Wide Area Augmentation System

Offline Monitoring Quarterly Report #1

1 Jan 2011 – 31 March 2011

12 July 2011

Prepared for:

Federal Aviation Administration

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Executive Summary

The WAAS Operations Team (AJW-192) was tasked with monitoring the Wide Area Augmentation System (WAAS) to ensure that the integrity requirements defined in Section 3.3 of Algorithm Contribution to HMI (A014-011). This report contains data collected and analyzed between 1/1/11 and 3/31/11. Data is collected from the WAAS Network and stored at the WAAS Support Facility (WSF) at the Mike Monroney Aeronautical Center in Oklahoma City, OK.

The primary evidence that WAAS meets the top level system integrity requirements relies on a mathematical proof supported by a comprehensive analysis of empirical data. The foundation of the proof is built upon a set of carefully constructed assertions. Some assertions require periodic monitoring to ensure that the physical environment has not changed or degraded in a manner that would invalidate the claim. Certain satellite failure modes which have a priori probabilities associated with them must be detected and corrected in a reasonable amount of time to limit the user's exposure to the failure.

The following assertions are monitored as called for in the Algorithm Contribution to HMI document include:

1. Code-noise and Multipath
2. Code-carrier-incoherence (CCC)
3. Signal Quality Monitor (SQM)
4. Satellite Clock Runoff
5. Ionospheric Threats
6. Ephemeris Monitoring

Additional monitoring criteria have been added to the original list. These additional monitoring criteria include Wide-area Reference Station (WRS) antenna positions, L1L2 bias levels, missed WAAS User Messages, monitor trips, CNMP resets, accuracy, GEO CCC, and Space Weather. This report will also include major anomalies that occurred during the time period covered in this report.

Below is a summary of the criteria that were monitored for this report.

Integrity Monitoring	
Code-carrier-coherence (CCC)	None on GPS Satellites. 14 trips on GEOs (all on CRE)
Code-noise and multipath (CNMP)	All data bounded
Signal-quality monitoring (SQM)	2 trips on March 4th
Satellite clock run-off	None
Ionospheric threat model	4 days of interest (Feb. 18th, March 1st, March 10th and 11th)
Continuity Monitoring	
Missed messages	83775 on CRW, 18 on CRE and 10725 on AMR
External Monitoring	
Antenna Positioning	All sites within 5 cm.
Anomaly Investigations	
AMR SIS outage	7 min SIS outage on Jan 18th
CRW SIS outage	61 min SIS outage on March 24th and 25th

The SQM Trips occurred on two Geosynchronous Satellites (CRW and CRE). These trips occurred while CRW as passing CRE. The satellites were very close (~.025 degrees) when the trips occurred. The root cause of this event is still under investigation.

Forward

The scope of this document is limited to analysis performed on data extracted from the WAAS system, or on data that would directly affect the WAAS system. Moreover, the target audience is the FAA WAAS management as well as the engineers that support the WAAS program. This includes (but is not necessarily limited to) federally employed personnel, contractors, sub-contractors, and other FAA WIPP support.

The data and information contained in this document is not for general use, as it may contain unexplained anomalies and/or data which may lead to unsupported conclusions. Any dissemination of this data should be coordinated with the appropriate management.

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1 Introduction

1.1 The definition of offline monitoring

The goal of Offline monitoring is to track the performance of WAAS, establish baseline performance and highlight anomalous behavior, potentially for further investigation.

1.2 Elements of system monitoring

The monitoring types addressed in this document can be categorized into five types, namely Integrity, Availability, Continuity, Accuracy and External Monitoring. Each of these represents a class of performance that the system exhibits. The goal of this document is to offer a short, up front section for several checks of each of the above types with condensed plots that show at a glance quarterly performance. Each monitoring subsection has a brief description of the relevant figures and tables along with a pointer to a section in appendix A, which contains more detailed (and more numerous) figures and tables. The five types of monitoring are described below.

1.2.1 Integrity

Integrity monitoring may be the most important type, as a breach of this class of performance represents a potentially hazardous situation. Loss of Integrity happens when an error in a user's position exceeds the protection limits that he computes. There are several monitors in WAAS which internally monitor that these error bounds represent an over-bound of the generated errors. Each monitor has a slightly different style of ensuring integrity, and the individual monitor integrity methodology is described in their monitor subsections.

1.1.1 Availability

Availability Monitoring is as simple as looking at the coverage of WAAS over the time period in question. There are specifics to be defined for this type, namely the Alarm Limits (Vertical and Horizontal) as well as the coverage contour.

1.1.2 Continuity

Continuity monitoring refers to anything which can cause a loss of availability, but not a breach of integrity. Typically, this looks at monitor tripping performance, setting satellites unusable (for one reason or another) or loss of data due to hardware issues.

