WAAS SCINTILLATION CHARACTERIZATION

Session 2B – Global Effects on GPS/GNSS

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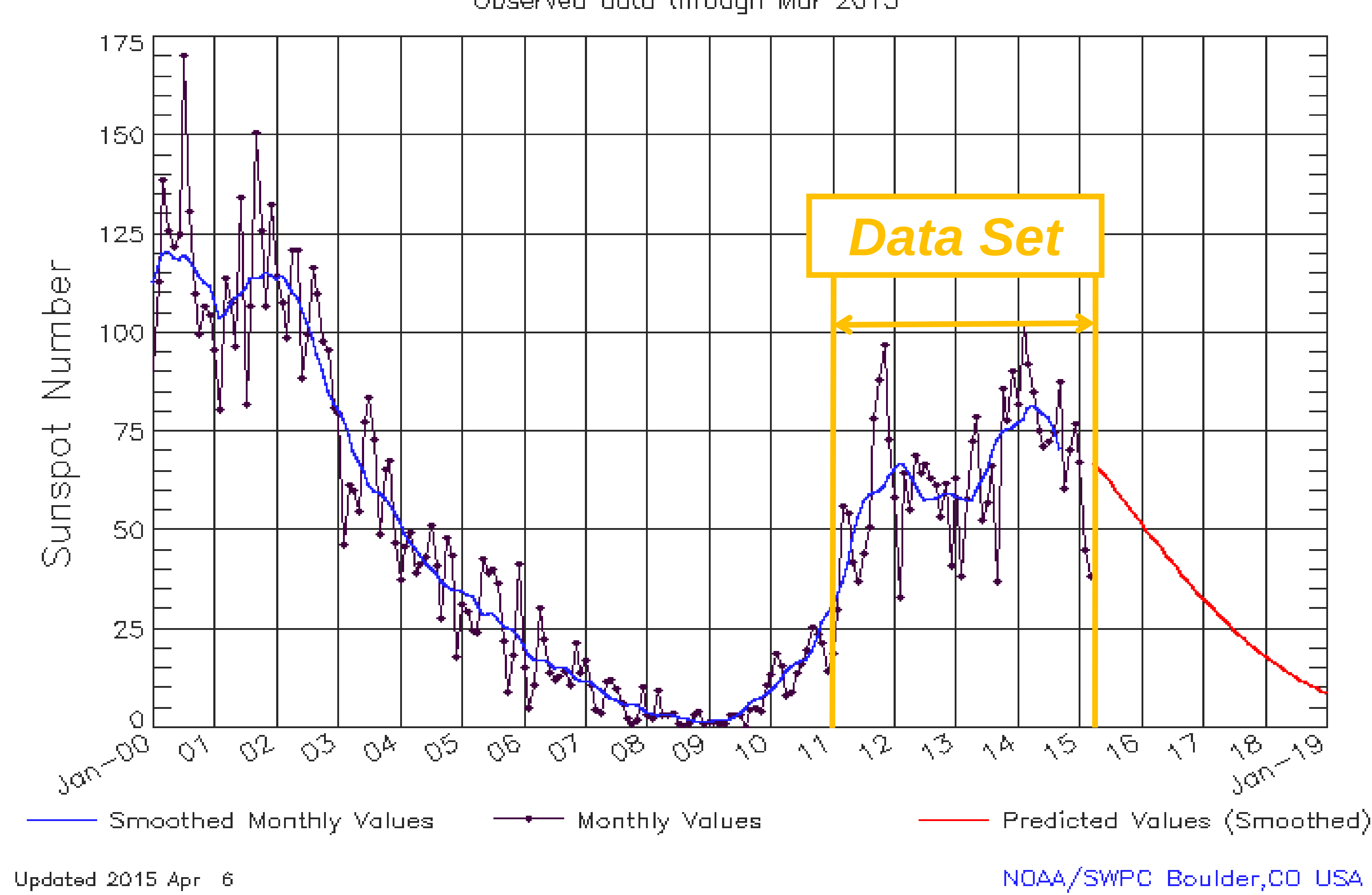
Purpose

- Characterize scintillation observed in WAAS from solar cycle 24
- Characterize frequency of occurrence and system performance
- Investigate geographic spatial extent of scintillation events in Auroral region


Data Set
Sunspot Number
175
150
125
100
75
50
25
0
Jan-00
01
02
03
04
05
06
07
08
09
10
11
12
13
14
15
16
17
18
Jan-19
Smoothed Monthly Values
Monthly Values
Predicted Values (Smoothed)
Updated 2015 Apr 6
NOAA/SWPC Boulder,CO USA

WAAS Reference Station Data Processing

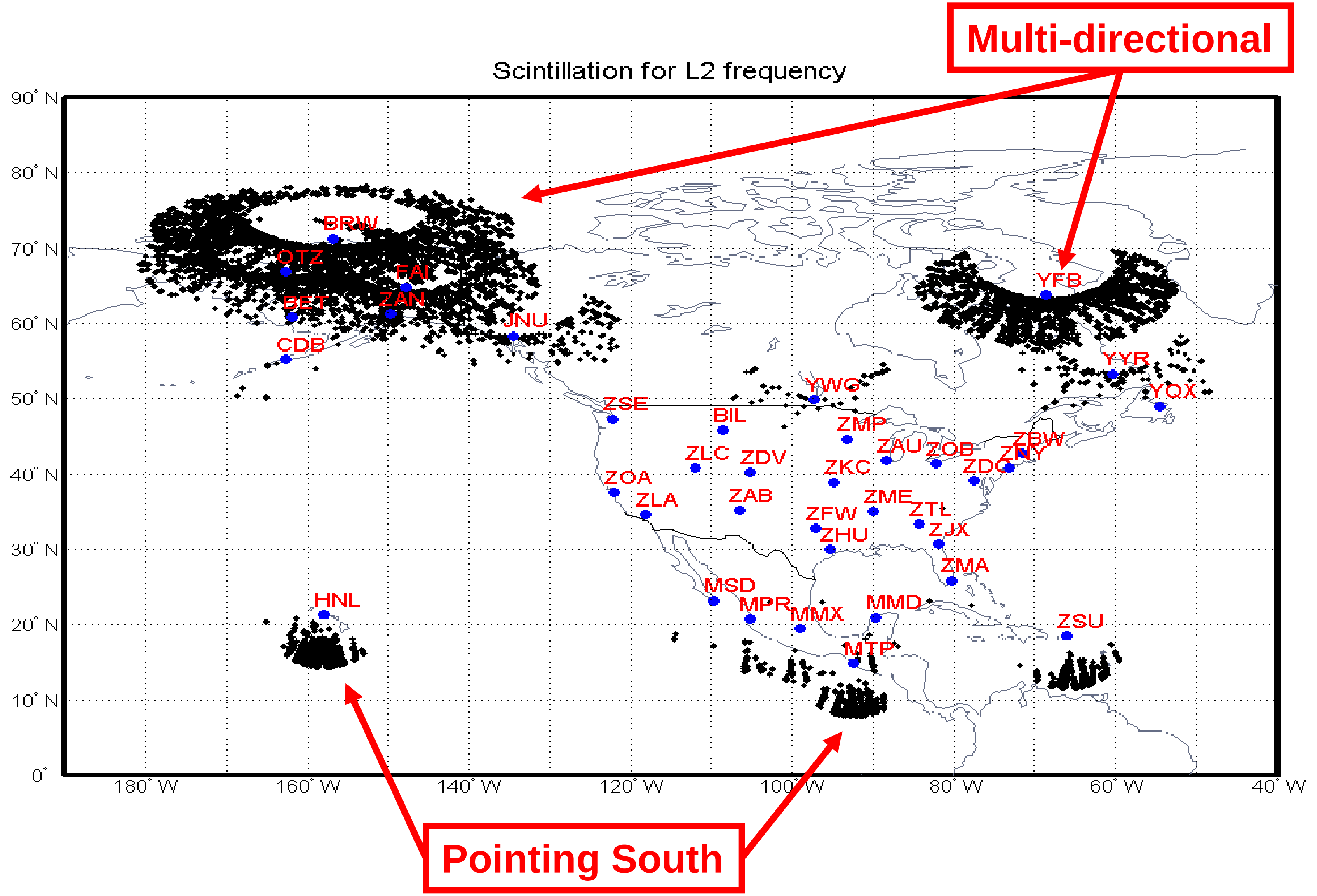
- Purpose of processing was to associate loss of L1 or L2 signal tracking or cycle slip detections to scintillation
  - Needed to identify and remove similar effects such as RF interference, satellite glitches, multipath, station obstructions, comm. outages…etc.
  - From a “WAAS” point of view, having a cycle slip is very similar to losing a signal, because our CNMP (noise sigma) curve is reset to the maximum value
- Processing utilized individual station data (AGC, ranging data), comparisons across threads, and comparisons across entire network
- Output of processing was L1 and L2 outages (seconds of lost tracking) for one station/satellite pair, as well as dual frequency cycle slip related outages (details in the paper)

