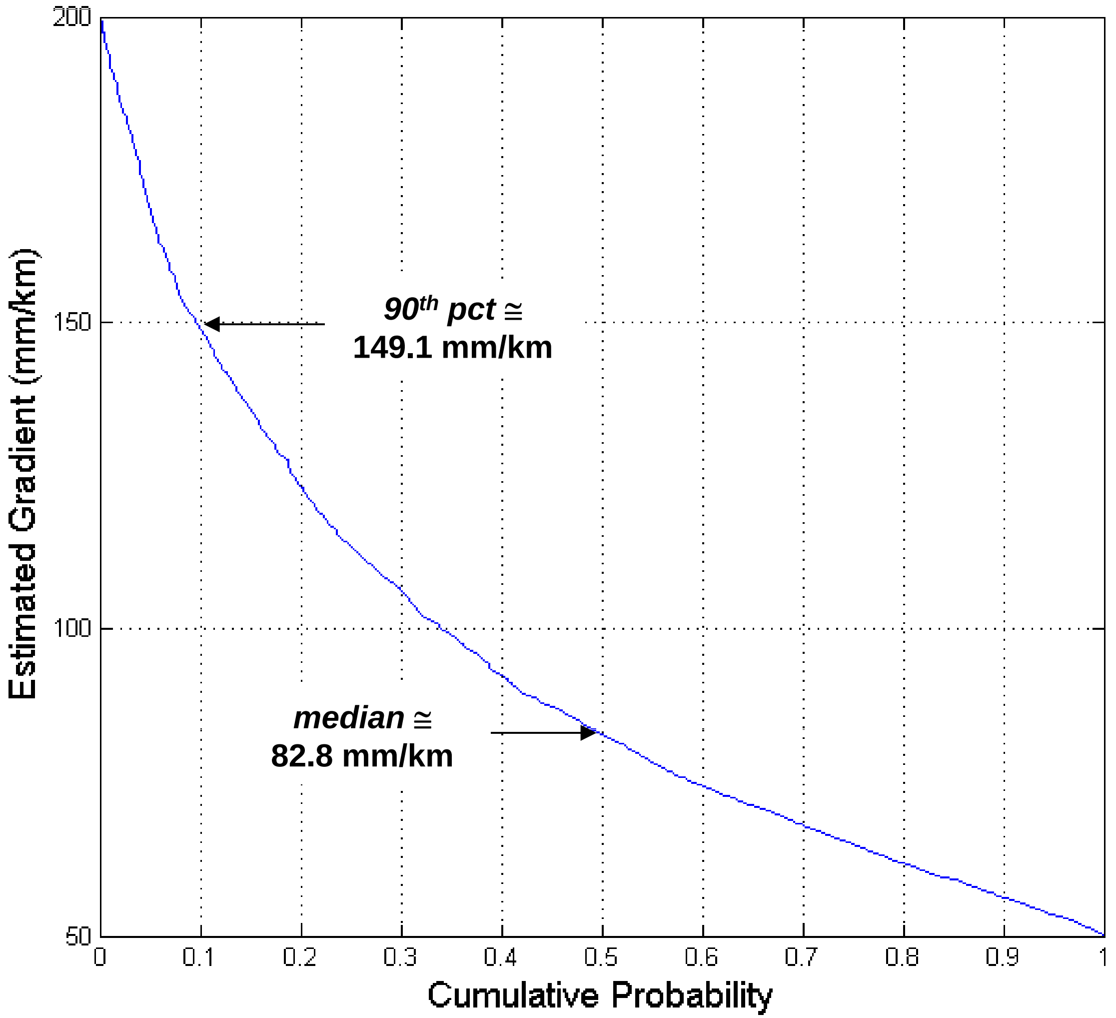
2929 automated candidates (not incl. those > 200 mm/km)

All 10 storm days generate results

4 days included on previous result provide *91.3%* of these results

Automated Candidates from 50 – 200 mm/km (2)

Cumulative Distribution of Estimated Gradients



Distribution of Anomalous Gradients

- **As expected, within the set of “anomalous gradients,” lower values dominate.**
- **However, the ratio of valid events within the results from 50 – 200 mm/km is not known.**
- ***Lower bound*: assume 30% of results are valid (based on result above 200 mm/km).**
  - **2929 × 0.3 ≅ 879 + 26 ≅ 905 valid events below 200 mm/km**
  - **73 / (905 + 73) => *7.5% of valid events are above 200 mm/km***
  - **13 / (905 + 73) => *1.3% of valid events are above 300 mm/km***
- ***Upper bound*: assume all results are valid**
  - **2929 + 26 ≅ 2955 valid events below 200 mm/km**
  - **73 / (2955 + 73) => *2.4% of valid events are above 200 mm/km***
  - **13 / (2955 + 73) => *0.4% of valid events are above 300 mm/km***

Summary

- **A comprehensive method of GPS data quality determination has been developed to support ionospheric anomaly monitoring.**
  - **Method identifies and excludes CORS stations with poor data quality**
  - **88% reduction of faulty anomaly candidates was achieved while removing only 16% of CORS stations**
- **This tool will also supply GPS observation data quality information to the broader navigation community.**
  - **Lists of CORS stations ranked by data quality will be available soon.**
- **Refinements to automated monitoring software enhance our understanding of past ionospheric events.**
  - **Over 10 storm days from 2000 – 2005, the vast majority of anomalous ionospheric spatial gradients were below 200 mm/km.**

Acknowledgements

- Thanks to John Warburton and his team at the FAA technical center for their support

- Thank you for your attention!