WAAS Technical Report
William J. Hughes Technical Center
Atlantic city International Airport, NJ
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Author(s): David Nelthropp

DR #130 Ionospheric Activity Effects on WAAS Performance March 6 & 7, 2016

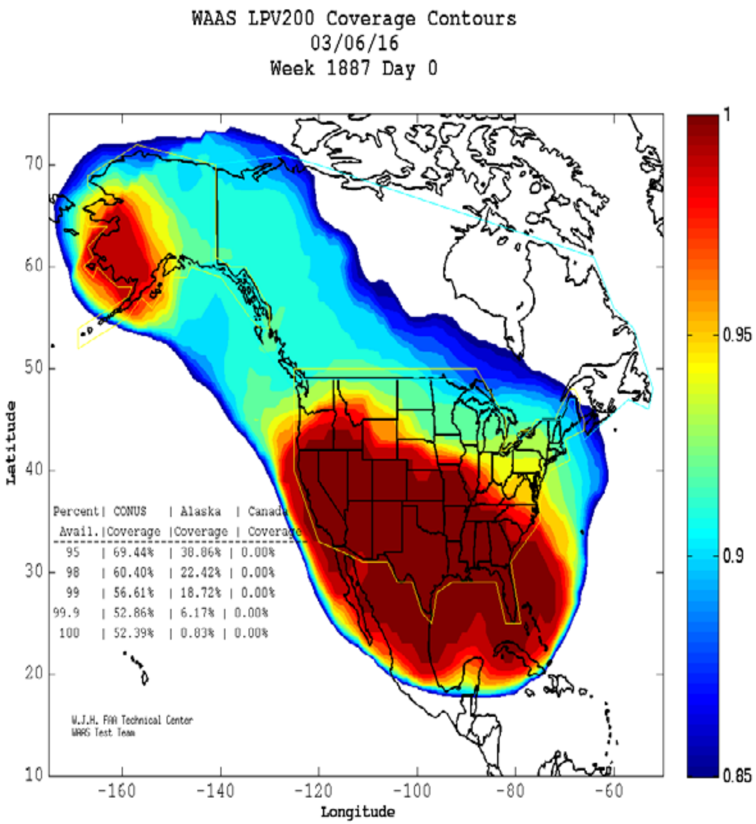
GPS Week/Day: Week 1887 Day 0 & Day1

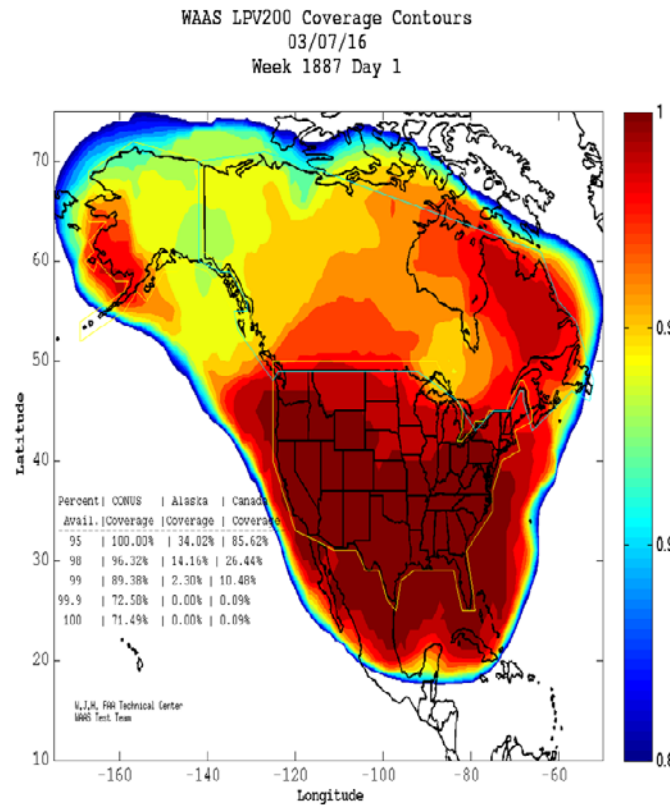
(03/06/2016 – 03/07/2016)

WAAS Performance 6 & 7 March 2016

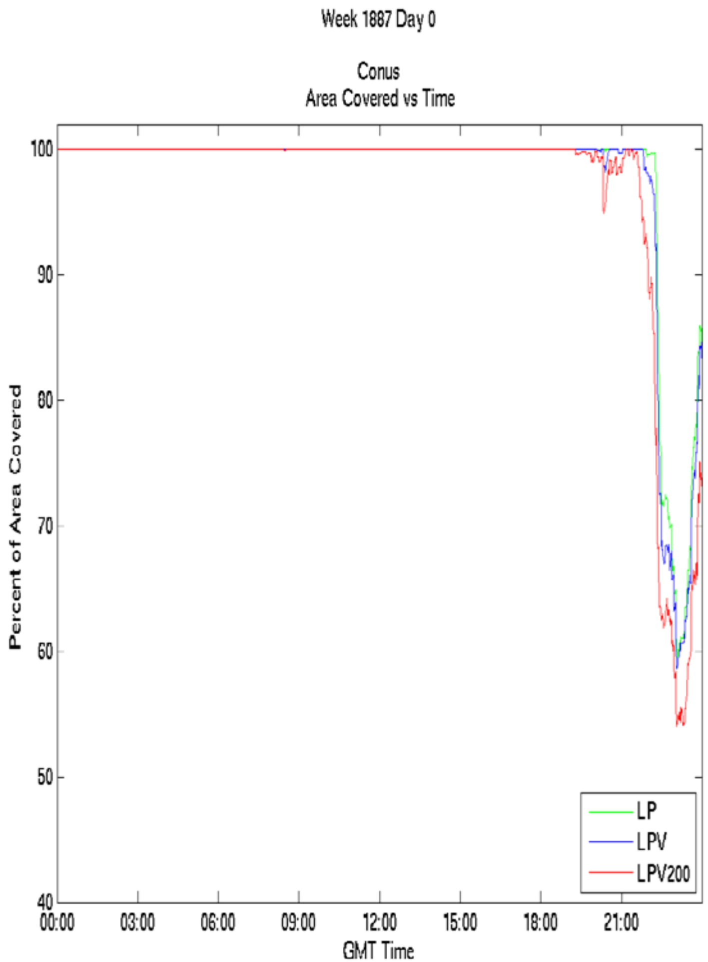
- Geomagnetic disturbance (KP = 7) and Ionospheric activity on the 6 & 7 March 2016 triggered WAAS ionospheric storm state at IGPs in Northern CONUS, Alaska and Canada
- LPV and LPV200 service outages in CONUS lasted approximately 2.25 hours starting at 22:00 GMT on 6 March and LPV service was available in CONUS at most locations at 00:15 GMT on 7 March
- LPV and LPV200 service outages in Alaska lasted approximately 3.5 hours starting at 22:00 GMT on 6 March
- WAAS accuracy was affected when LPV service was available at WRSs in North Eastern CONUS and Canada
- The Vertical ionospheric delays over 8 meters reached 45 degrees latitude while delays were below 3 meters at 60 degrees latitude
- Spatial de-correlation of Ionospheric delays occurred in Canada, CONUS, and Alaska and the magnitude was computed between receivers as delay gradients
- When delay gradients increase WAAS can detect changes in the Ionospheric delays and reduce service before errors propagate in user navigation