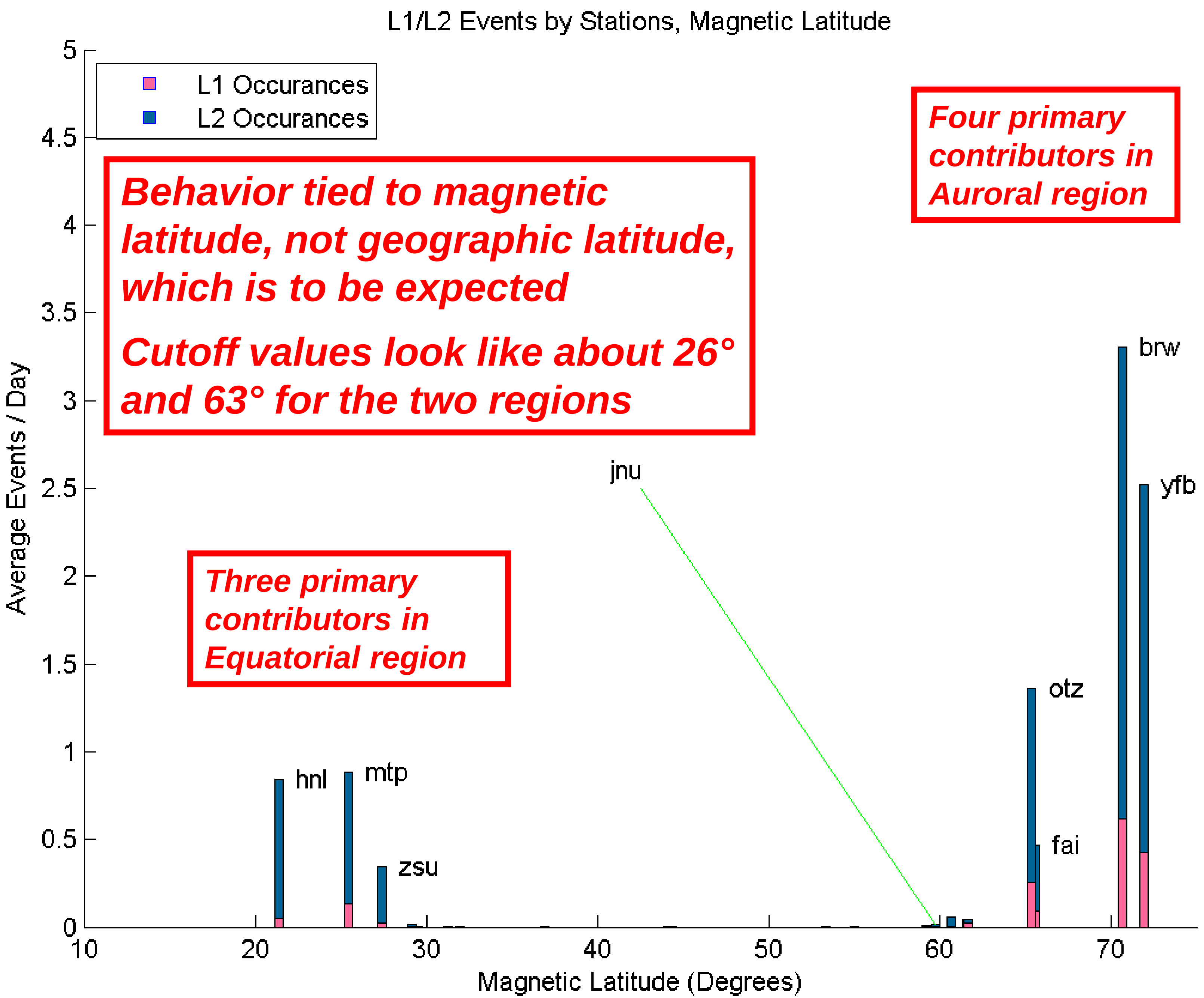
Equatorial vs. Auroral Behavior

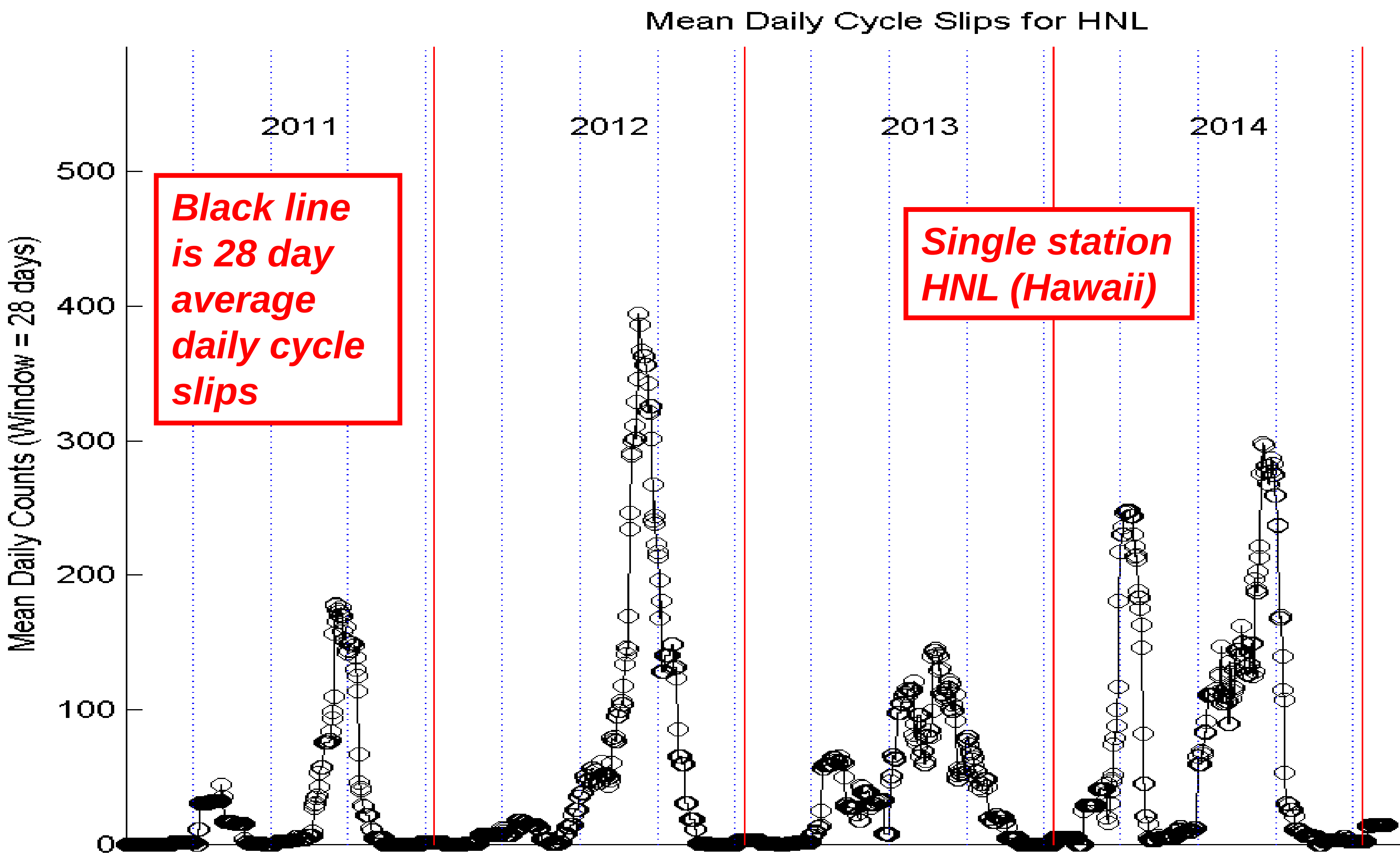
- Directional dependence (Azimuth / Elevation)
- Boundary regions with respect to mid-latitude
- Time series over entire 4.0 year data set

- NOTE: “Equatorial” in this sense means furthest south, to the point that a station can sample the equatorial anomaly. There are no WAAS stations actually in the equatorial region.

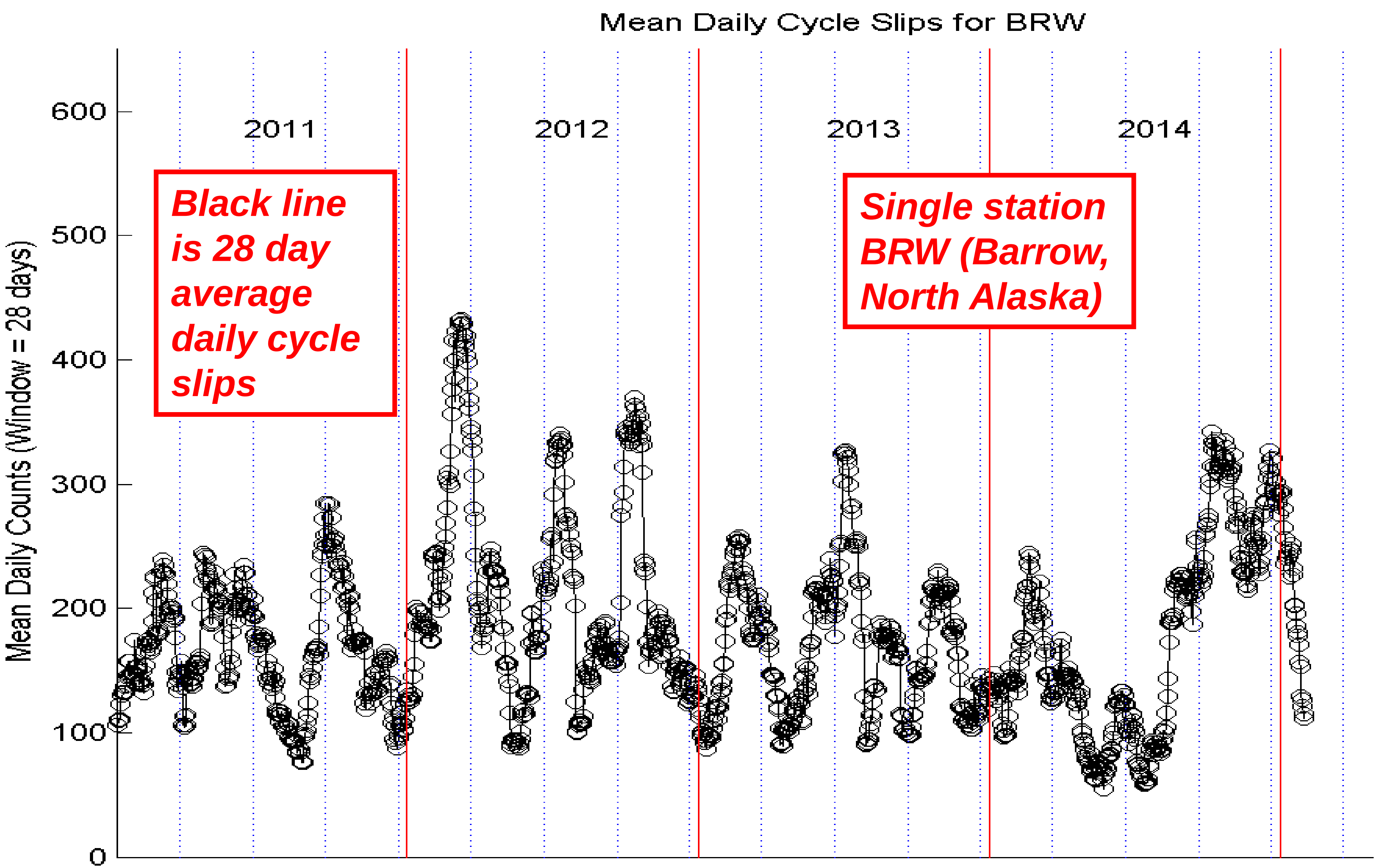
Scintillation Outages for L2



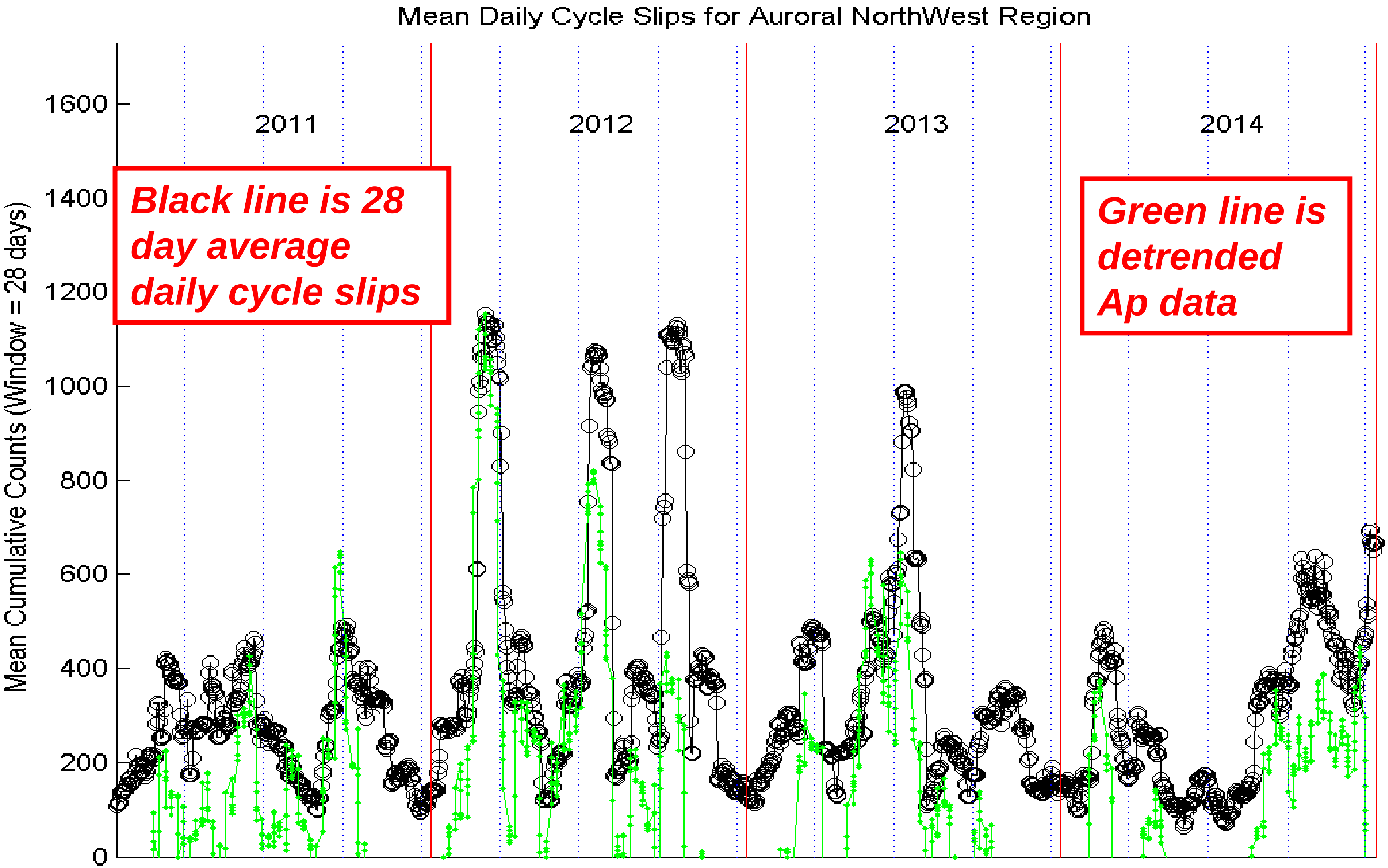

L1/L2 Events by Stations, Magnetic Latitude
L1 Occurances
L2 Occurances
Behavior tied to magnetic latitude, not geographic latitude, which is to be expected
Cutoff values look like about 26° and 63° for the two regions
Four primary contributors in Auroral region
Three primary contributors in Equatorial region
hnl
mtp
zsu
jnu
otz
fai
brw
yfb
Average Events / Day
Magnetic Latitude (Degrees)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
10
20
30
40
50
60
70