1.1.3 Accuracy

Accuracy Monitoring refers to the ability of the WAAS corrections to provide an accurate estimate of the user's position.

1.1.4 External Monitoring

External monitoring monitors anything external to the WAAS system. This includes broadcasted ephemerides, plate-tectonic movement (antenna positions), space weather, etc.

2 Integrity Monitoring

2.1 Code-noise and multipath (CNMP)

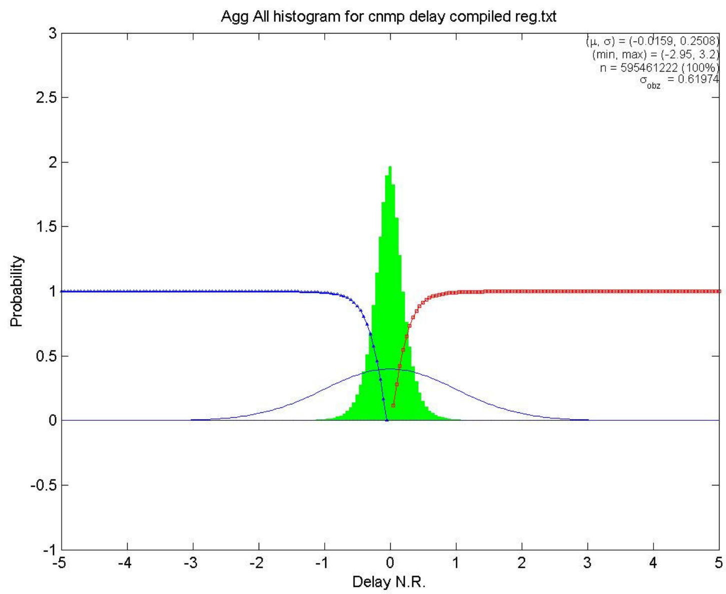


Figure 2.1-1 Aggregate CNMP Delay

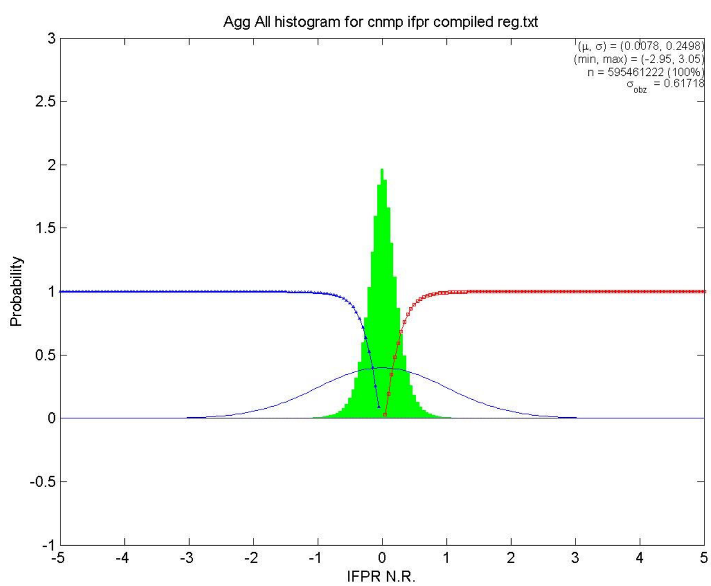


Figure 2.1-2 Aggregate CNMP IFPR

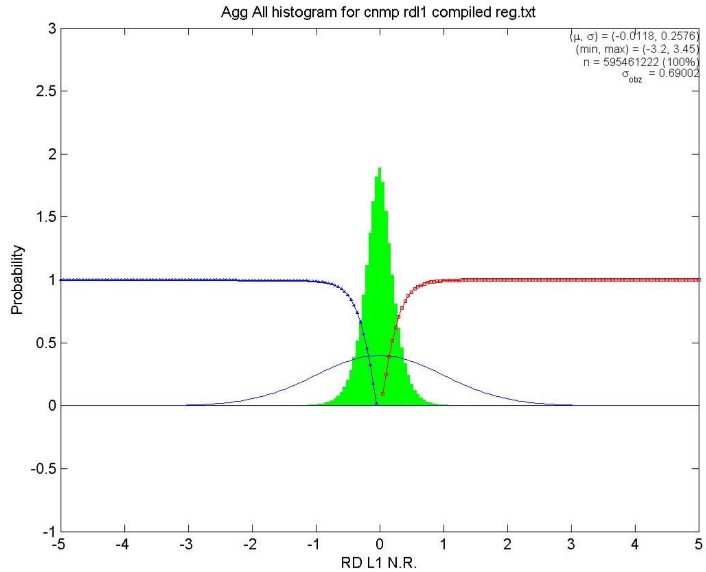


Figure 2.1-3 Aggregate CNMP RDL1

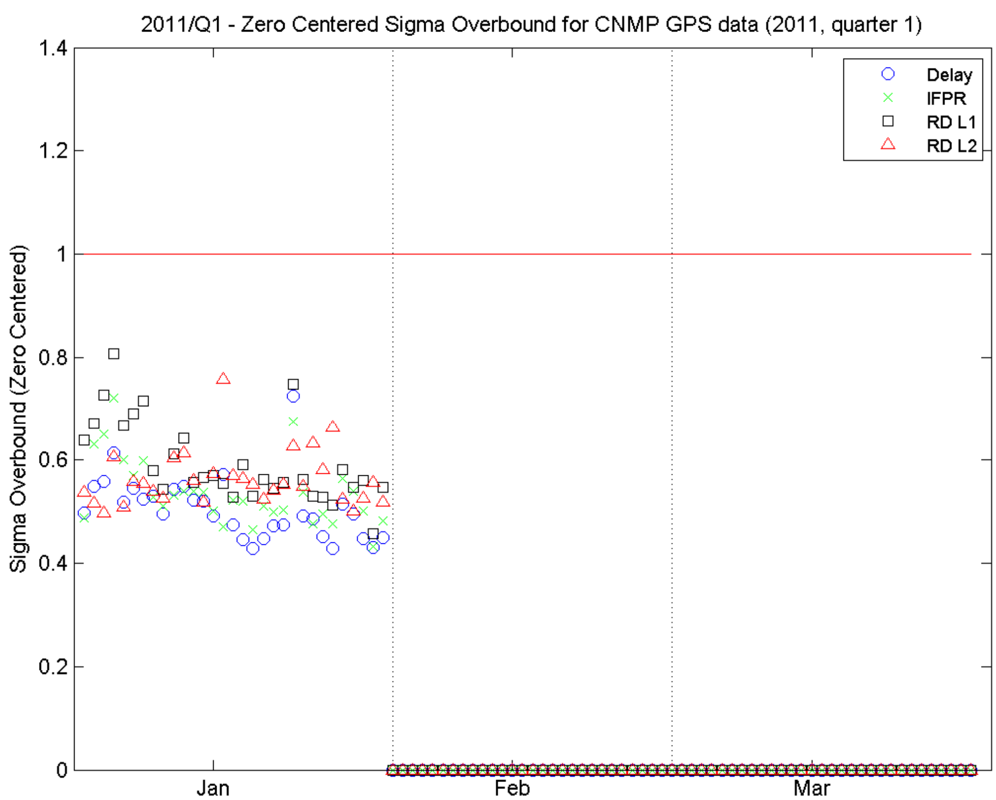


Figure 2.1-4 GPS CNMP RDL1 sigma overbound values

2.2 Code-carrier-incoherence (CCC)

Anik, Galaxy 15 and all GPS satellites are monitored for CCC trips for Q1 2011.

AMR is not currently monitored (not used as ranging source, UDRE floor=50m)

For WIPP presented material, prototype was ran on all days from Q1.

All CCC monitor trips are investigated whenever a trip occurs to determine source of trip

Minimum data sources used in correlation and analysis:

- CCC test statistic
- UDRE threshold value
- CMCI measurements from NETS SQA
- WAAS Iono calculation
- L1/L5 Iono GUST calculation
- published planetary K_p and A_p values
- Chi^2 values