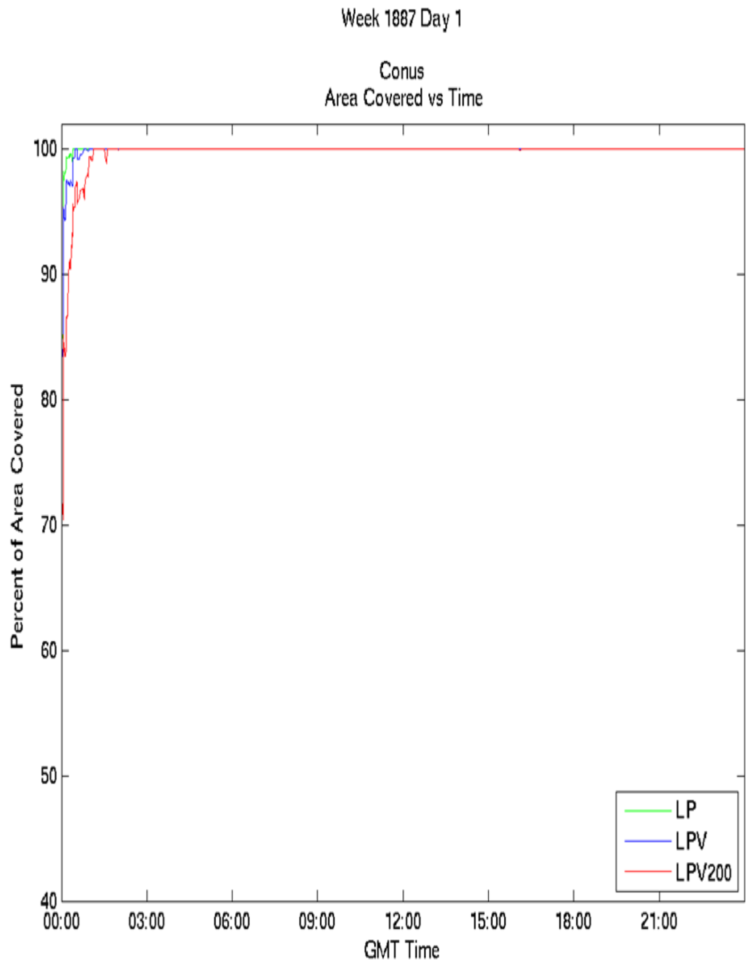
WAAS LPV200 Coverage 6 & 7 March 2016





WAAS CONUS Coverage Vs Time 6 & 7 March





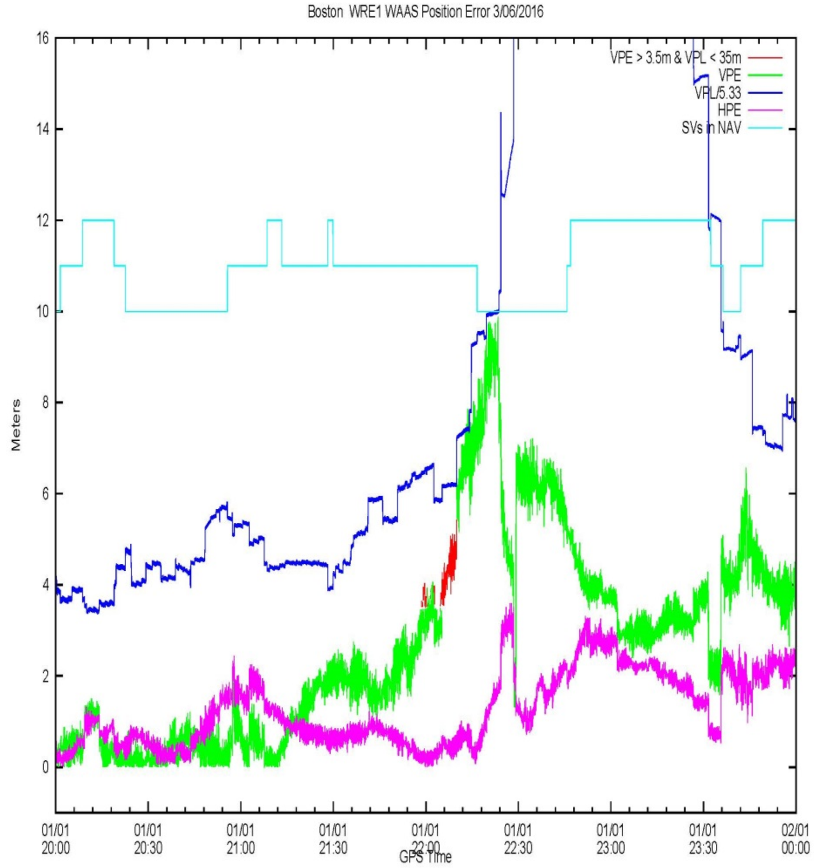
WAAS Maximum Position Error 6 March

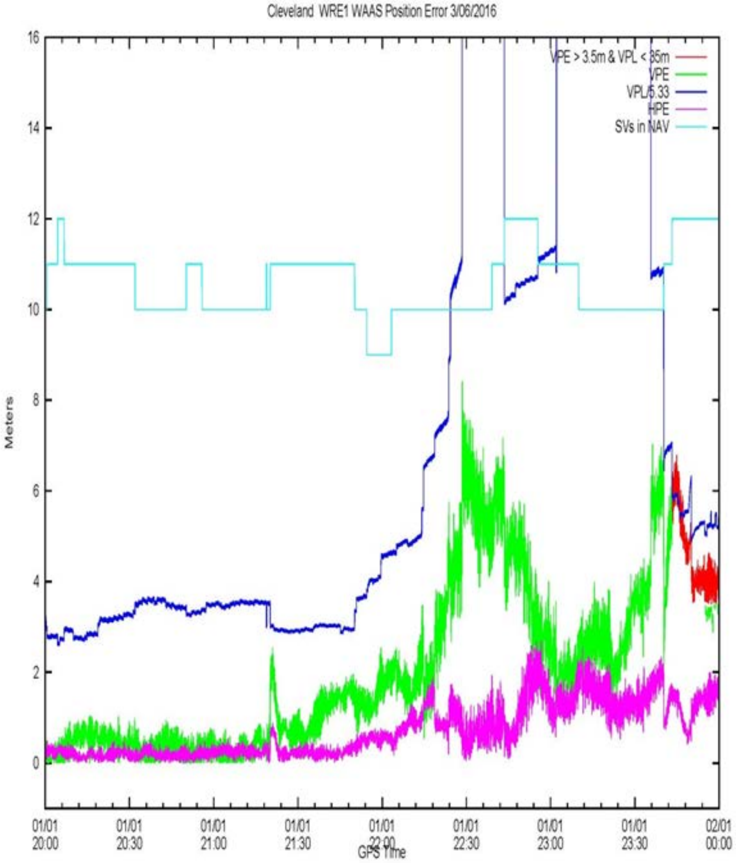
WAAS RCVR	ID	City	Horz Max (HPL)	HORZ RATIO	Vert Max (VPL)	VERT RATIO
28097	6DC1	Chicago	3.95 (20.6490)	0.1910	8.8410 (34.2990)	0.2580
28353	6EC1	Boston	2.6840 (25.2240)	0.1310	8.0220 (49.6210)	0.1980
36547	8EC3	Tapachula	5.6130 (39.3780)	0.1430	8.02 (39.8870)	0.2010
37059	90C3	Iqaluit	3.1330 (36.8760)	0.1460	7.12 (40)	0.2240
32449	7EC1	Cleveland	2.3430 (39.15)	0.14	6.7890 (31.4740)	0.2160
36033	8CC1	Goose Bay	2.6960 (38.6030)	0.1040	5.90 (42.7320)	0.1620
31937	7CC1	New York	1.4790 (28.1340)	0.1240	5.7570 (44.3760)	0.13
28609	6FC1	Washington DC	1.5130 (10.1850)	0.1490	5.0620 (44.30)	0.1290
35265	89C1	Mexico City	1.18 (25.7840)	0.0710	4.6870 (24.4720)	0.2090
36289	8DC1	Winnipeg	2.0740 (36.5910)	0.1180	4.6130 (46.2030)	0.1420
34499	86C3	Kotzebue	1.5760 (14.0140)	0.1120	4.4140 (24.9040)	0.1950

WAAS Position Accuracy 6 and 7 March

- WAAS Vertical and Horizontal position errors increased during LPV and LPV200 service at several locations
- Vertical position errors (VPE - green trace) at Boston increased from 3.5 m to 5.4m (red trace VPE > 3.5m and VPL < 35m) while vertical protection level (VPL/5.33 - blue trace) remained below LPV200 service thresholds between 22:05 – 22:10
- Boston VPE increase to 8 m between 22:10 – 22:15 before LPV service was lost
- The VPL at Cleveland began to increase at 21:50 and LPV200 service was lost at 22:15 before navigation accuracy decreased
- VPE at Cleveland increased to 6 m and VPL decreased below LPV200 service thresholds when PRN 1 was added to the Navigation solution at 23:43 GMT
- All position errors were bounded by their protection levels at all locations

WAAS Position Error at Boston and Cleveland 6 March

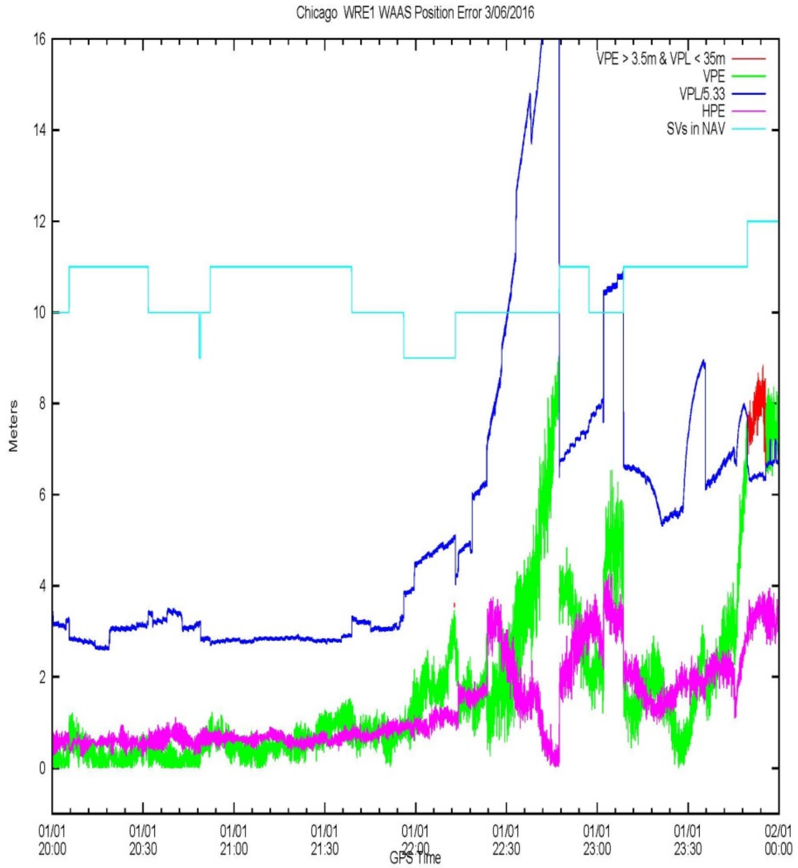


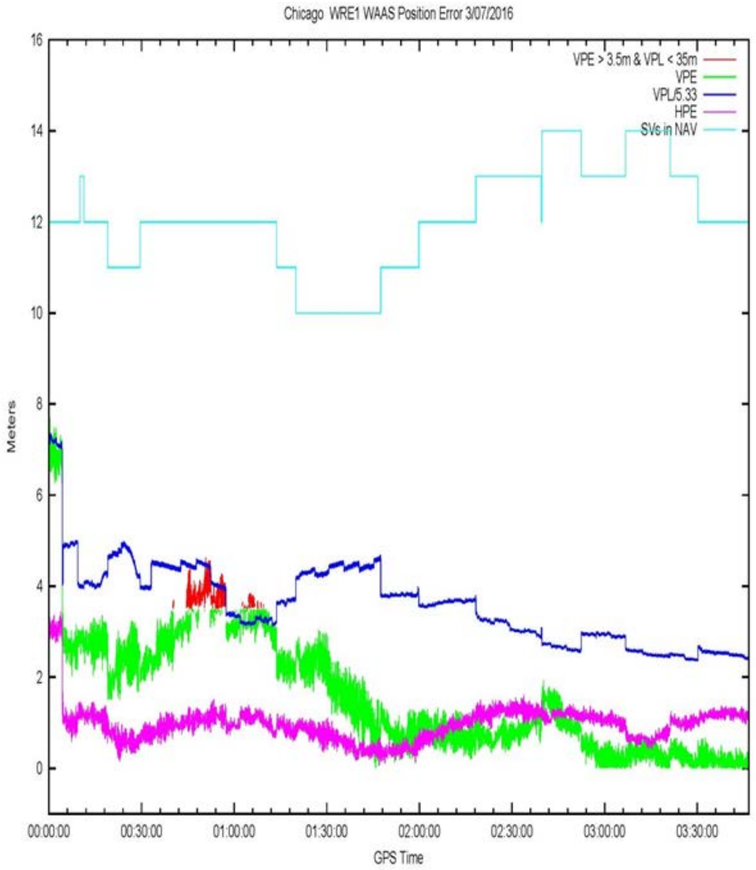


Chicago WAAS Position Accuracy 6 and 7 March

- The VPL at Chicago increase at 22:00 and LPV200 service was lost at 22:26 before navigation accuracy was affected
- LPV and LPV200 service at Chicago became available intermittently 22:47 and 00:06 March 7
- VPE at Chicago increased to 8.8m and VPL decreased just below LPV200 service thresholds between 23:49 – 23:54 GMT When SV PRN 1 was added the Navigation solution
- Chicago VPE remained at 7.7m when LPV service was available between 23:54 March 6 – 00:06 March 7
- All position errors were bounded by their protection levels