Several periods of time where all activity drops to almost nothing



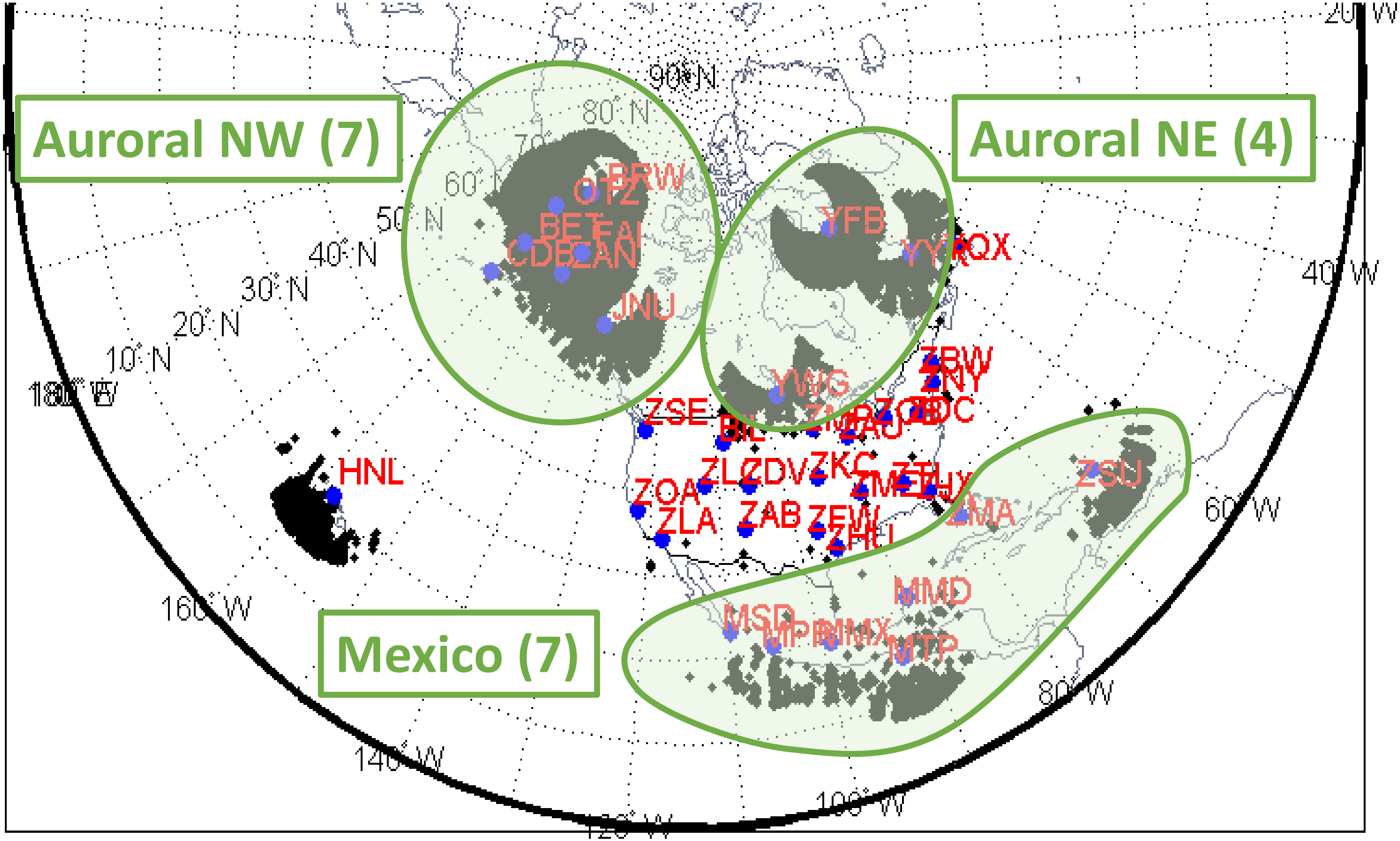
Cycle Slip Activity never drops completely to zero



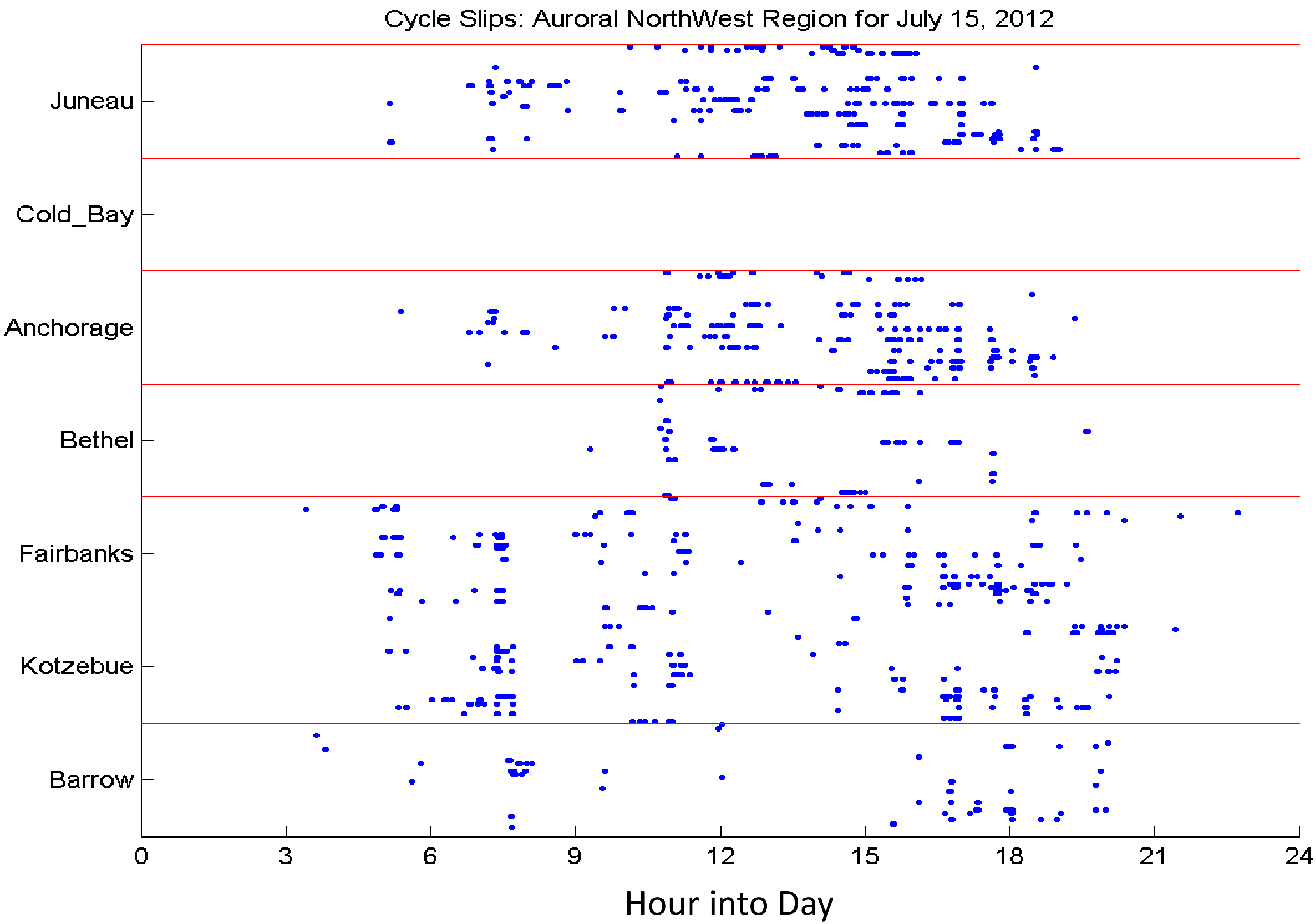
Cycle Slip Activity aligned with ionospheric trends