WAAS Position Error at Chicago 6 & 7 March

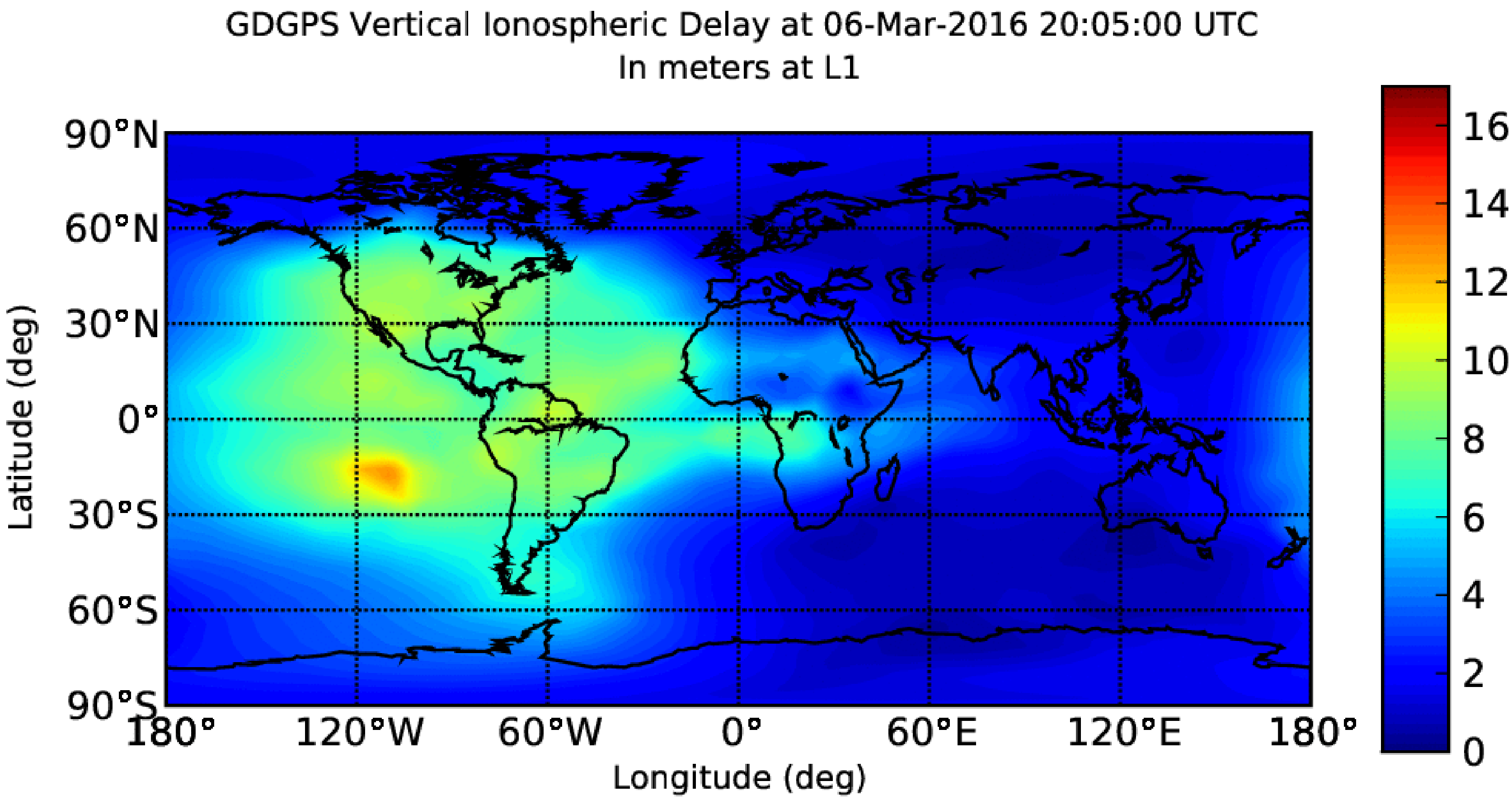




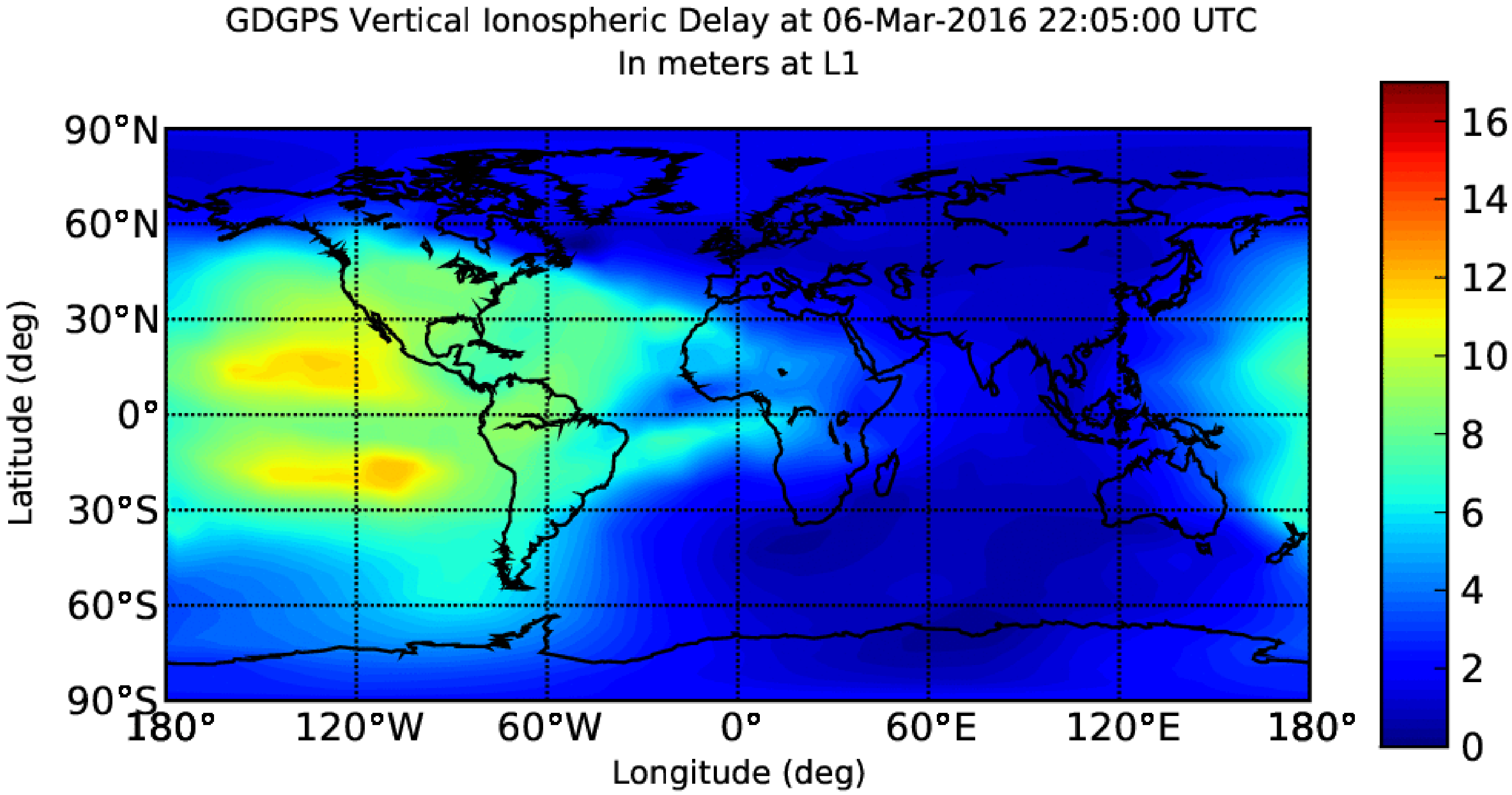
Vertical Ionospheric Delay 6 & 7 March 2016

- Ionospheric disturbance detected by the WAAS is depicted by the GDGPS vertical ionospheric delay graphics
- Sharp contrast in the ionosphere delay observed at the mid Latitudes
- Delays at approximately 8 meters at 60 deg Latitude in North America at 20:05 GMT March 6
- At 22:05 GMT Delays decrease to 3 meters at 60 deg Latitude but remain at 8 meters at 50 deg Latitude
- At 00:05 on March 7 Delays decrease to 3 meters at 50 deg Latitude

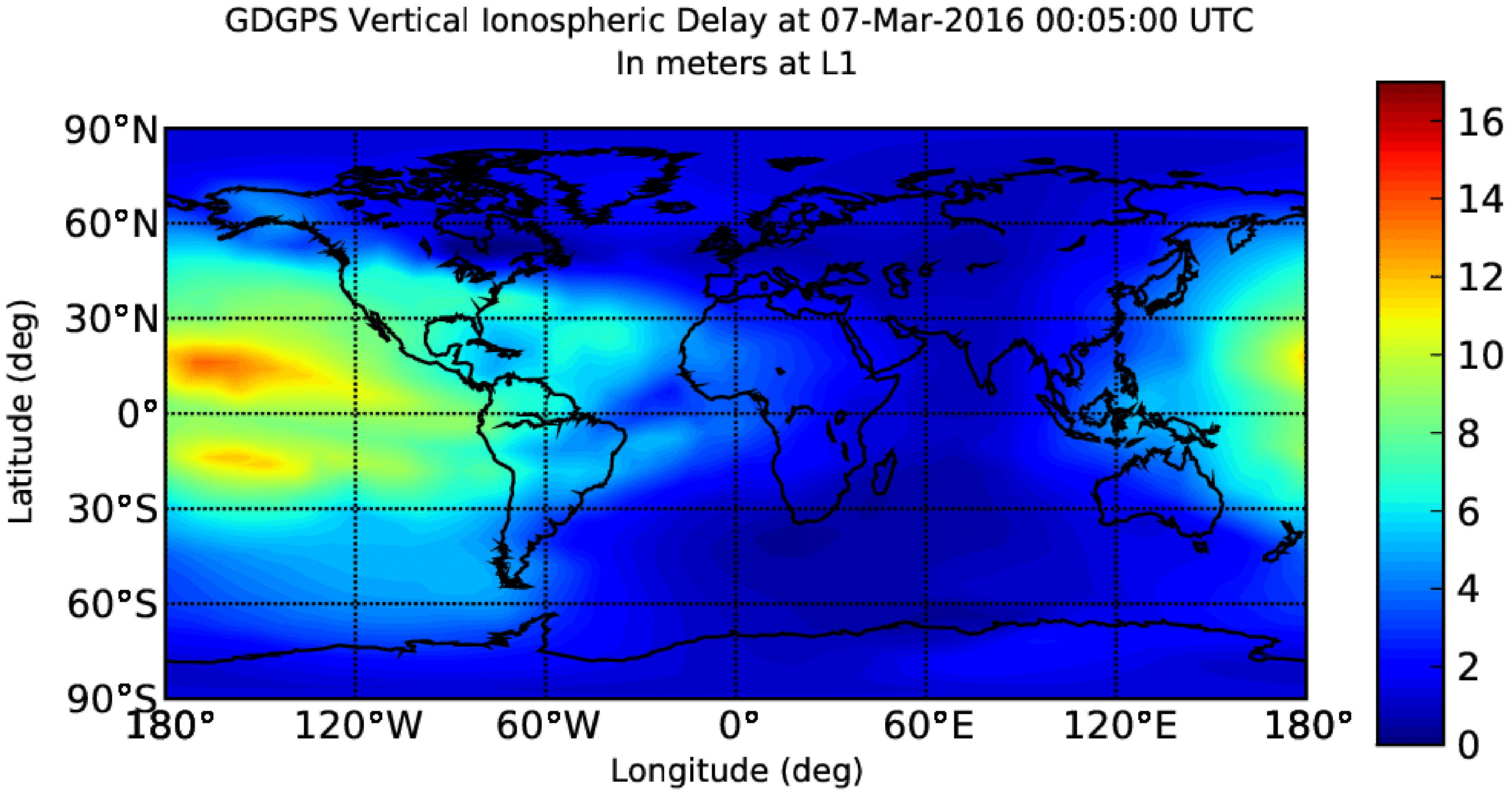
Vertical Ionospheric Delay 6 March at 20:05 GMT



Vertical Ionospheric Delay 6 March at 22:05 GMT



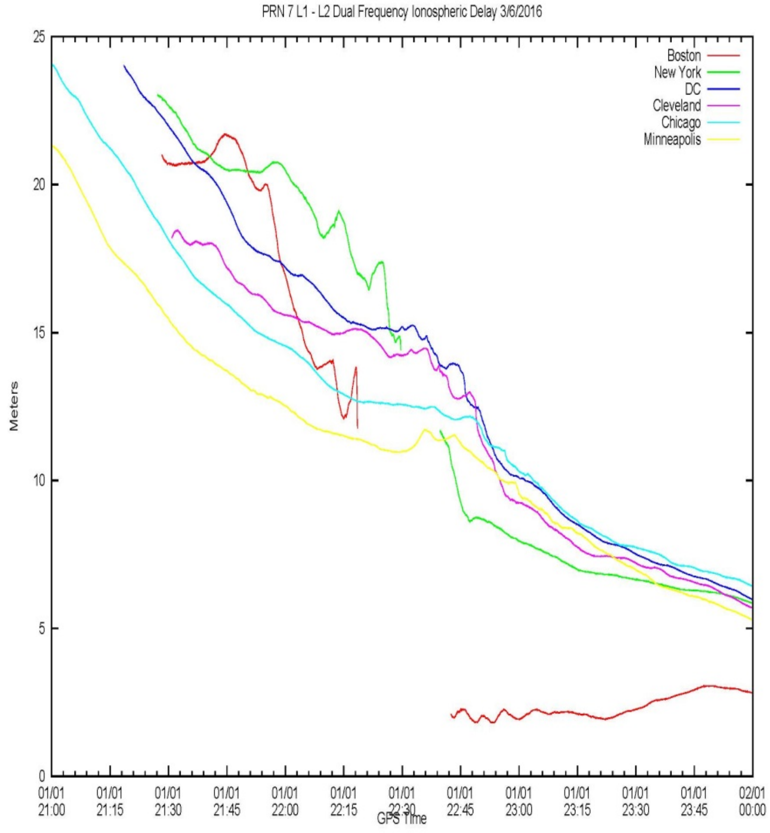
Vertical Ionospheric Delay 7 March at 00:05GMT

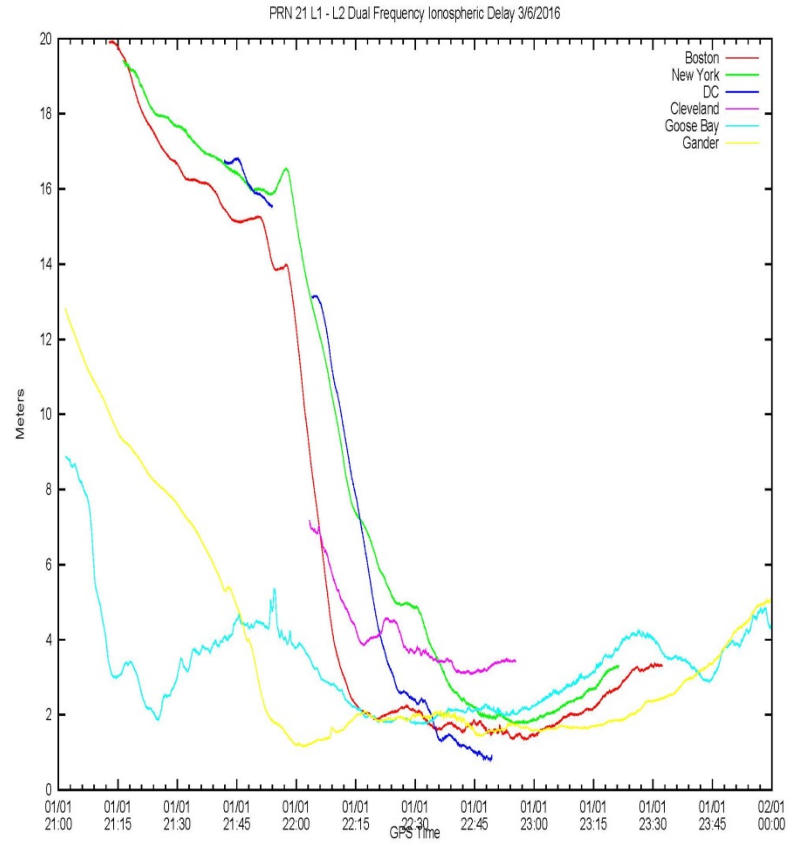


Spatial De-correlation of Dual Frequency Slant Ionospheric Delay

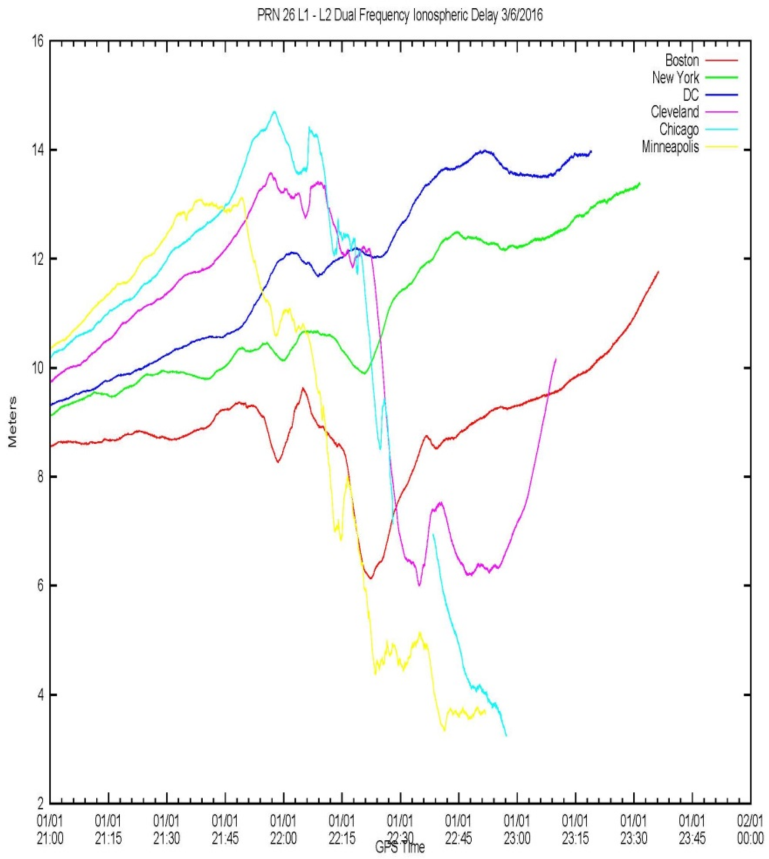
- GPS satellite slant ionospheric delay was computed from each receiver L1 frequency and L2 frequency observations
- Code measurements were carrier smoothed with 100 second filter to remove receiver noise
- Measurements were processed to remove multipath, using a Code Noise and Multipath (CNMP) lag filter
- Process provides a carrier leveled dual frequency slant ionospheric delay for each receiver satellite observation
- Ionospheric delays of each GPS satellite were compared across receivers to determine the spatial de-correlation that occurred over time
- ionospheric delays on a baseline day are within 1 - 2 meters between receivers analyzed
- Ionospheric delays on PRN 7 at Boston (red trace) and New York(green trace) experienced rapid changes and L1/L2 carrier cycle slips between 22:15 and 22:45 GPS Time