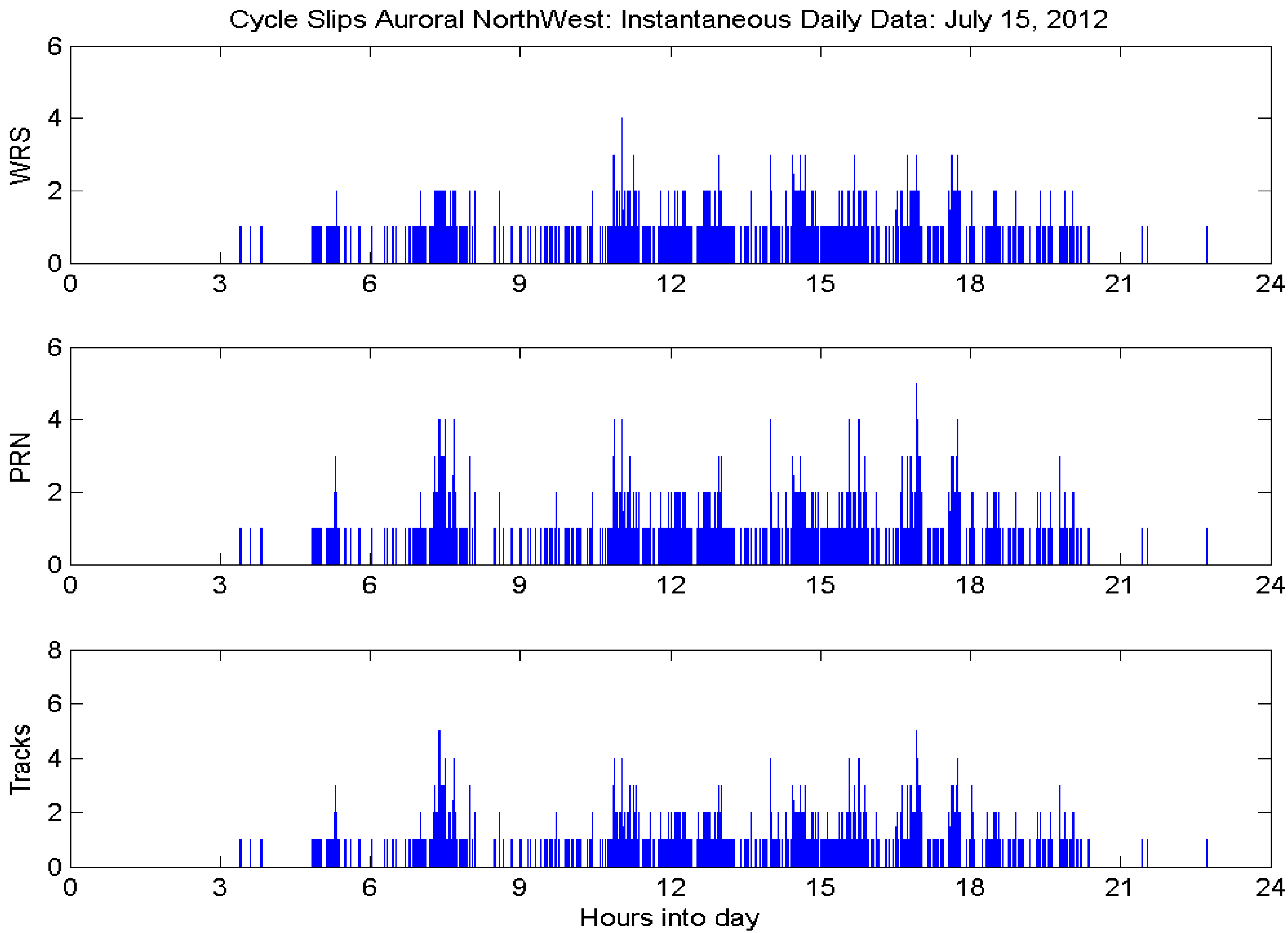
Regional Analysis

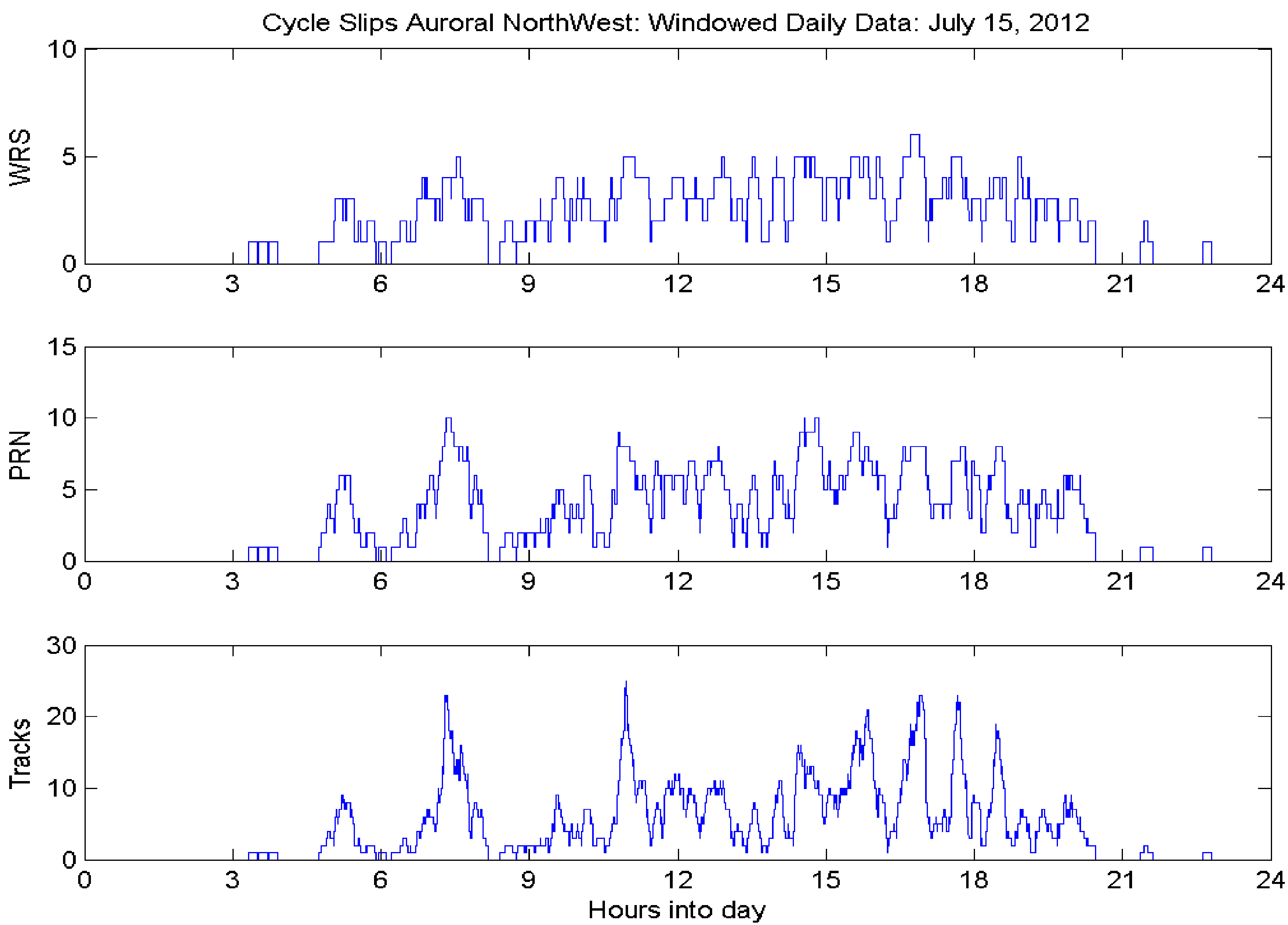
- Spatial and temporal analysis conducted to assess size and frequency of events
- Analysis of instantaneous events does not show significant correlation, as many events are close in time, but do not happen at exact same epoch
- Windowing of cycle slip indications from particular geographic regions conducted to assess correlation and geographic extent of scintillation events
- Two pieces of analysis were conducted with the windowed data
  - Correlated Satellite Outages
  - Geographic Spatial Extent

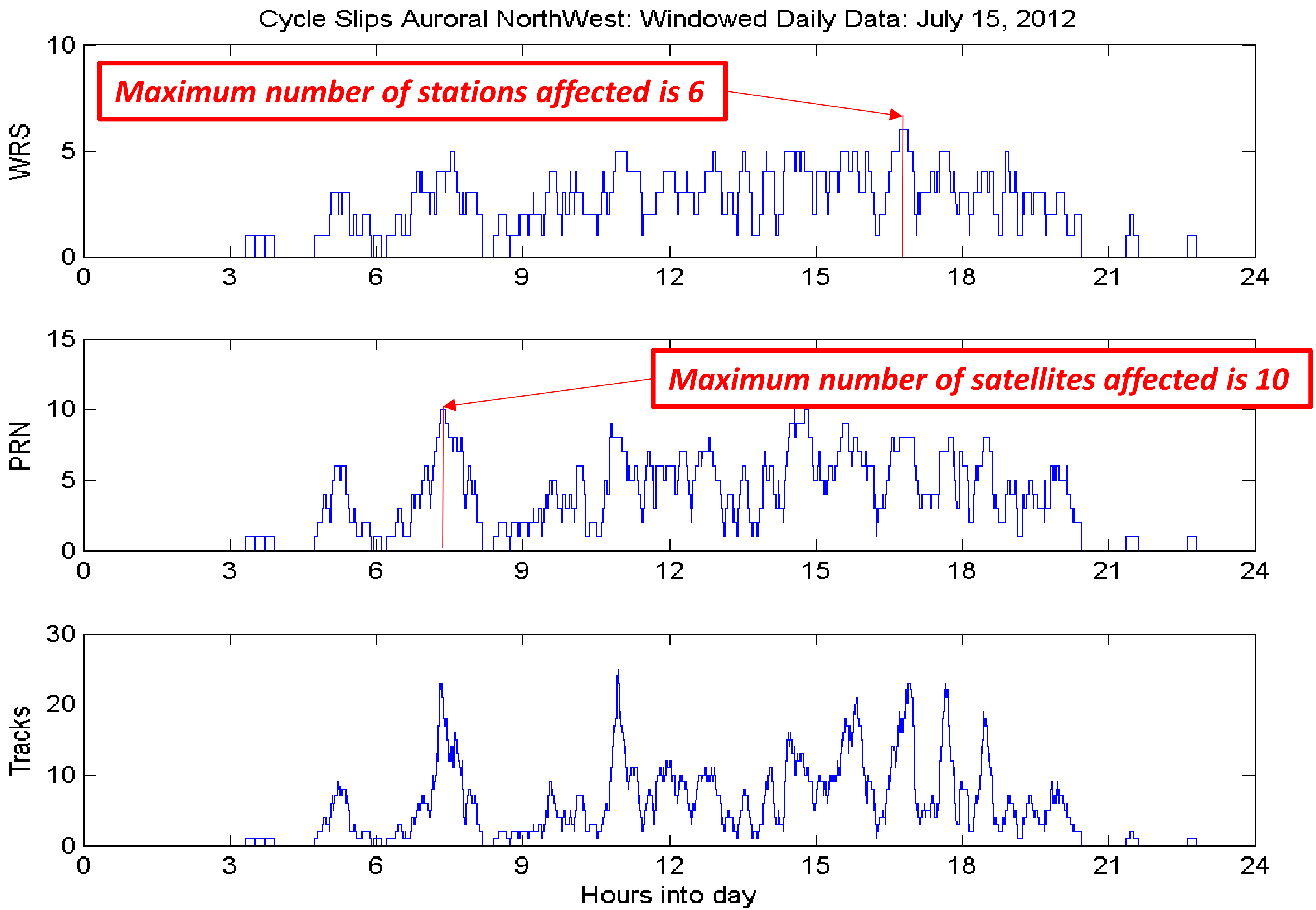


Auroral NW (7)
Auroral NE (4)
Mexico (7)
HNL
ZSE
ZOA
ZLA
ZAB
ZSU
ZMA
MMD
MSD
MTP
JNU
YFB
YWG


Cycle Slips: Auroral NorthWest Region for July 15, 2012
Juneau
Cold_Bay
Anchorage
Bethel
Fairbanks
Kotzebue
Barrow
0
3
6
9
12
15
18
21
24
Hour into Day

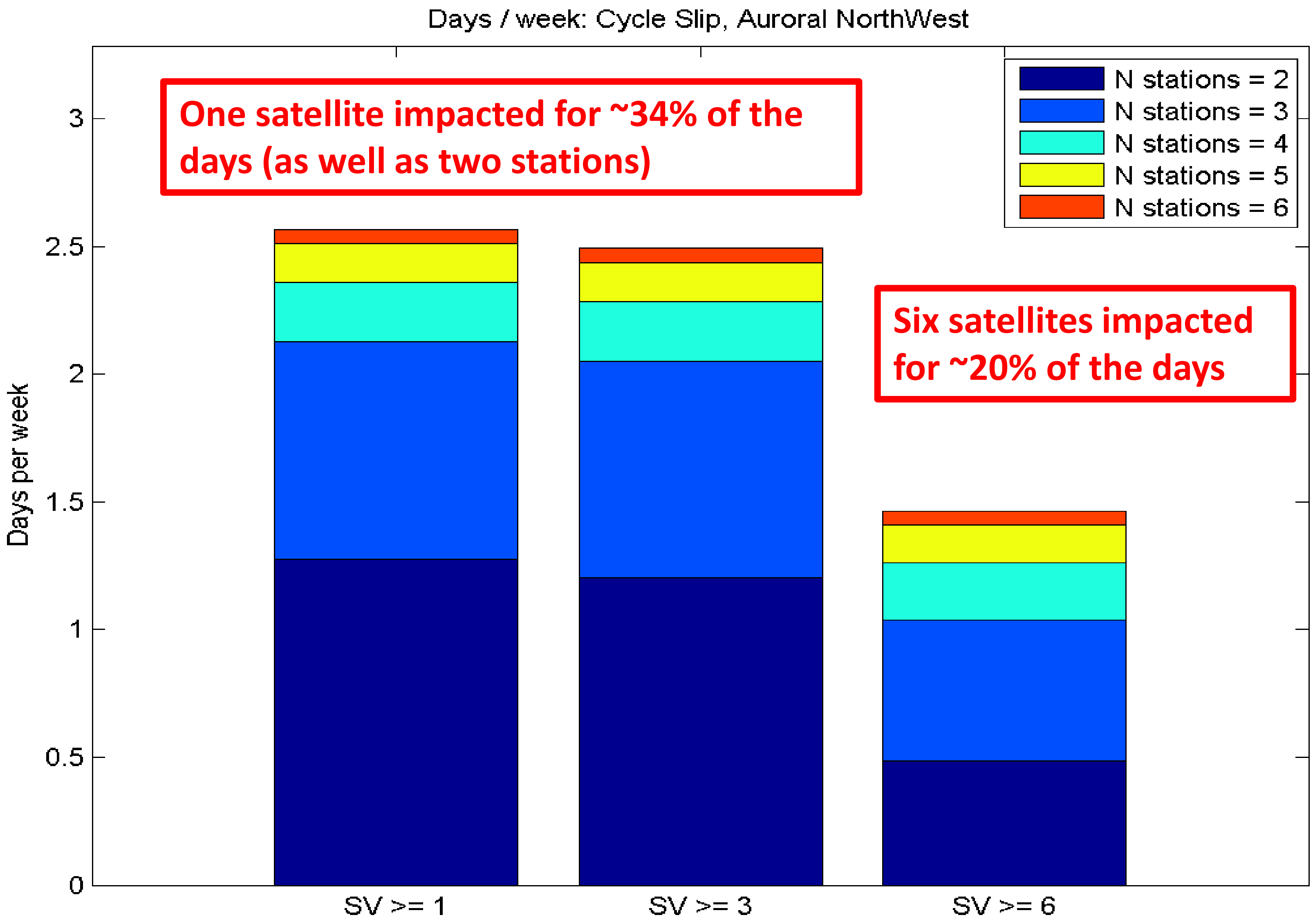

Cycle Slips Auroral NorthWest: Instantaneous Daily Data: July 15, 2012
WRS
PRN
Tracks
0
2
4
6
8
0
3
6
9
12
15
18
21
24
Hours into day

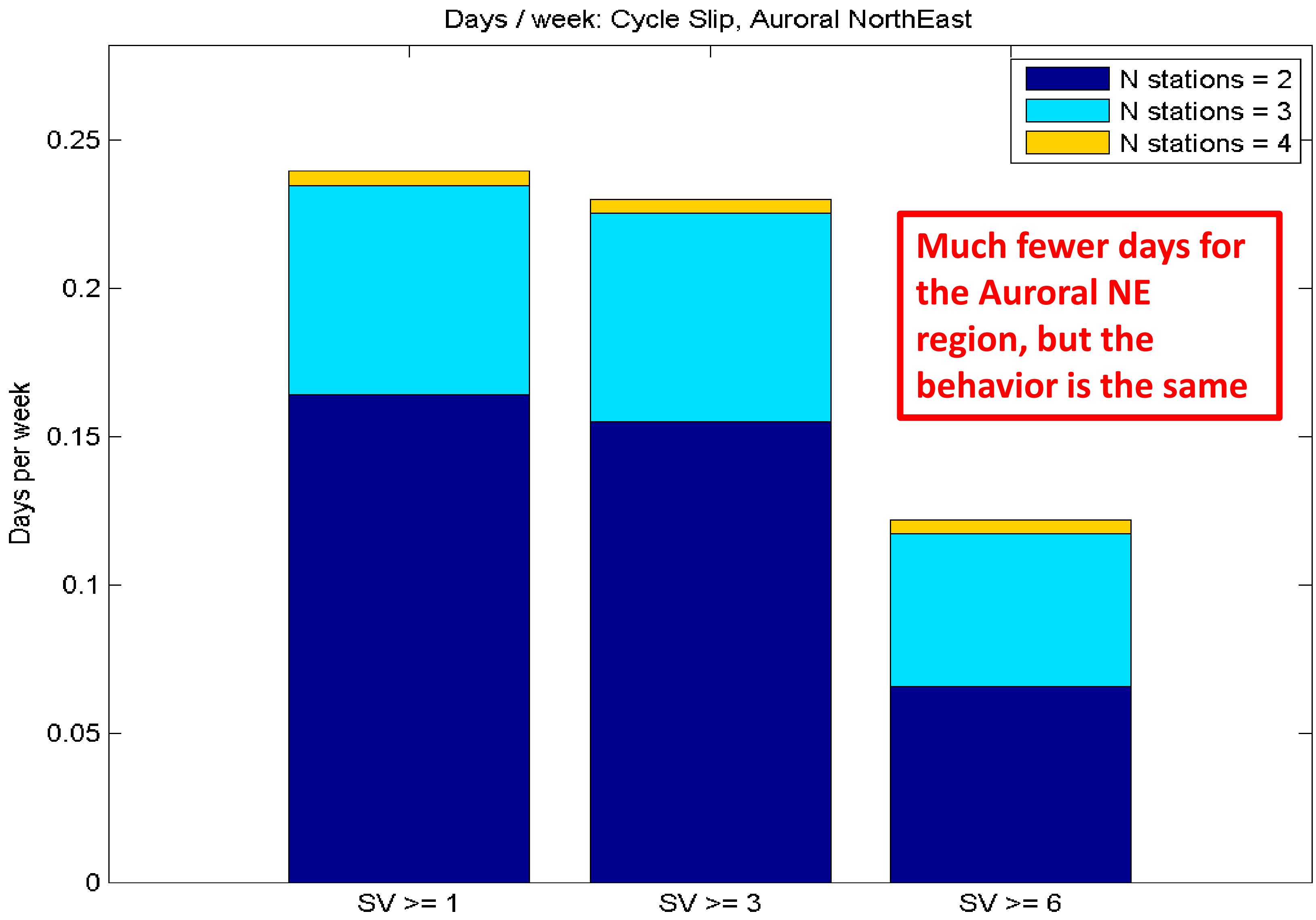

Cycle Slips Auroral NorthWest: Windowed Daily Data: July 15, 2012
WRS
PRN
Tracks
0
3
6
9
12
15
18
21
24
Hours into day

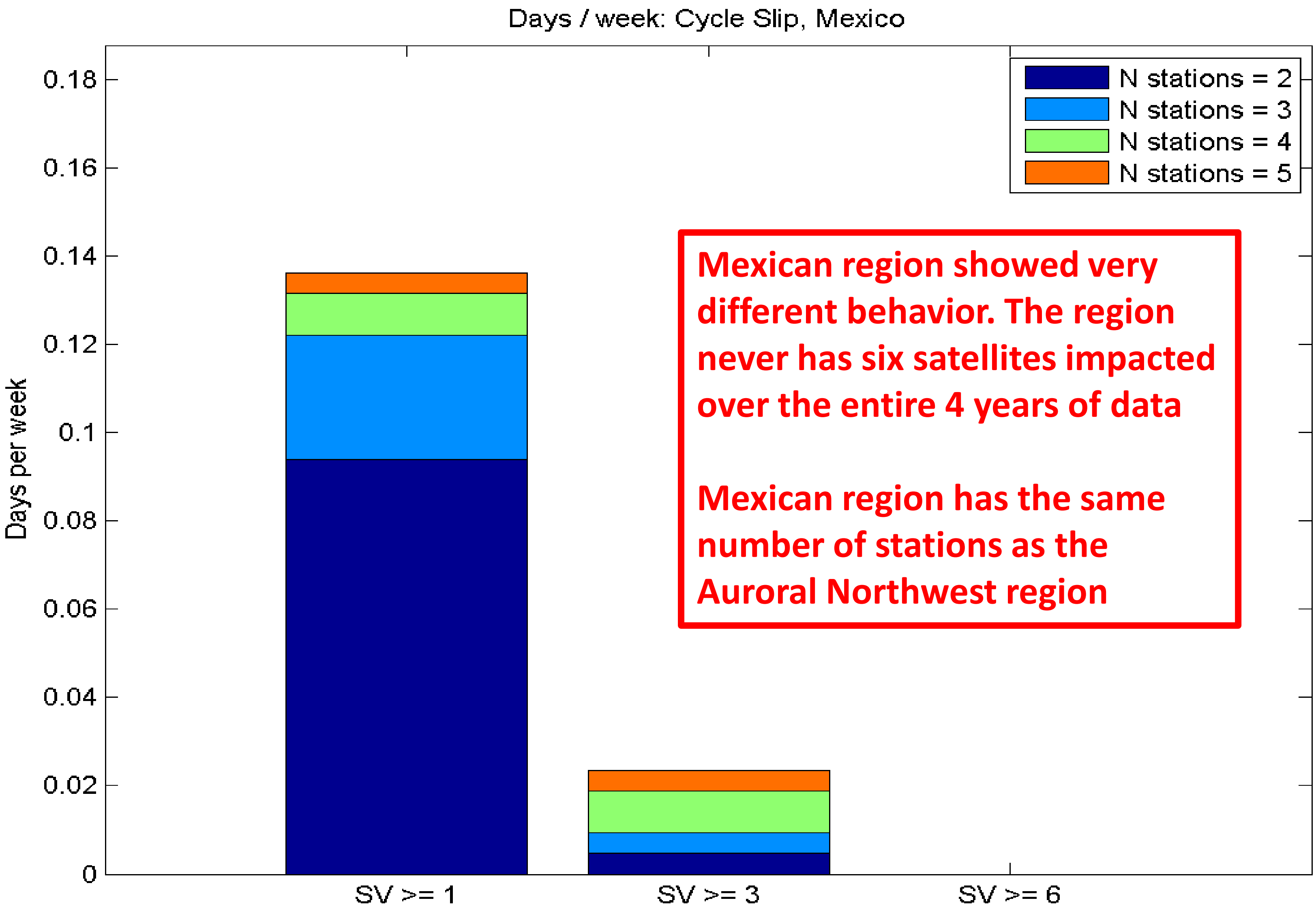

Cycle Slips Auroral NorthWest: Windowed Daily Data: July 15, 2012
Maximum number of stations affected is 6
WRS
Maximum number of satellites affected is 10
PRN
Tracks
Hours into day
0
3
6
9
12
15
18
21
24

Satellites Impacted

- Statistics generated for entire data set by applying ten minute windowing
  - Required at least two stations were lost for this analysis
- Three levels of satellite impacts considered
  - At least one satellite affected
  - At least three satellites affected
  - At least six satellites affected
- Total number of days in entire data set for each level is computed and histogrammed
  - Data is further broken down by number of stations affected for day
  - Time series over whole 4.0 year data set shown on next slide


Days / week: Cycle Slip, Auroral NorthWest
One satellite impacted for ~34% of the days (as well as two stations)
Six satellites impacted for ~20% of the days
N stations = 2
N stations = 3
N stations = 4
N stations = 5
N stations = 6
Days per week
0
0.5
1
1.5
2
2.5
3
SV >= 1
SV >= 3
SV >= 6


Days / week: Cycle Slip, Auroral NorthEast
N stations = 2
N stations = 3
N stations = 4
Days per week
0
0.05
0.1
0.15
0.2
0.25
SV >= 1
SV >= 3
SV >= 6
Much fewer days for the Auroral NE region, but the behavior is the same



Mexican region showed very different behavior. The region never has six satellites impacted over the entire 4 years of data

Mexican region has the same number of stations as the Auroral Northwest region

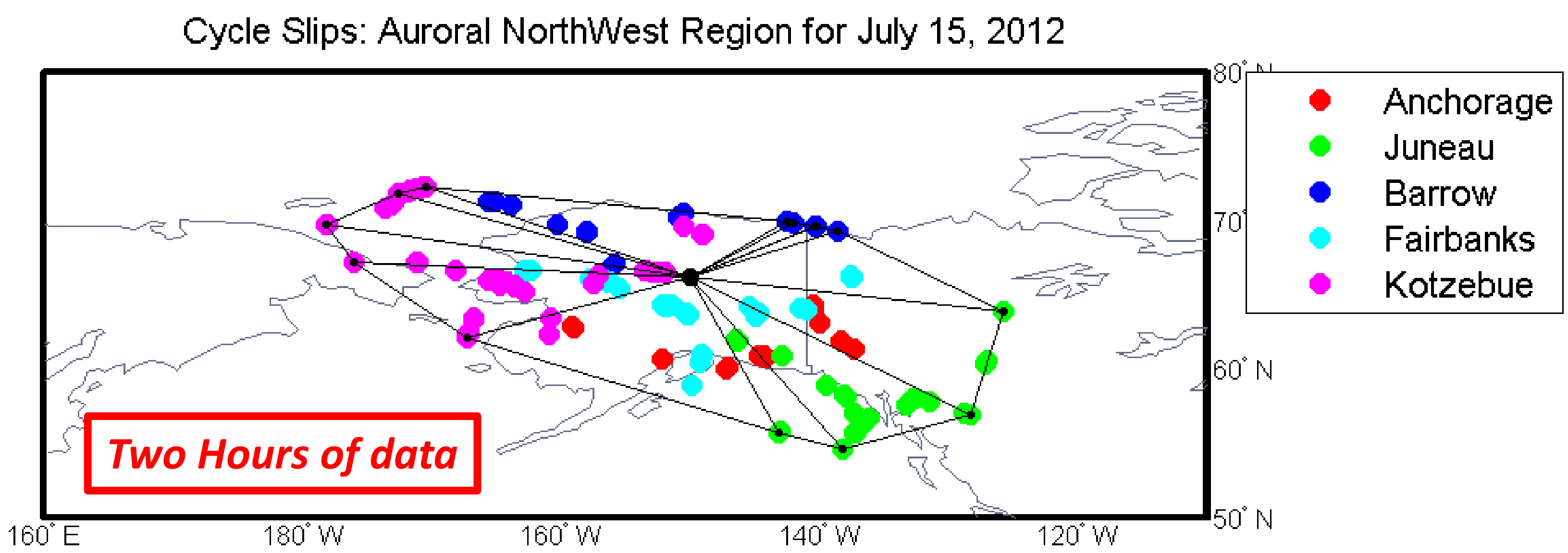
Conclusions for Correlated SVs

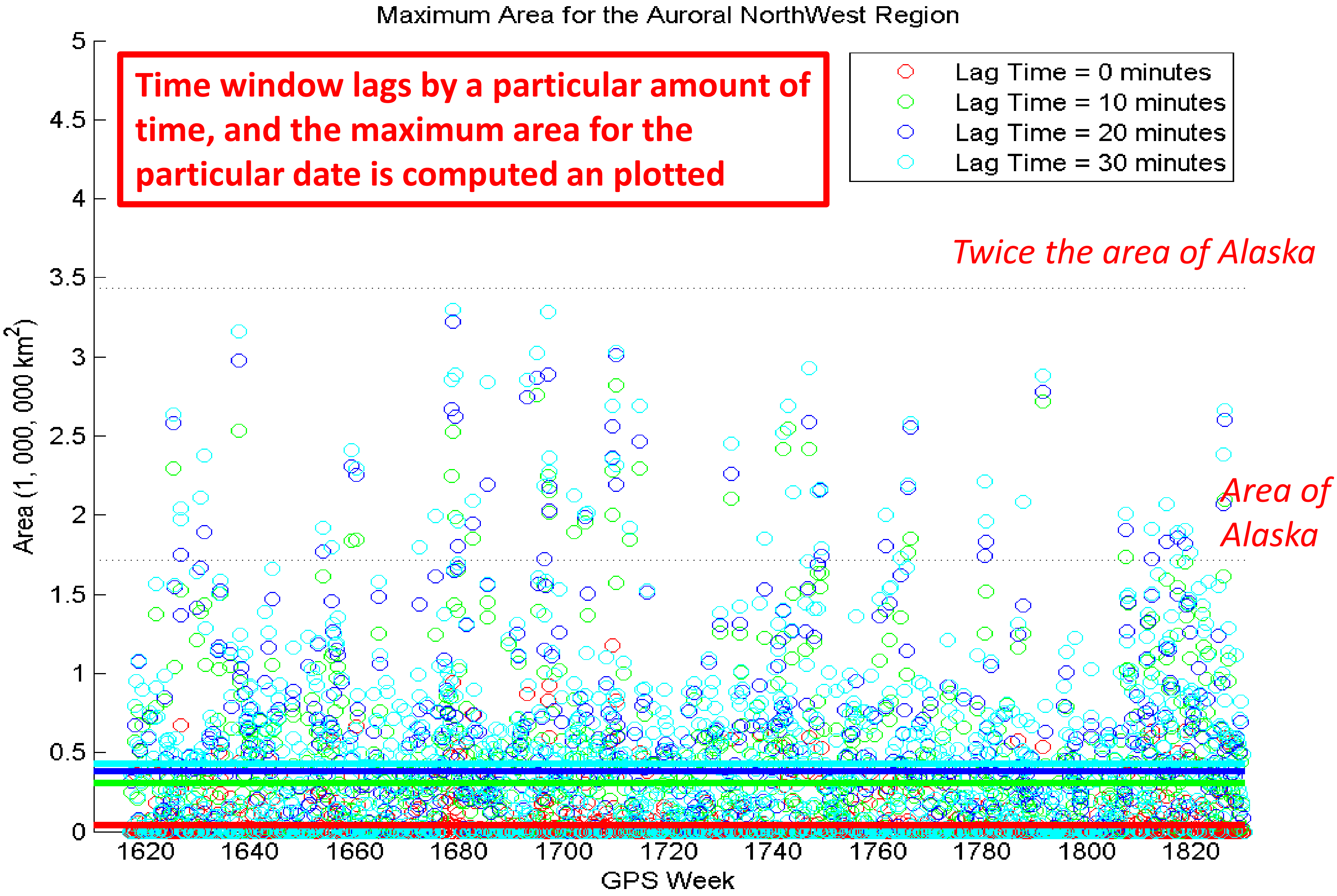
- Scintillation in Auroral Regions impacts multiple satellites at multiple stations almost simultaneously
  - Impact to one satellite virtually implies impact to three
  - Impact to one satellite creates ~50% chance of impacting six satellites
  - Auroral Northwest region appears to have a much higher rate of scintillation than the Auroral Northeast
- Mexican region satellite loss histogram shows much different behavior
  - Impact to one satellite does not imply impacting three satellites