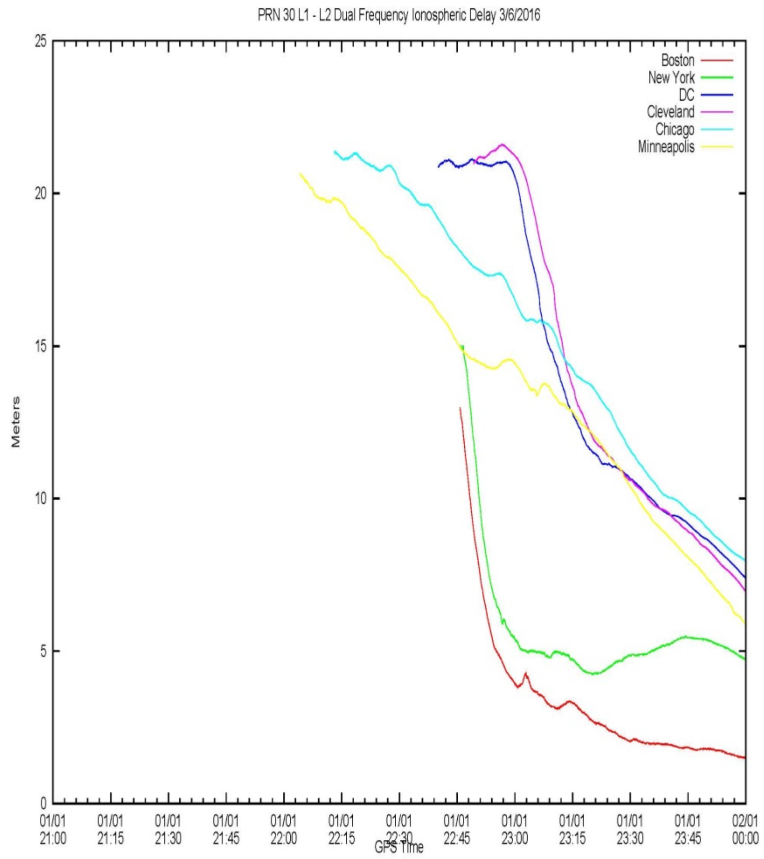
Spatial De-correlation of PRN 7 & PRN 21
Dual Frequency Slant Ionospheric Delay March 6





Spatial De-correlation of PRN 26 & PRN 30
Dual Frequency Slant Ionospheric Delay March 6

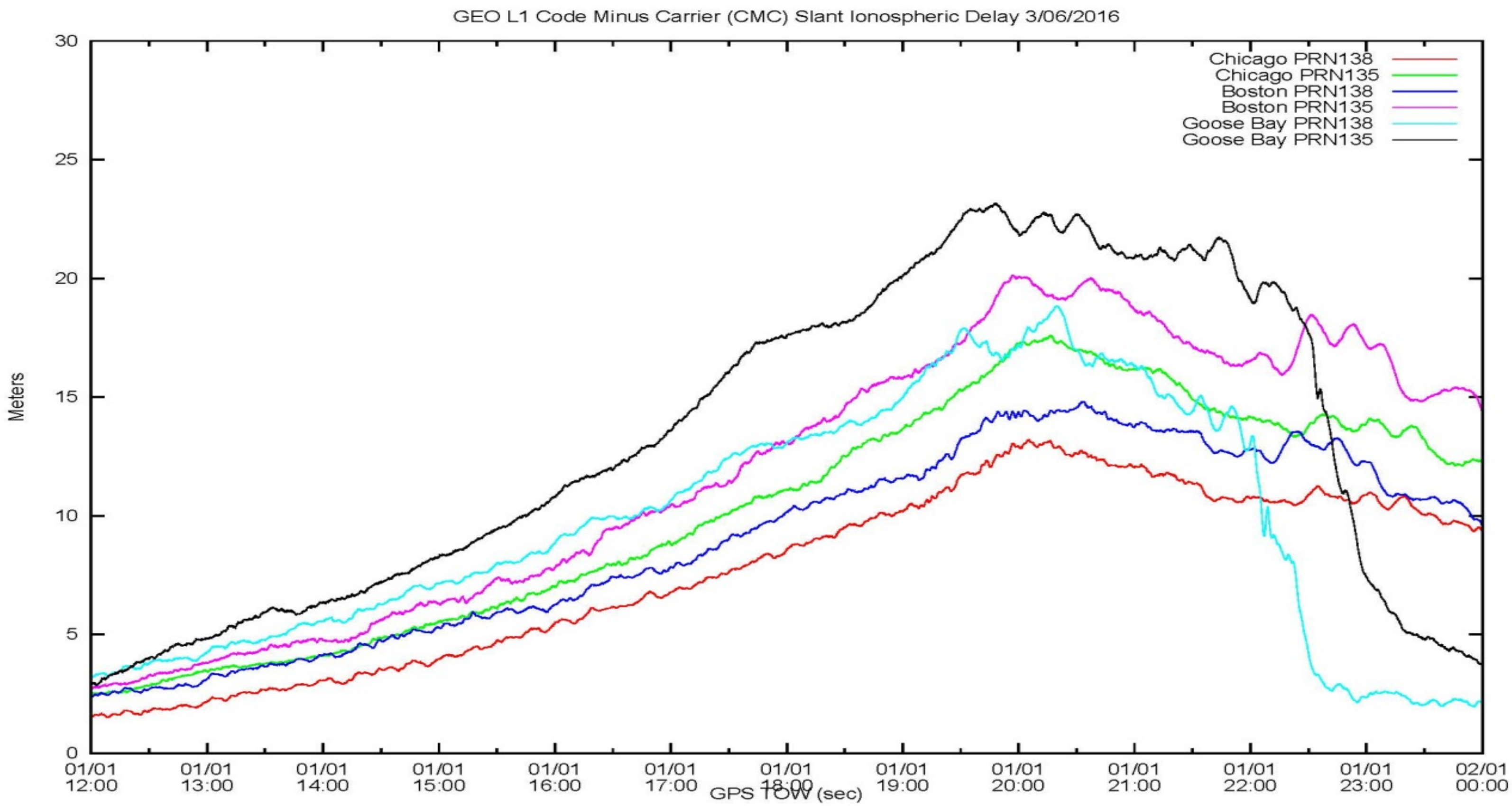




GEO L1 CMC Slant Ionospheric Delay

- GEO satellite slant ionospheric delay was computed from each receiver L1 frequency code and carrier observations
- L1 code measurement was carrier smoothed with 100 second filter to remove receiver noise then the measurements were differenced with the L1 carrier measurement (L1 CMC)
- L1 CMC difference was normalized to remove the carrier cycle ambiguity and divided by 2 to produce the Ionospheric delay for PRN 135 (GEO CRW) and PRN 138 (GEO CRE)
- delays at the GEO IPPs provide useful information of the nature of the ionospheric activity since they are at the same location throughout the event
- Goose Bay PRN 138 delay (cyan trace) and PRN 135 delay (black trace) decreased 11 meters in 40 minutes (28 cm/min) between 22:00 and 23:00 GMT

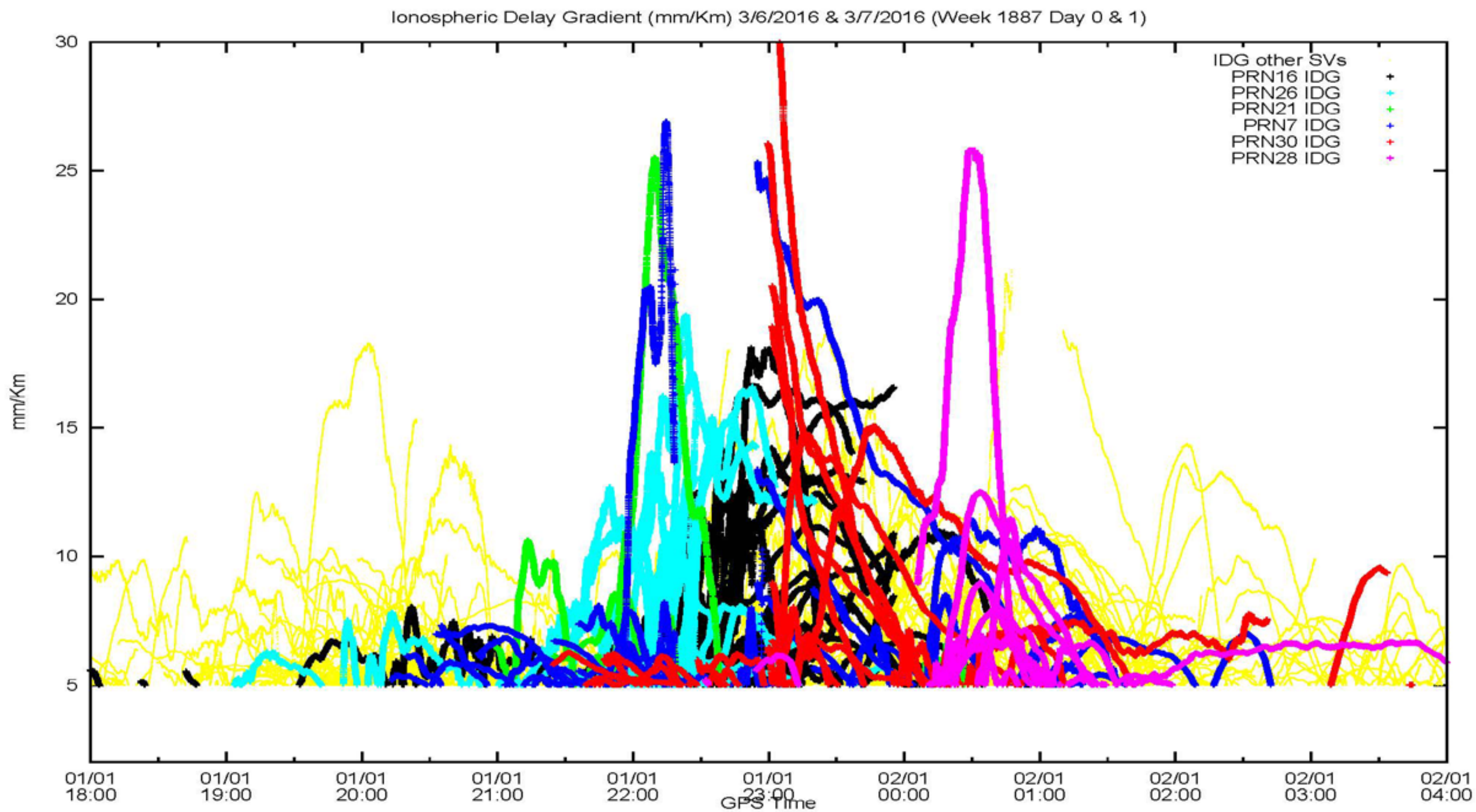
GEO L1 CMC Slant Ionospheric Delay



Measuring Spatial De-correlation with Ionospheric Delay Gradients

- ionospheric delays of each GPS satellite were compared across receivers within 1000Km to determine the spatial de-correlation that occurred over time
- ionospheric delay difference (D1 – D2) between two observations of the same satellite divided by the distance in locations (Baseline) used to compute the delay spatial rate of change (mm/Km) or ionosphere delay gradient (IDG) between the two observables ; IDG = (D1 – D2) / Baseline
- IDG analyzed when satellite elevation at receiver (D1) is above 10 deg
- IDG computed for observations when distance between receivers (Baseline) is less than 1100Km within CONUS and Alaska
- The Baseline is increased to 1500Km to join observations outside of CONUS and Alaska for selected receiver locations
- Approximately 1120 IDGs computed every second and logged when magnitude exceeds 5 mm/Km = 0.56 m/degree at the equator (10 meter delay difference between IGPs at 5 degrees separation is approximately 18 mm/Km)
- IDG at several satellites were above 20 mm/Km between 22:00 and 23:15 GMT