Spatial Extent Analysis

- Spatial extent of scintillation in Auroral region implied by cycle slip indications on multiple satellites/stations at nearly the same time
  - Convex hull algorithm / triangulation algorithm creates an estimate of the area of the event
- Short study on different time windows conducted and showed 10 minutes was sufficient to capture majority of events
  - Using data that was instantaneous did not yield significant sizes of scintillation events
- Example for July 15th, 2012 shown in subsequent slides

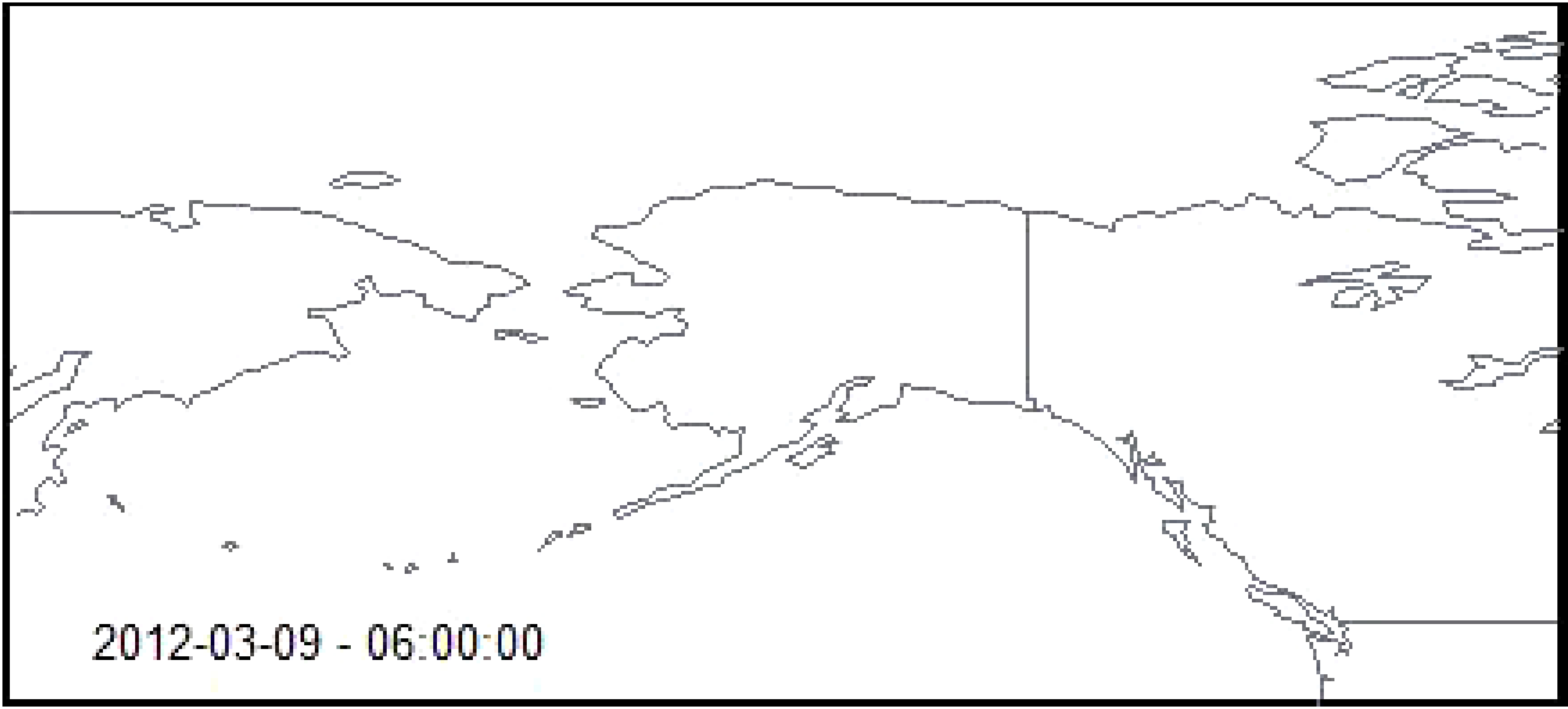
- Geographic Area Computation
  - For some period of time, compute the Ionospheric Pierce Points (IPPs) at 350 km. above the surface of the earth
  - Select the IPPs which form the convex hull (CH) of the set
  - Compute the median latitude and longitude of the CH
  - Project the points to the surface of the earth in ECEF
  - Compute the areas of the (three dimensional) triangles and sum




Maximum Area for the Auroral NorthWest Region
Time window lags by a particular amount of time, and the maximum area for the particular date is computed an plotted
Lag Time = 0 minutes
Lag Time = 10 minutes
Lag Time = 20 minutes
Lag Time = 30 minutes
Twice the area of Alaska
Area of Alaska
Area (1, 000, 000 km^2)
GPS Week
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
1620
1640
1660
1680
1700
1720
1740
1760
1780
1800
1820

Conclusions

- Multiple satellites impacted across multiple stations nearly simultaneously across Auroral Regions
  - Detection of one satellite having cycle slip indications virtually guarantees multiple satellites will be impacted
- Auroral Northwest appears to be most active scintillation region for the WAAS service volume
- Geographic extent of scintillation events in Auroral Northwest region can be very large, exceeding the area of the state of Alaska on several occasions
- Other studies have shown that WAAS is robust, and WAAS coverage is only affected by scintillation in a minor way
  - Results are potentially helpful for future WAAS processing improvements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Appendix

- Data processing

Paper Outline

- DATA SET
- WAAS REFERENCE STATION DATA PROCESSING
- EQUATORIAL VS AURORAL BEHAVIOR
- SCINTILLATION CORRELATED WITH SPACE WEATHER
- SATELLITE OUTAGE STATISTICS (BY REGION)
- GEOGRAPHIC SPATIAL EXTENT ANALYSIS

Geographic Regions

Auroral NW	Auroral NE	Mexico
Barrow	Iqaluit	Tapachula
Kotzebue	Goose Bay	San Juan
Fairbanks	Gander	Merida
Bethel	Winnipeg	Mexico City
Anchorage		Puerto Vallarta
Cold Bay		San Jose Cabo
Juneau		Miami

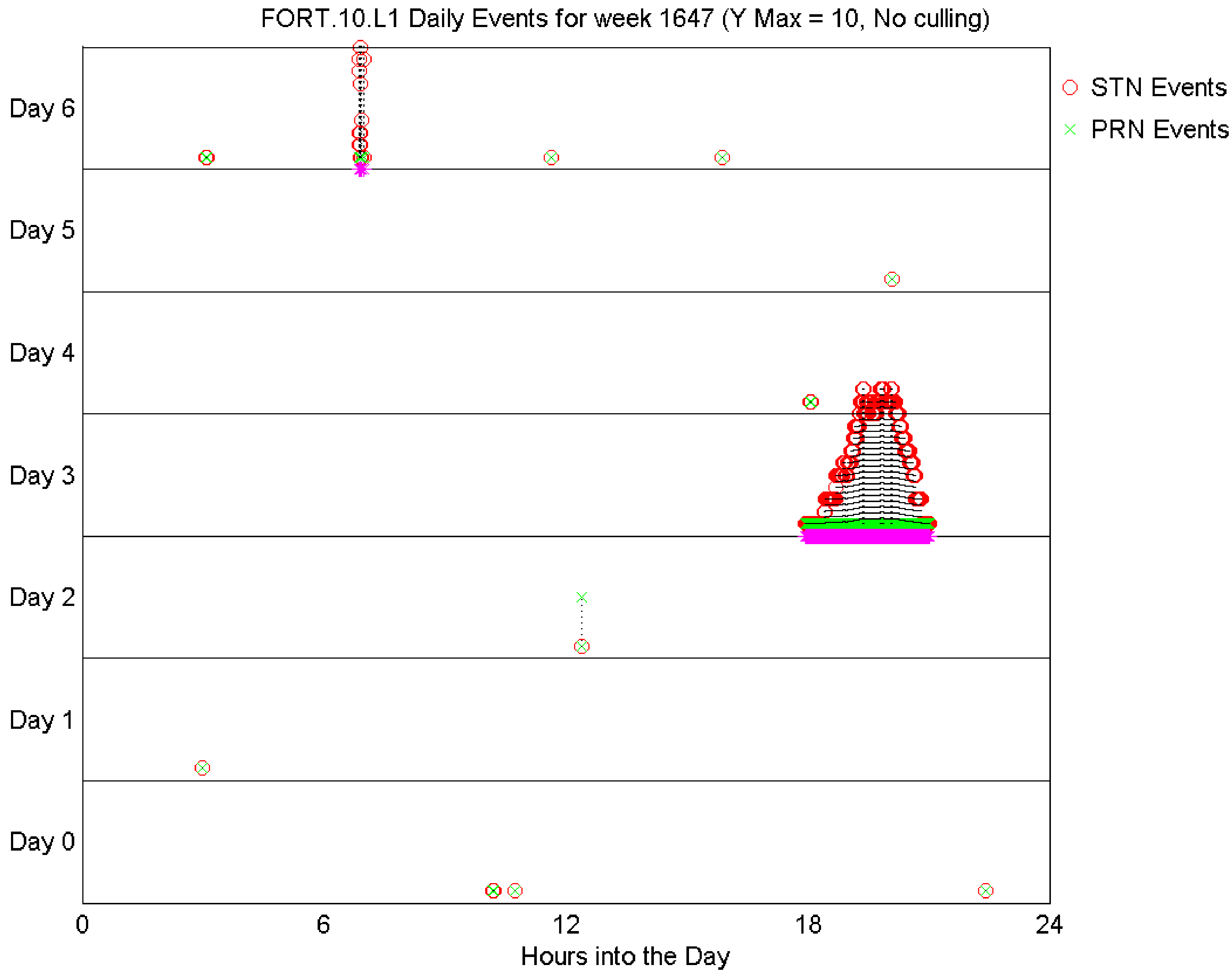
Next three slides show the affect of a ten minute windowing algorithm for the Auroral Northwest, July 15th, 2012