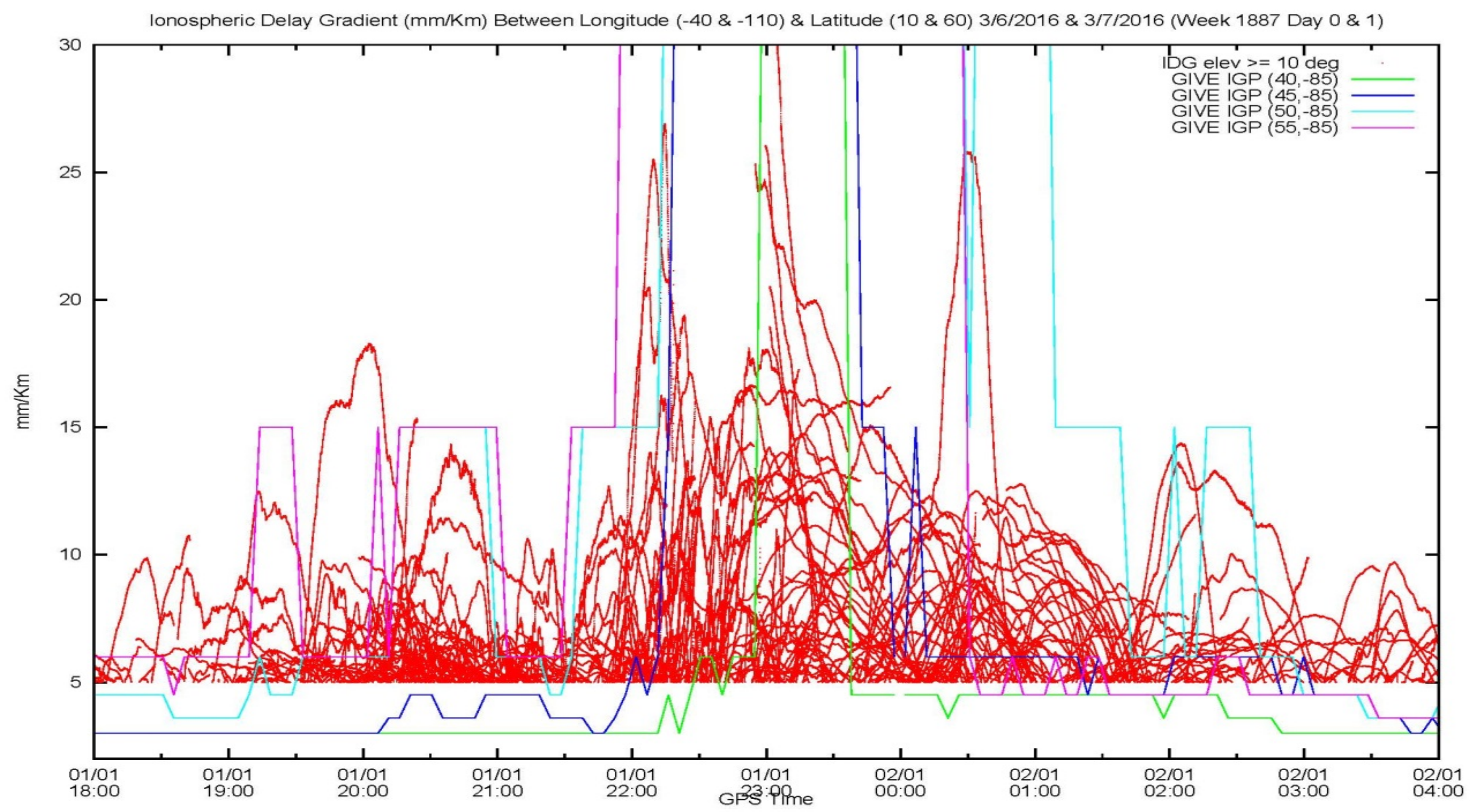
Ionospheric Delay Gradients Vs Time 6 & 7 March in North America color coded by SV PRN



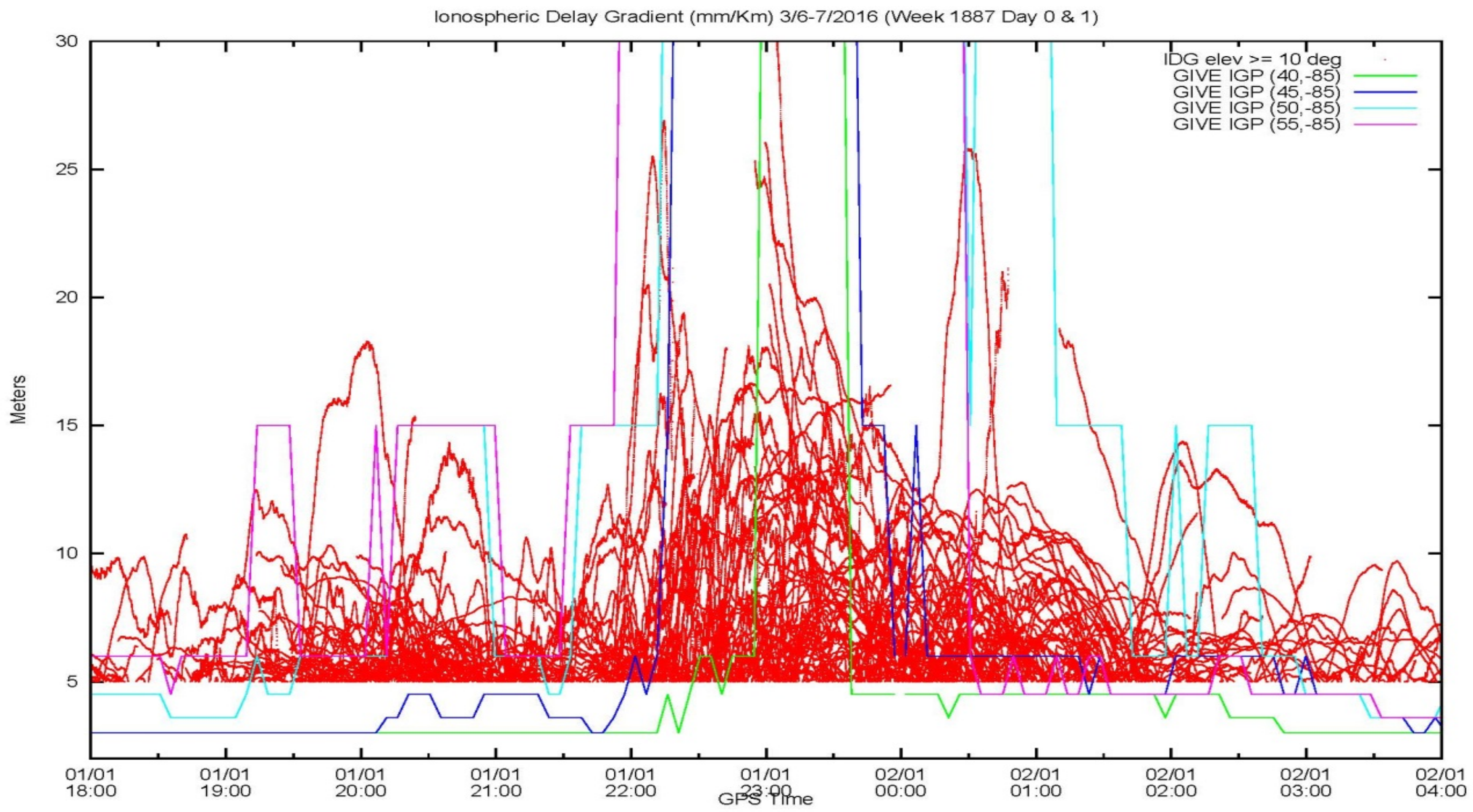
Ionospheric Delay Gradients and WAAS Service

- The number of IDGs over 5 mm/Km began to increase at 19:45 GMT and GIVEs at IGPs in the East at high latitude increased to 45 m (ionospheric storm state)
- The IGP at 85 deg longitude used to represent WAAS service response in CONUS
- IGP (55, -85) and (50, -85) increased to 15 m when several IDGs exceeded 10 mm/Km at 20:10 and 21:35
- IDGs increased above 15 mm/Km at 22:00 and the IGPs at (50, -85) and (45, -85) were set to storm state within approximately 15 minutes
- IGP (40, -85) was set to storm state at 22:57 approximately 5 minutes after IDG of 25 mm/Km was observed on PRN 7 and IDG of 36 mm/Km was observed on PRN 30
- The IDGs increase in the Alaska region at the same time as they did in CONUS and NE Canada region

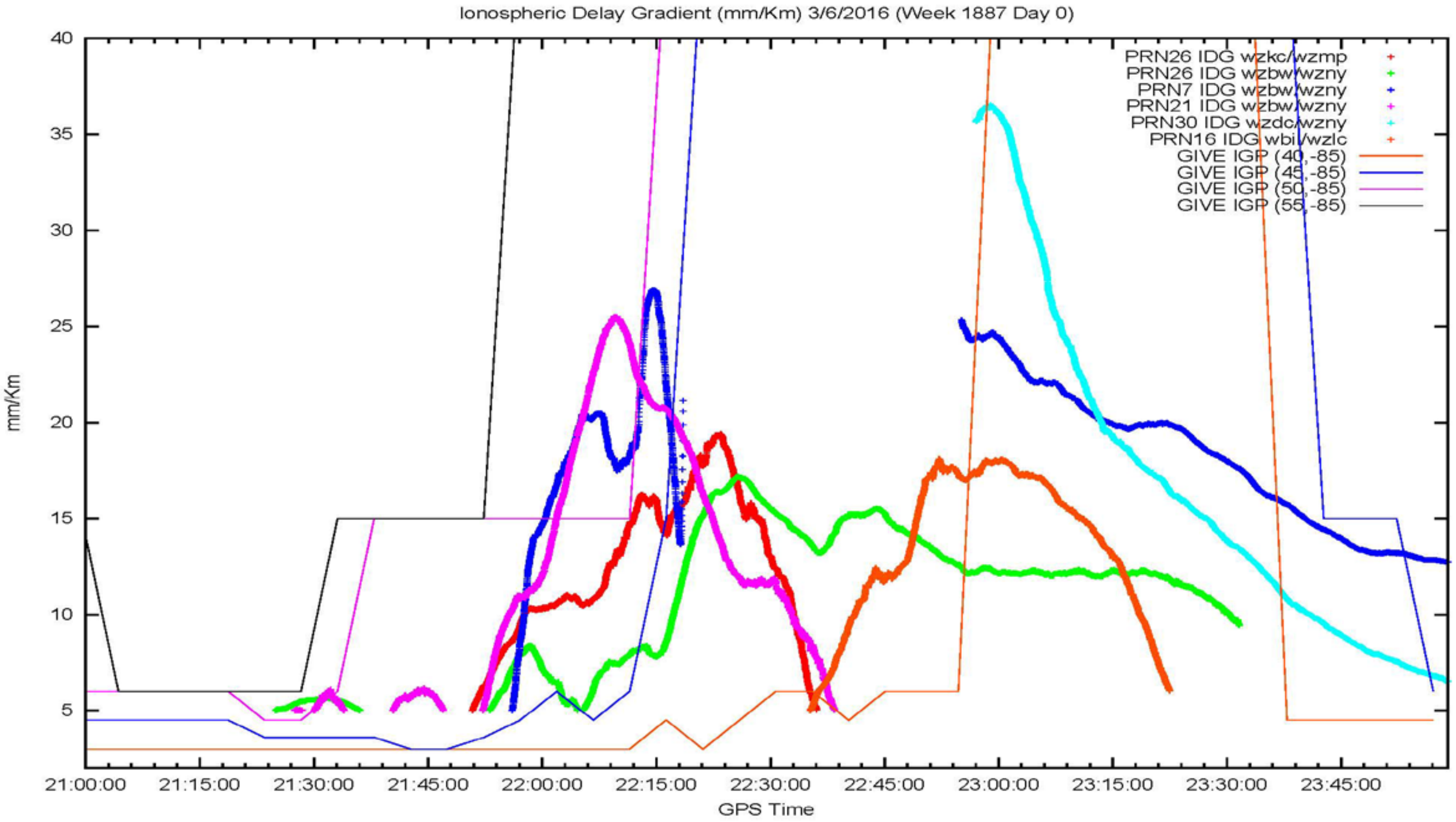
Ionospheric Delay Gradients Vs Time 6 & 7 March in CONUS and NE Canada with WAAS IGP GIVE (m)



Ionospheric Delay Gradients Vs Time 6 & 7 March in North America with WAAS IGP GIVE (m)



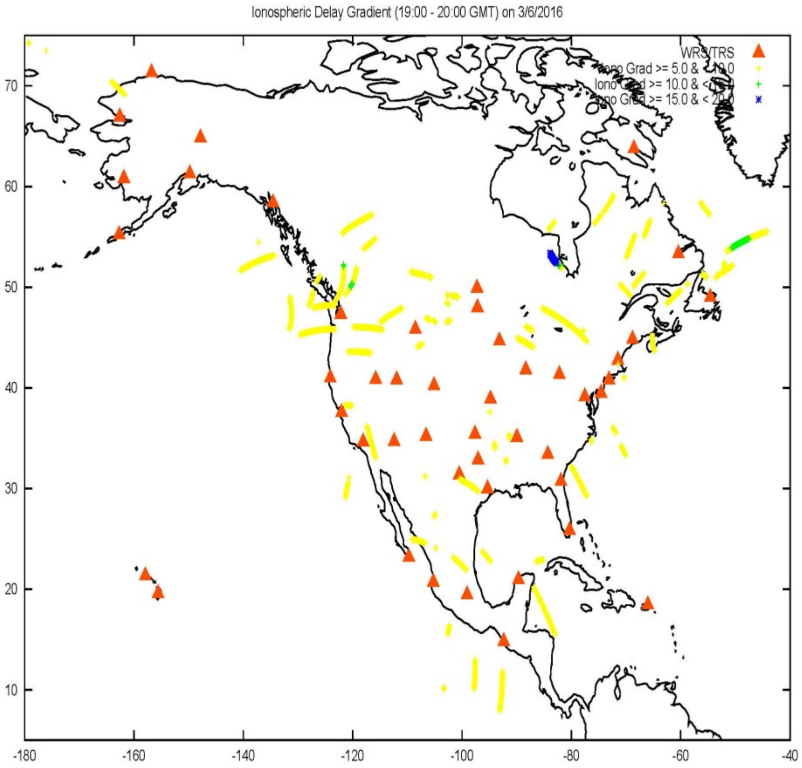
Maximum Ionospheric Delay Gradients Vs Time 6 March with WAAS IGP GIVE (m)