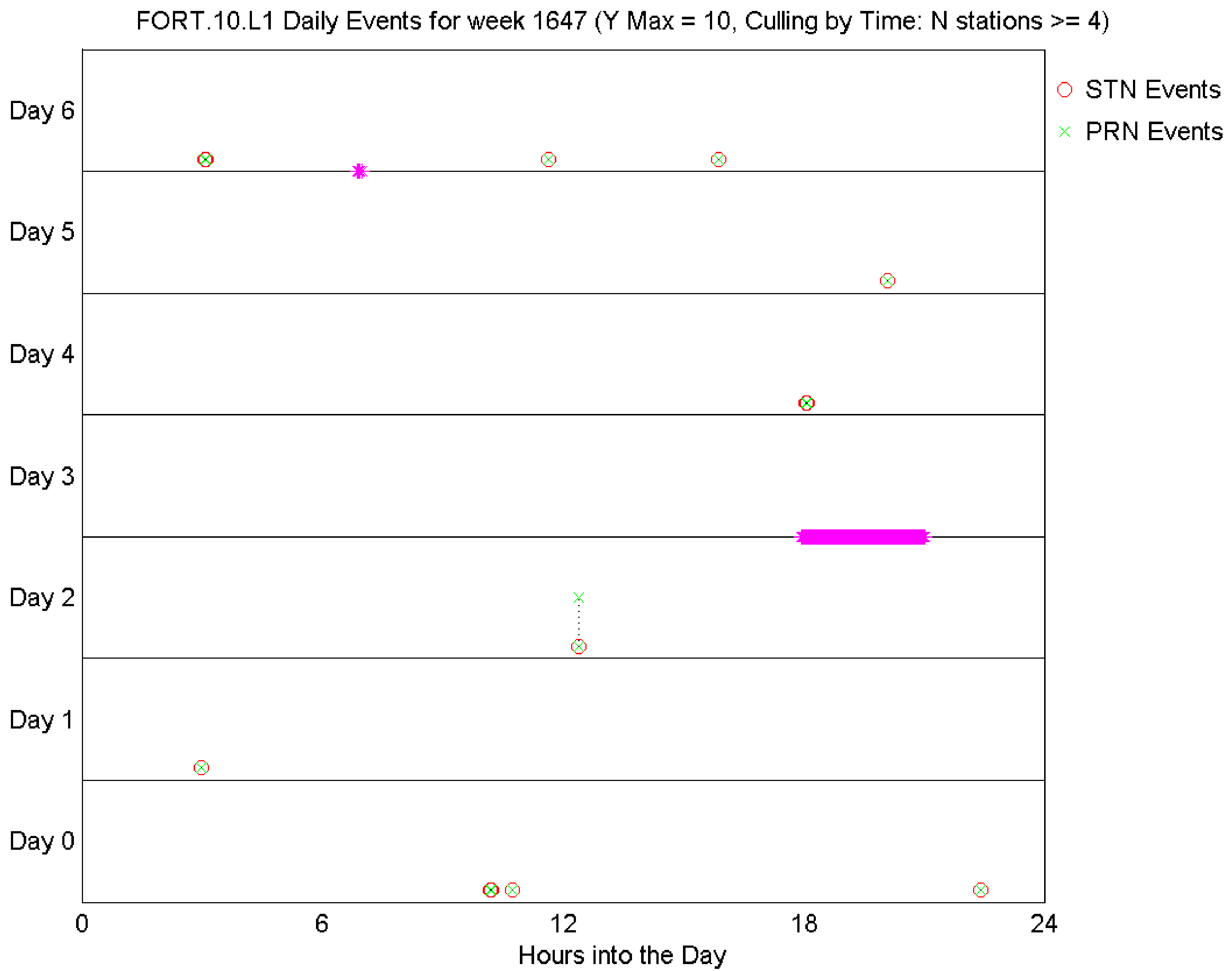
Culling

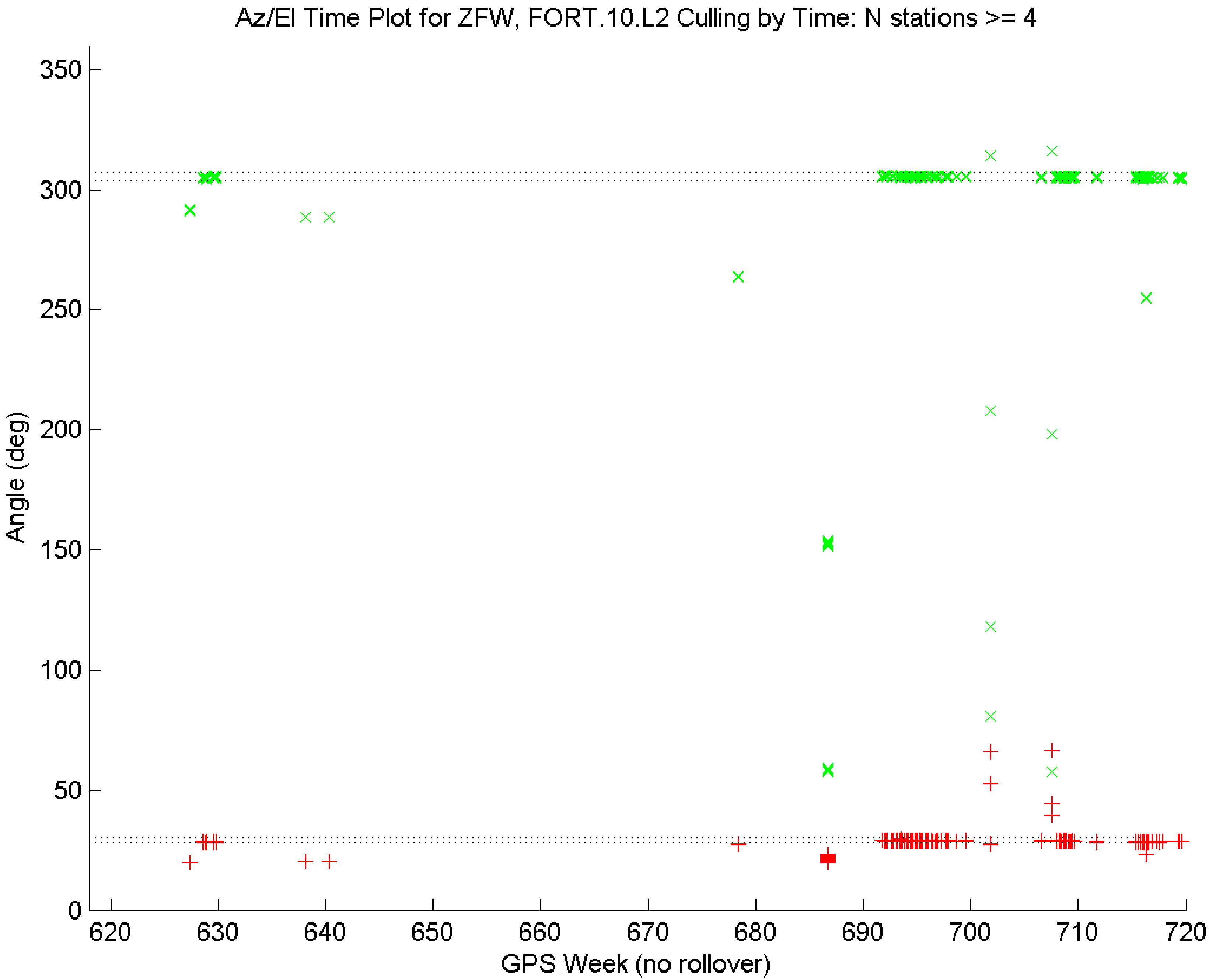
- Care taken to remove incidents which are most likely not scintillation.
  - RFI events are flagged using processing of receiver L1 and L2 AGC gain
  - Periods of time where more than four stations are not tracking a single satellite are assumed to be a satellite issue
  - Azimuth / Elevation “windows” for particular stations which show repeatable patterns are assumed to be from line of site blockage

Processing Overview

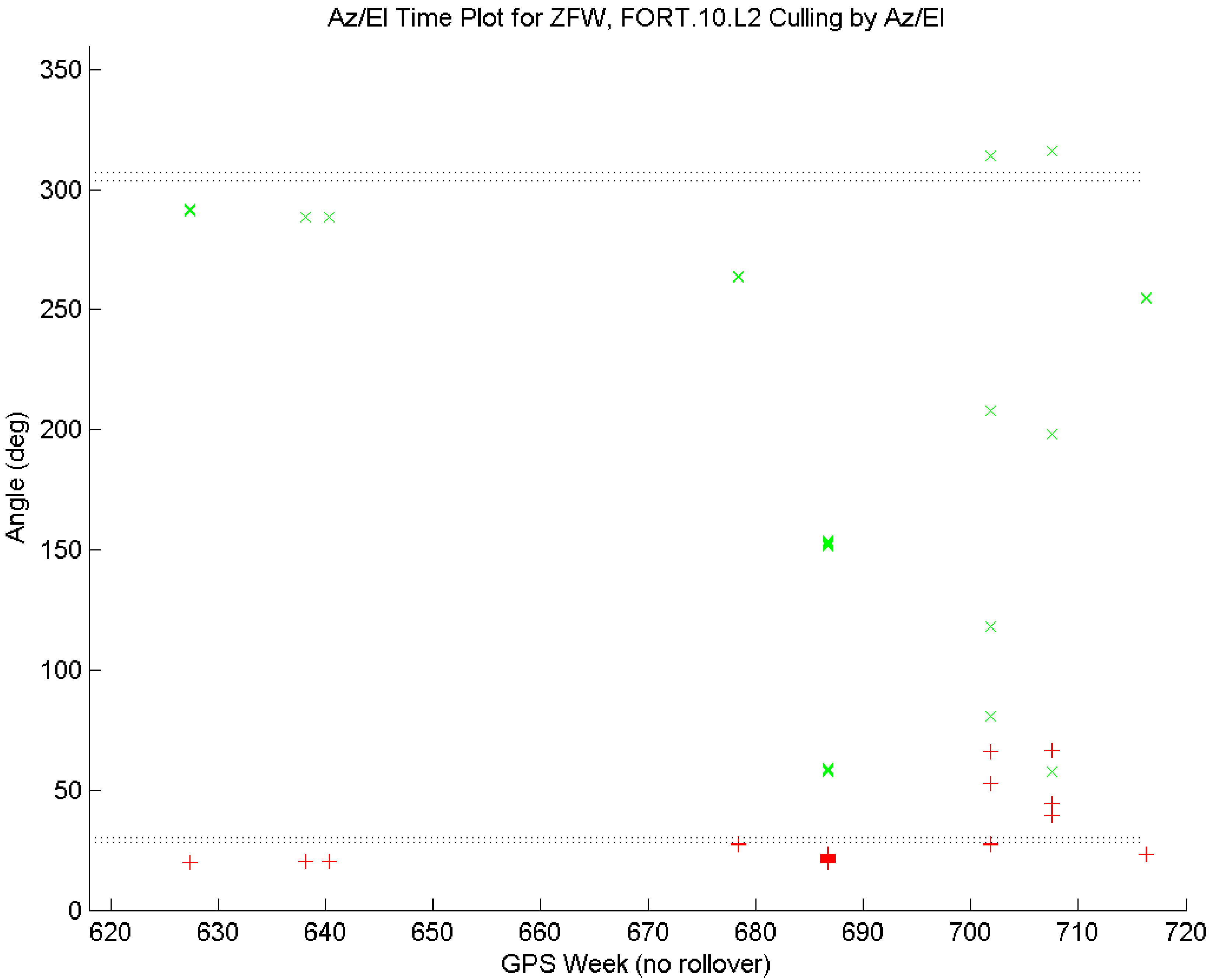
- Processing performed on WAAS measurement data to associate missing measurements with loss of tracking from scintillation activity
    - Processing differentiates scintillation from RFI, network disruptions, satellite maintenance…etc..
- Results contain epoch, PRN, Azimuth, Elevation for each station and frequency number, sorted by week
    - Currently using A thread only (other two redundant threads at each station not processed)
    - Output contains instances of lost tracking not attributed to other sources
    - Mask angle used in processing is 20 degrees (lost tracking below this elevation not considered)
    - Additional culling utilized to remove events that clearly are not scintillation
- Data set spans a little more than two years, starting on January 2nd 2011 and continuing to present day (August 24th, 2013)
    - Currently 138 weeks (~2.6 years)


FORT.10.L1 Daily Events for week 1647 (Y Max = 10, No culling)
Day 6
Day 5
Day 4
Day 3
Day 2
Day 1
Day 0
0
6
12
18
24
Hours into the Day
STN Events
PRN Events