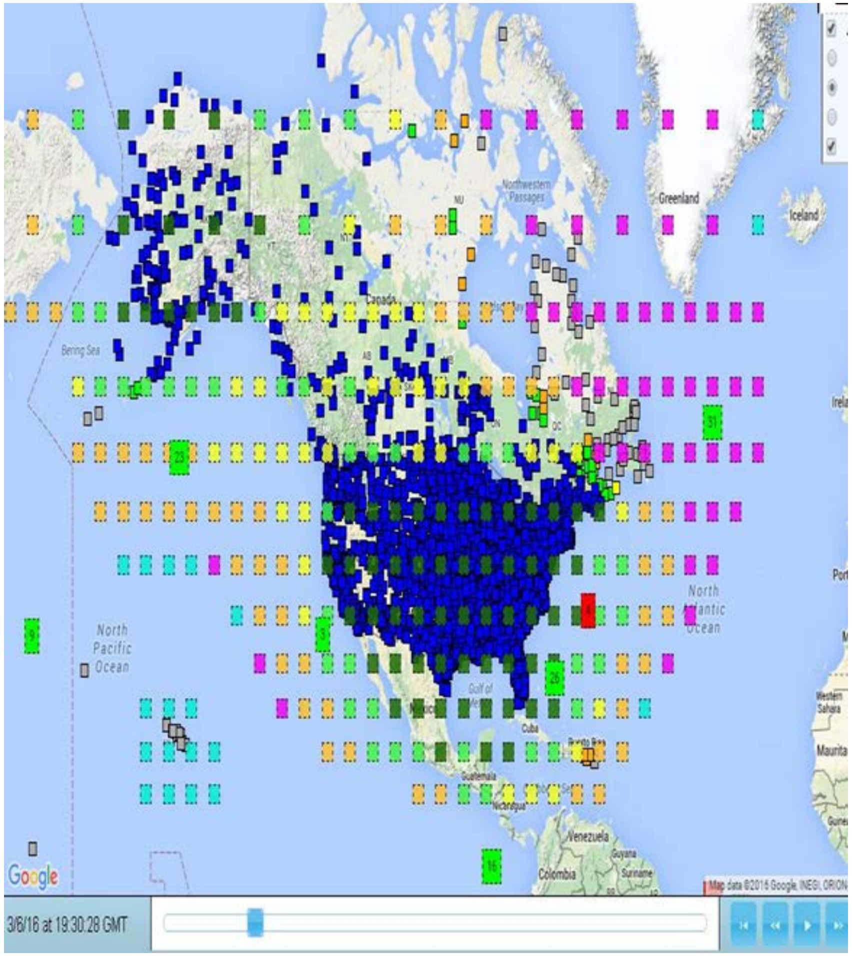


Ionospheric Delay Gradients and WAAS Service

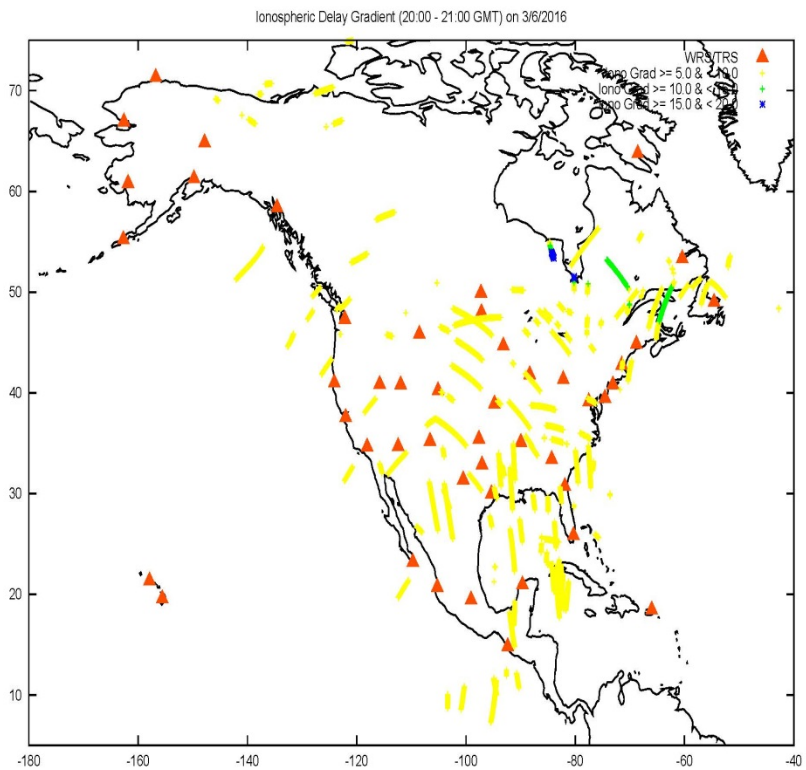
- The magnitude and location of each IDG is plotted geographically when the IDG >= 5 mm/Km and the satellite elevation >= 10 deg for each 60 min interval
- IDG Magnitude (mm/Km) Color Code on left graphic
  (Yellow >= 5 & < 10, Green >= 10 & < 15 , Blue >= 15 & < 20, Red > 20)
- WAAS Service state at airports (blue = LPV200, green = LPV, Gray = RNP 0.1) depicted with GPS satellites relative position appearing as green squares with PRN number inscribed within on right graphic
- IGPs depicted as large solid squares and color coded by GIVE index
  (Green <= 4.5 m, Yellow = 6m, Orange = 15m, Magenta = 45m [storm state])
- Prior to 22:00 IDGs with magnitude above 10 mm/Km were observed in NE Canada north 50 deg latitude and east of -85 deg longitude and IGP in that region were set to storm state and WAAS LPV service was lost in NE Canada
- After 22:00 many IDGs with magnitude above 10 mm/Km were observed in CONUS below 50 deg latitude, and in NE Alaska at 65 deg latitude and WAAS LPV service was lost in Northern CONUS, Canada, and Eastern Alaska

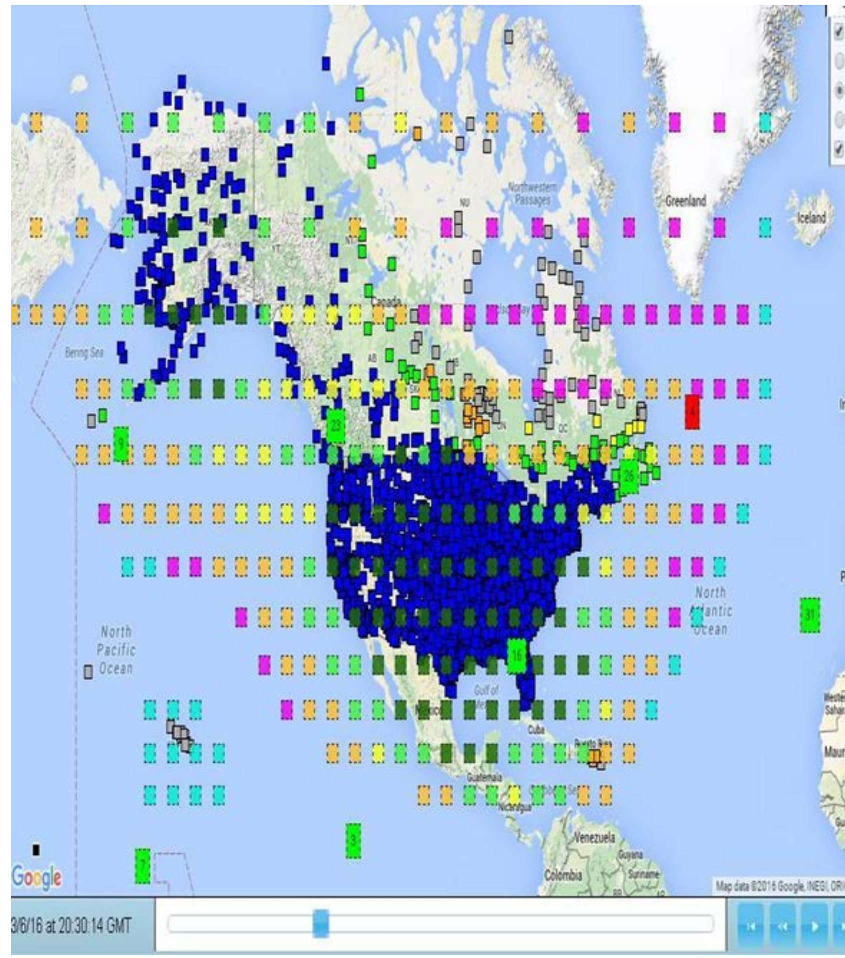
Ionospheric Delay Gradients (19:00 – 20:00 GMT) and WAAS Service at 19:30 GMT March 6



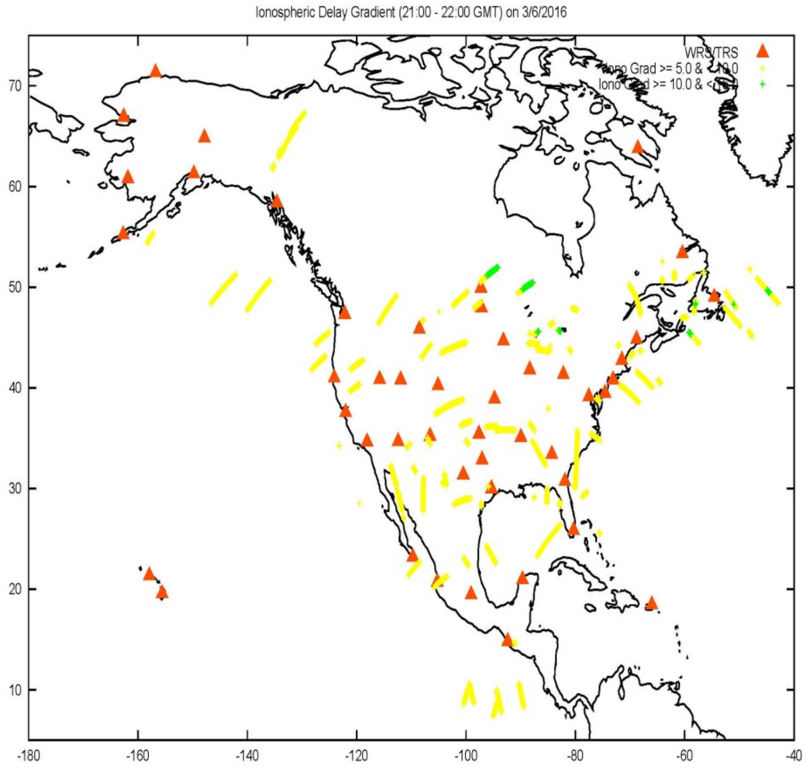


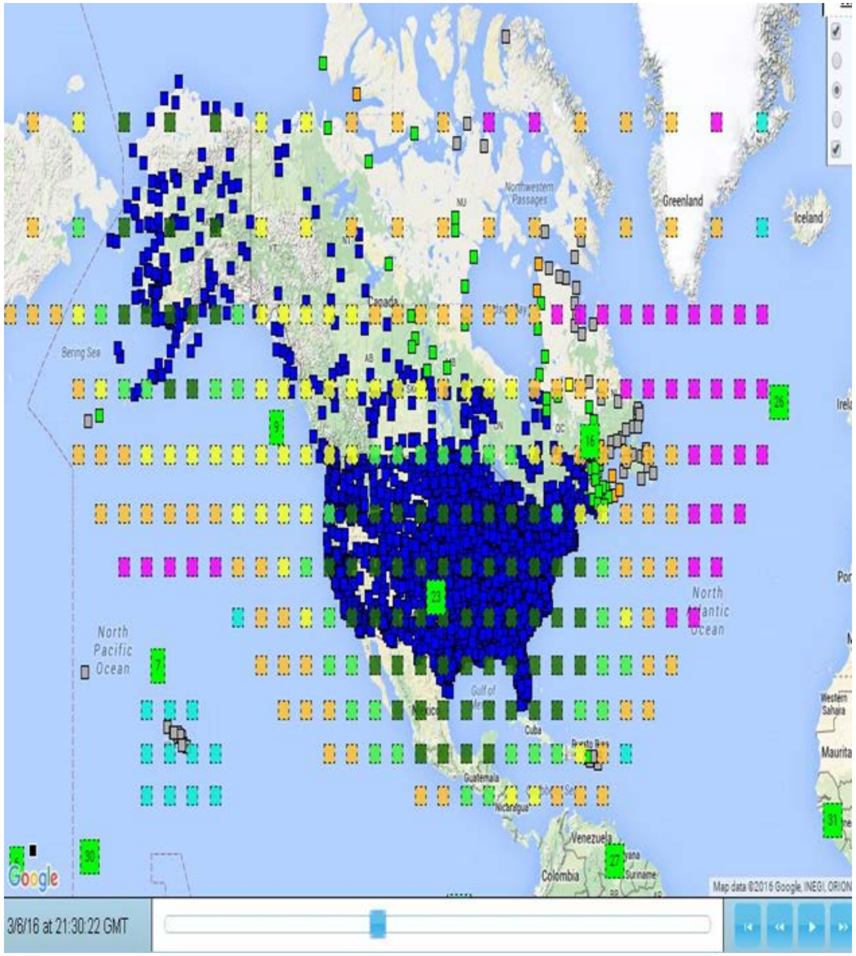
Ionospheric Delay Gradients (20:00 – 21:00 GMT) and WAAS Service at 21:30 GMT March 6



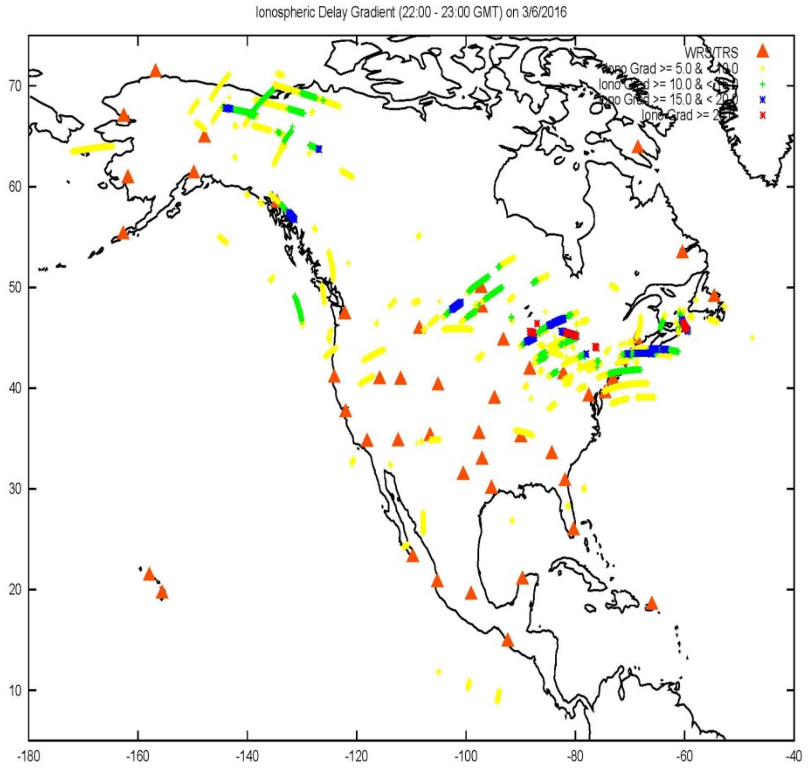


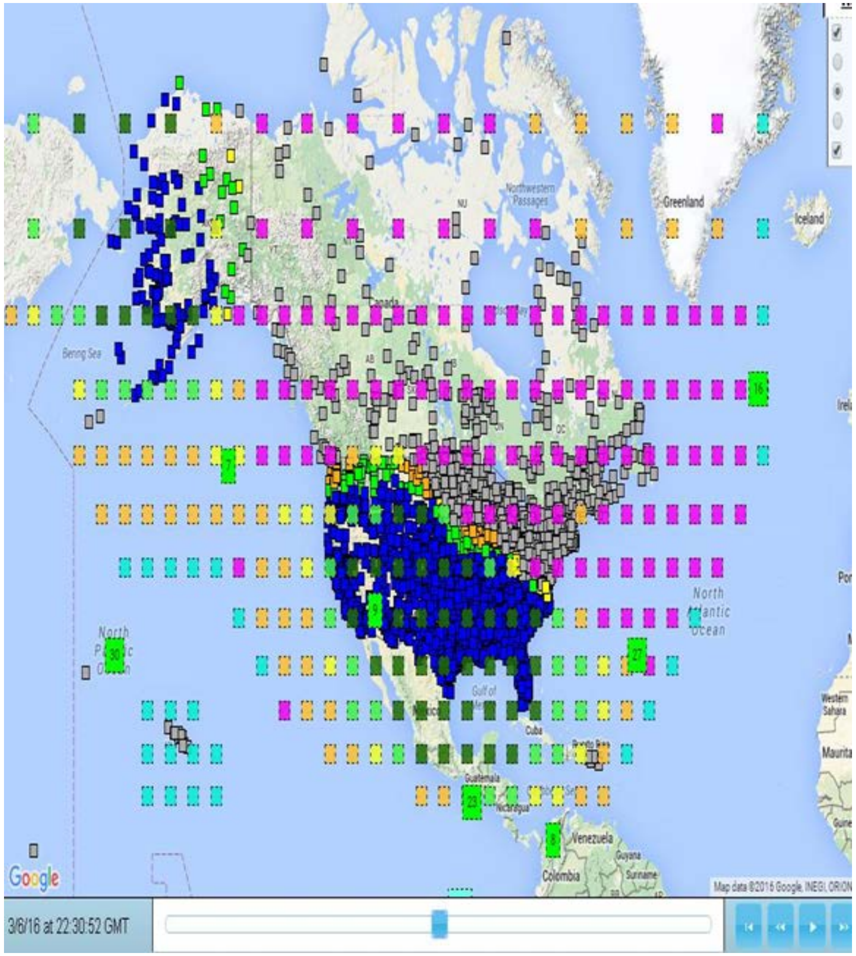
Ionospheric Delay Gradients (21:00 – 22:00 GMT) and WAAS Service at 21:30 GMT March 6



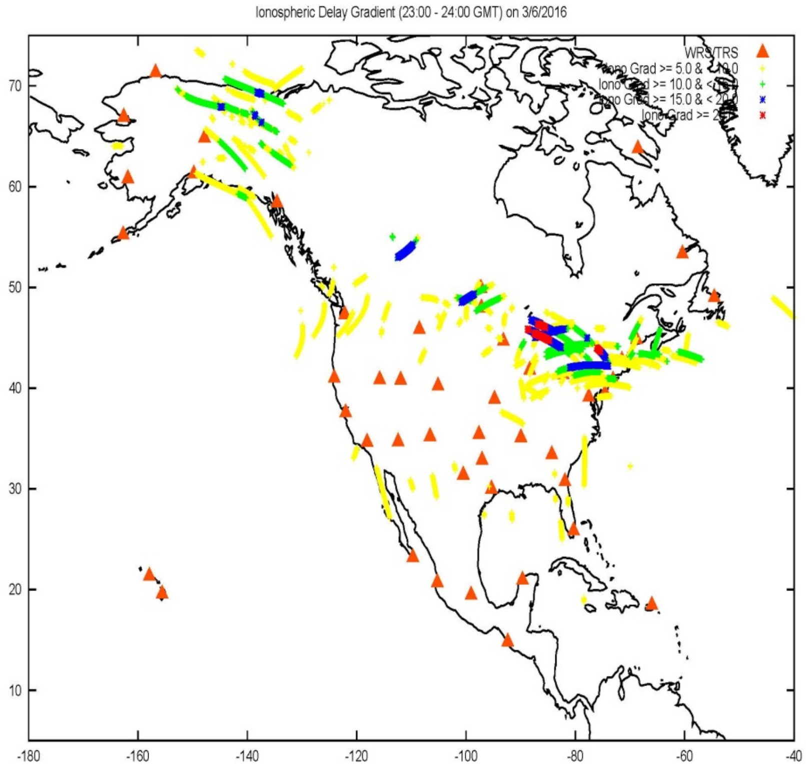


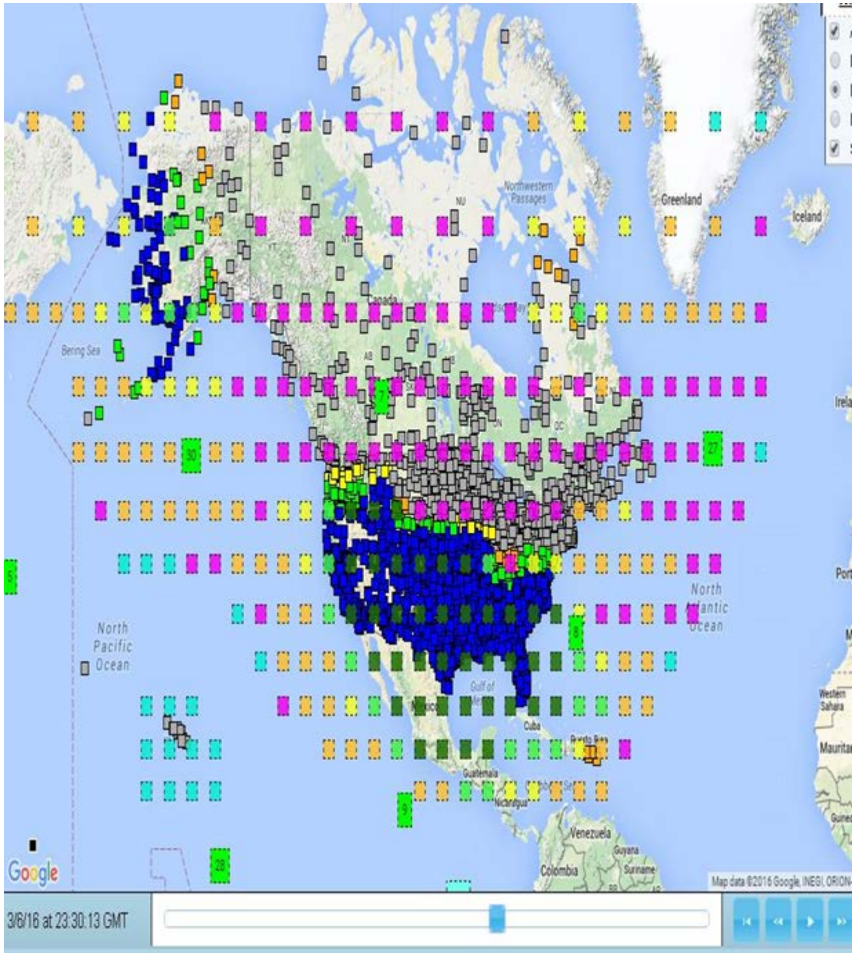
Ionospheric Delay Gradients (22:00 – 23:00 GMT) and WAAS Service at 22:30 GMT March 6