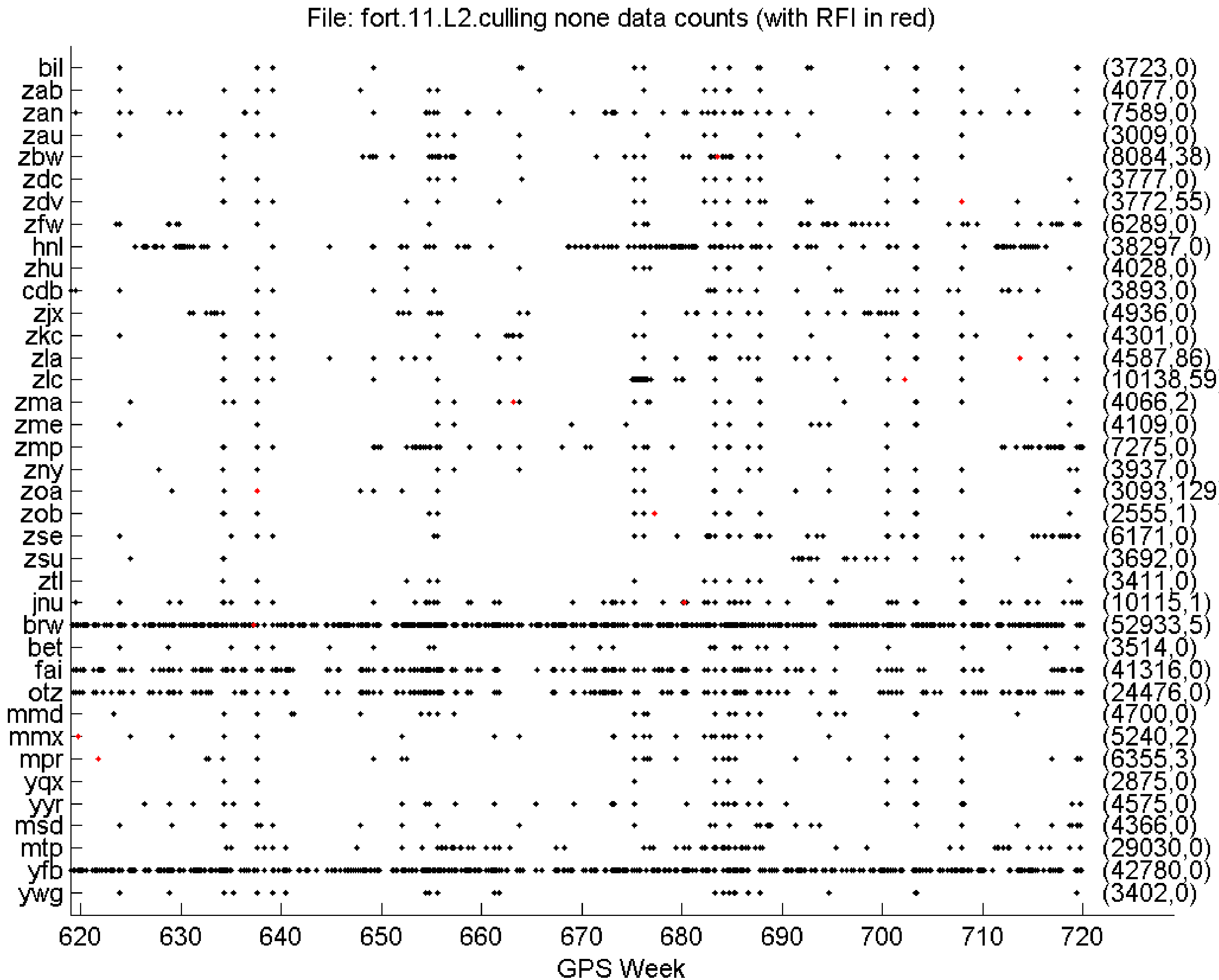

FORT.10.L1 Daily Events for week 1647 (Y Max = 10, Culling by Time: N stations >= 4)
STN Events
PRN Events
Day 6
Day 5
Day 4
Day 3
Day 2
Day 1
Day 0
0
6
12
18
24
Hours into the Day

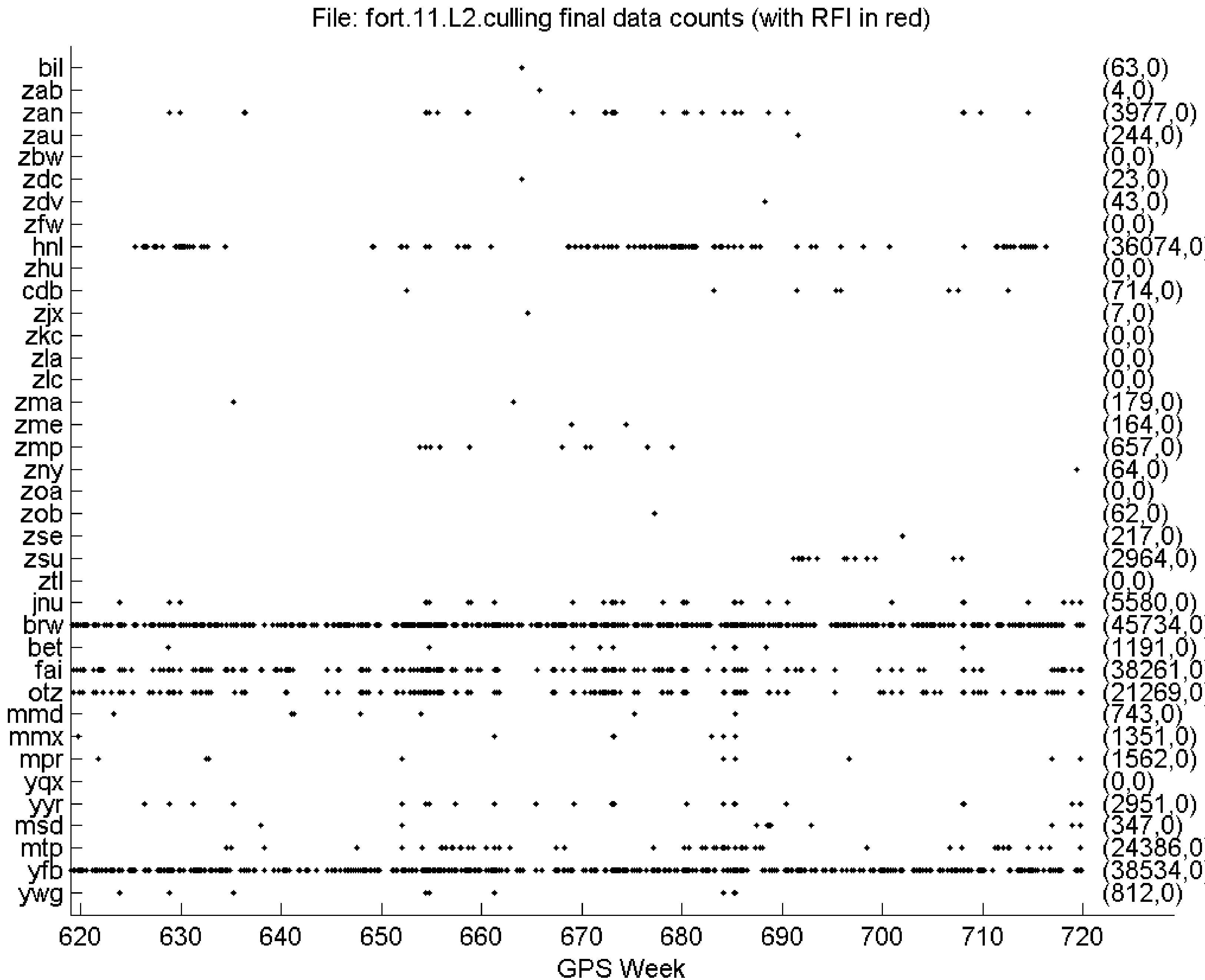


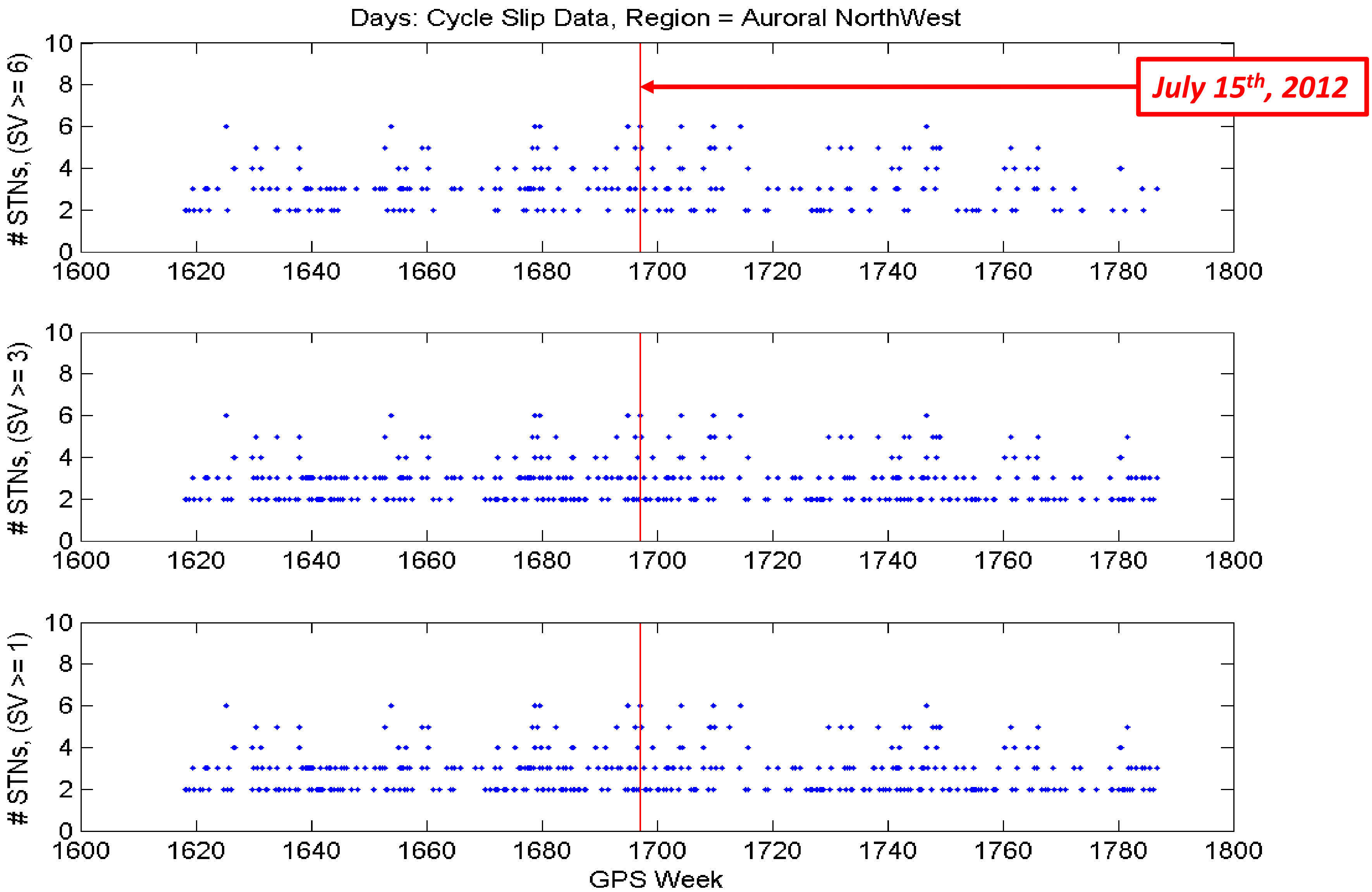
Az/El Time Plot for ZFW, FORT.10.L2 Culling by Time: N stations >= 4
Angle (deg)
350
300
250
200
150
100
50
0
620
630
640
650
660
670
680
690
700
710
720
GPS Week (no rollover)



Az/El Time Plot for ZFW, FORT.10.L2 Culling by Az/El
Angle (deg)
0
50
100
150
200
250
300
350
620
630
640
650
660
670
680
690
700
710
720
GPS Week (no rollover)


File: fort.11.L2.culling none data counts (with RFI in red)
bil
zab
zan
zau
zbw
zdc
zdv
zfw
hnl
zhu
cdb
zjx
zkc
zla
zlc
zma
zme
zmp
zny
zoa
zob
zse
zsu
ztl
jnu
brw
bet
fai
otz
mmd
mmx
mpr
yqx
yyr
msd
mtp
yfb
ywg
(3723,0)
(4077,0)
(7589,0)
(3009,0)
(8084,38)
(3777,0)
(3772,55)
(6289,0)
(38297,0)
(4028,0)
(3893,0)
(4936,0)
(4301,0)
(4587,86)
(10138,59)
(4066,2)
(4109,0)
(7275,0)
(3937,0)
(3093,129)
(2555,1)
(6171,0)
(3692,0)
(3411,0)
(10115,1)
(52933,5)
(3514,0)
(41316,0)
(24476,0)
(4700,0)
(5240,2)
(6355,3)
(2875,0)
(4575,0)
(4366,0)
(29030,0)
(42780,0)
(3402,0)
620
630
640
650
660
670
680
690
700
710
720
GPS Week


File: fort.11.L2.culling final data counts (with RFI in red)
bil
zab
zan
zau
zbw
zdc
zdv
zfw
hnl
zhu
cdb
zjx
zkc
zla
zlc
zma
zme
zmp
zny
zoa
zob
zse
zsu
ztl
jnu
brw
bet
fai
otz
mmd
mmx
mpr
yqx
yyr
msd
mtp
yfb
ywg
(63,0)
(4,0)
(3977,0)
(244,0)
(0,0)
(23,0)
(43,0)
(0,0)
(36074,0)
(0,0)
(714,0)
(7,0)
(0,0)
(0,0)
(0,0)
(179,0)
(164,0)
(657,0)
(64,0)
(0,0)
(62,0)
(217,0)
(2964,0)
(0,0)
(5580,0)
(45734,0)
(1191,0)
(38261,0)
(21269,0)
(743,0)
(1351,0)
(1562,0)
(0,0)
(2951,0)
(347,0)
(24386,0)
(38534,0)
(812,0)
620
630
640
650
660
670
680
690
700
710
720
GPS Week


Days: Cycle Slip Data, Region = Auroral NorthWest
July 15th, 2012
STNs, (SV >= 6)
STNs, (SV >= 3)
STNs, (SV >= 1)
GPS Week
0
2
4
6
8
10
1600
1620
1640
1660
1680
1700
1720
1740
1760
1780
1800