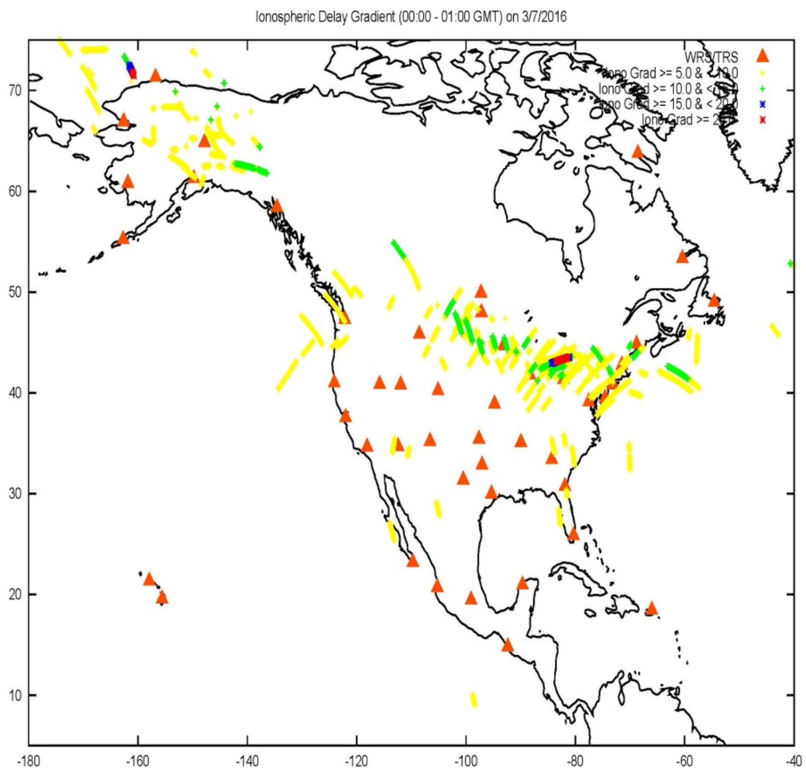


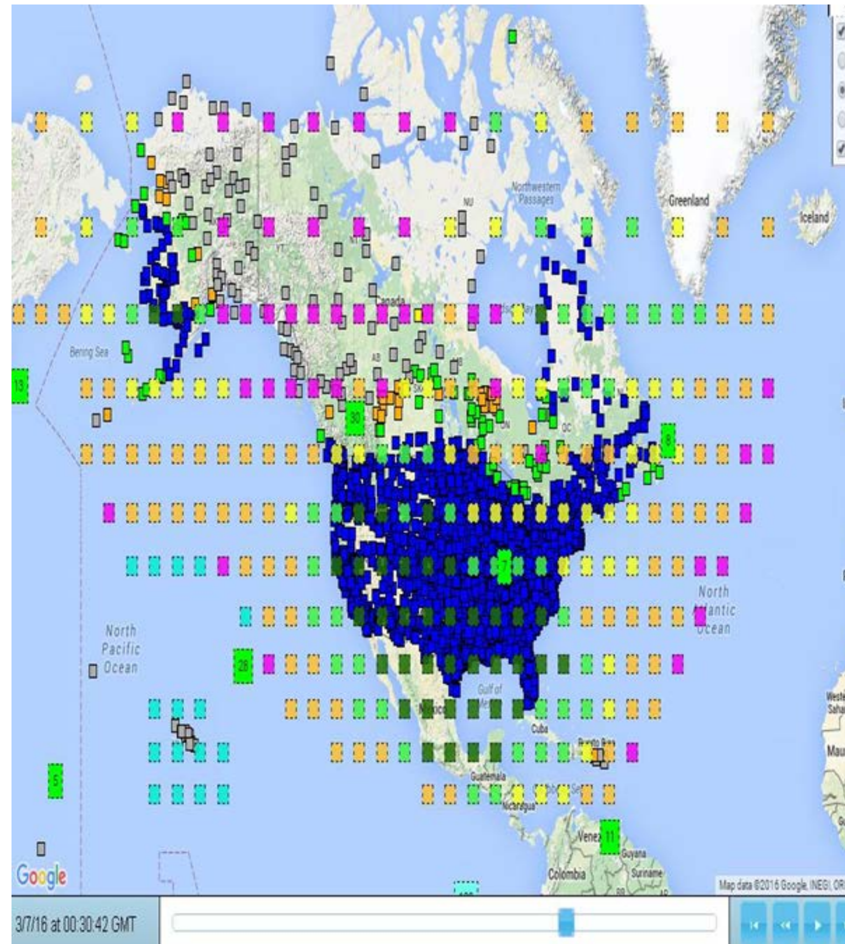
Ionospheric Delay Gradients (23:00 – 23:59 GMT) and WAAS Service at 23:30 GMT March 6



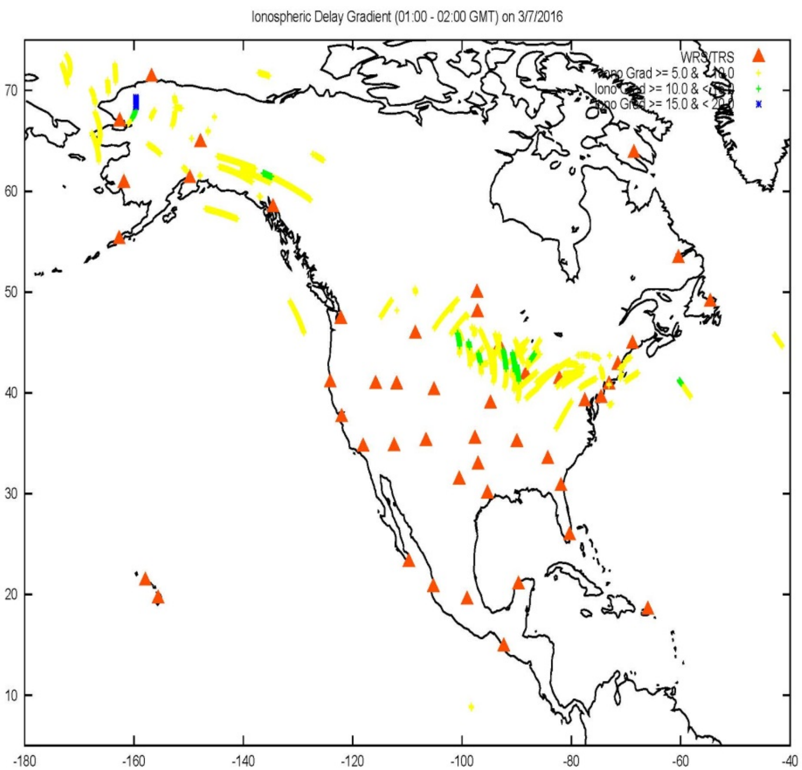


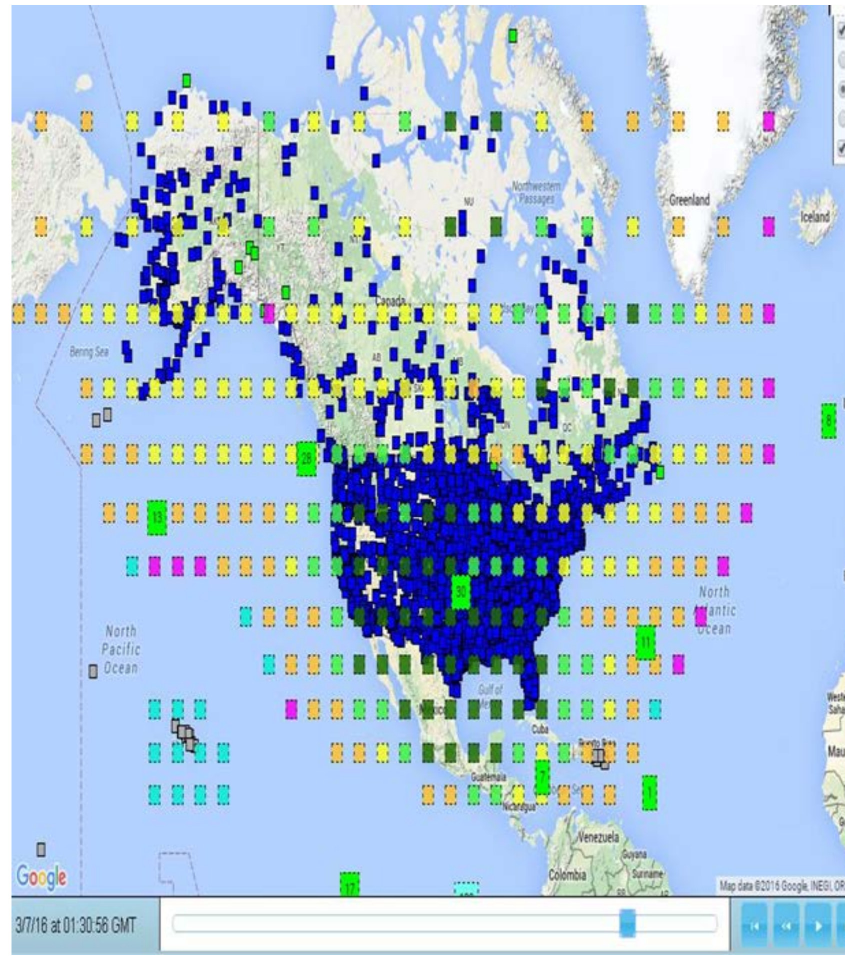
Ionospheric Delay Gradients (00:00 – 01:00 GMT) and WAAS Service at 00:30 GMT March 7





Ionospheric Delay Gradients (01:00 – 02:00 GMT) and WAAS Service at 01:30 GMT March 7

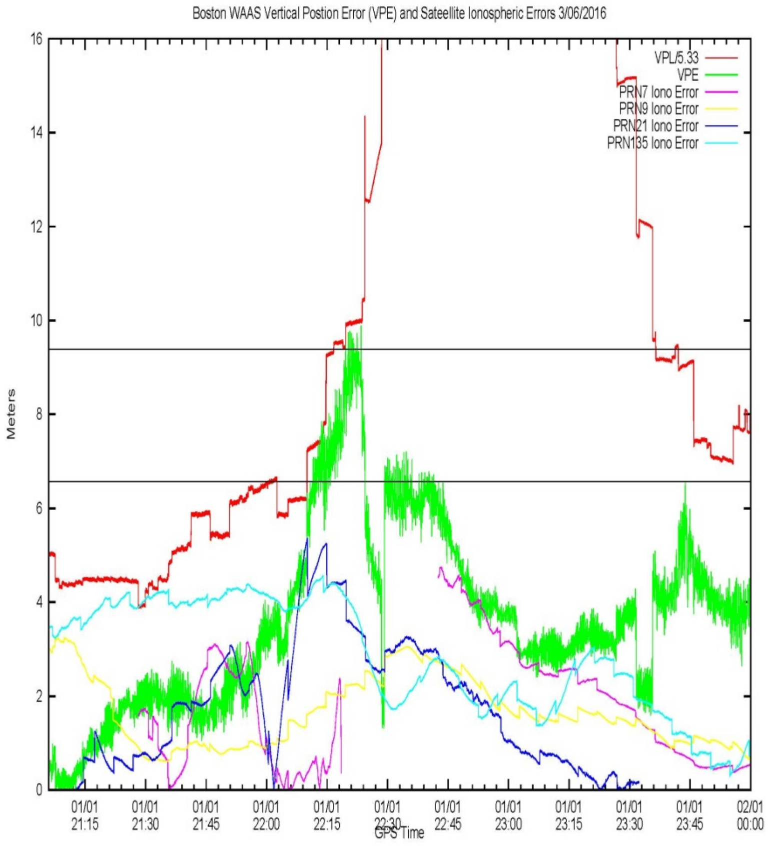


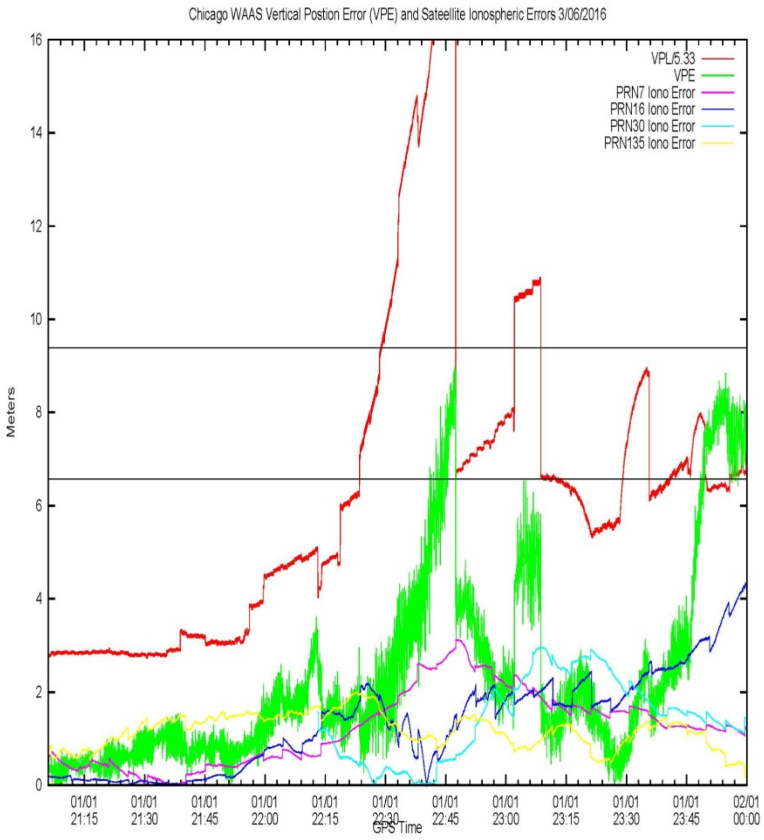


WAAS Vertical Position Error and WAAS ionospheric errors

- The WAAS service was available in CONUS on the GPS day roll over and IDGs over 10 mm/Km were observed in northern CONUS
- After 01:00 March 7 the number IDGs with magnitude above 10 mm/Km were observed to diminish and WAAS LPV service became available
- During the event WAAS LPV service was available south of 40 deg latitude and LPV service was lost north of 40 deg latitude
- The IDGs above 10 mm/Km were primarily located between 43 deg and 50 deg latitude in CONUS and when IDG increased above 15 mm/Km the IGPs in the vicinity and north were set to storm state
- WAAS ionopheric errors ranged from 2m - 4m before IGP were set to storm state in Eastern CONUS (Boston, NY) at 22:10
- WAAS WAAS ionopheric errors ranged from 2m - 4m in central CONUS (Chicago, Cleveland) after IGP GIVEs decreased from storm state at 23:43
- locations with increased position errors were in the region were many IDGs exceeded 15 mm/Km

WAAS Vertical Position Error & WAAS ionospheric errors at Boston & Chicago 6 March





Conclusion

- WAAS detected the Ionospheric activity which increased GIVES and then set IGPs to storm state in Northern CONUS, Alaska and Canada regions
- The WAAS Ionospheric errors were always bounded by the interpolated IGP GIVE values, however the increase in WAAS ionospheric errors from 0.5m to 4.0m at receivers in Northern CONUS were observed when LPV service was available
- WAAS vertical errors at receivers in Northern CONUS increased during Ionospheric activity on March 6 & 7 due to rapid changes in ionospheric propagation delays that could not be effectively modeled by WAAS broadcast corrections
- Analysis of ionospheric delay gradients (IDG) indicated disturbance in northern CONUS and Eastern Alaska that intensified between 21:30 March 6 and 01:30 March 7 , WAAS service was reduced in the area of higher IDGs
- Increase in VPE occurred while LPV service was available 10 minutes before and 20 minutes after the service outages at several receivers from Boston to Chicago, all positions error were bounded by protection levels