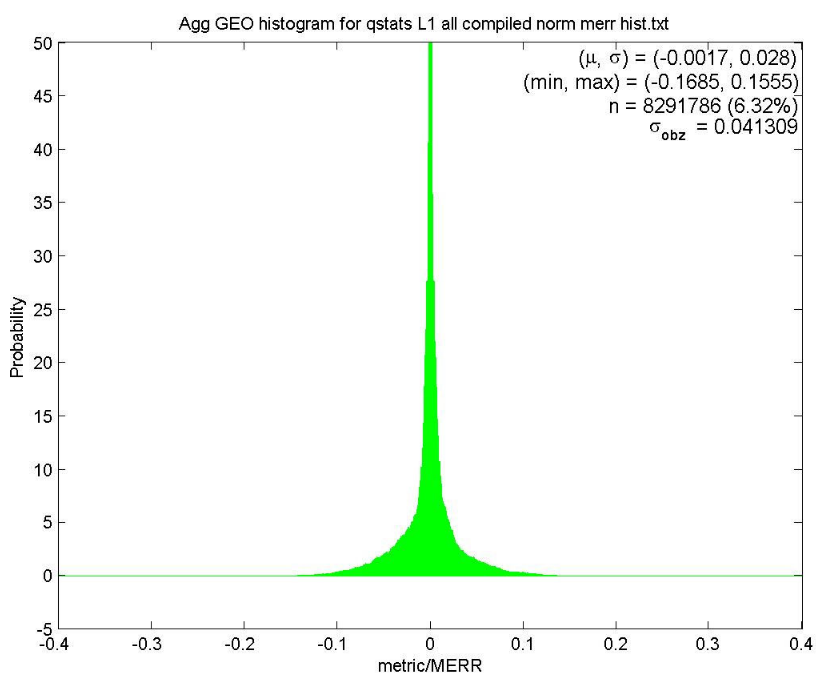


Figure 2.2-1 CCC GEO aggregrate plot for L1

2.3 Signal-quality monitoring (SQM)

All SQM GPS metrics pass. There was an SQM trip on 2011-03-04 during the CRW fly-by crossing the path of CRE. The SQM value during the fly-by was periodic in nature.

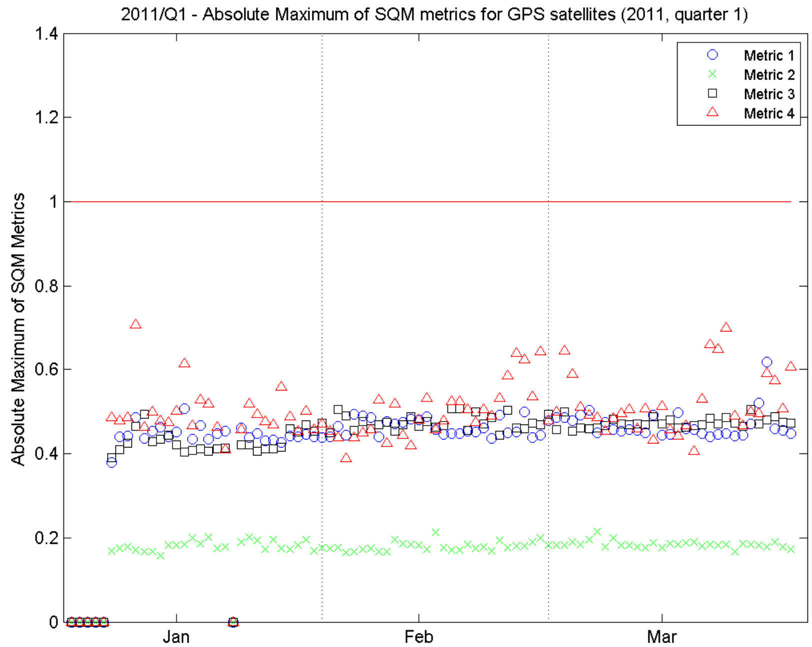


Figure 2.3-1 SQM GPS metrics 1 through 4

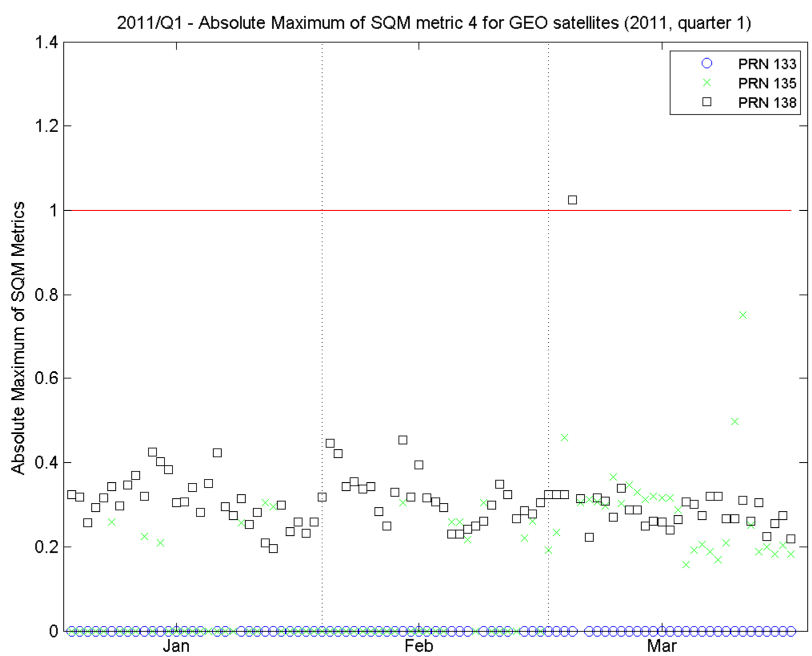


Figure 2.3-2 SQM GEO metric 4 for all 3 GEOs

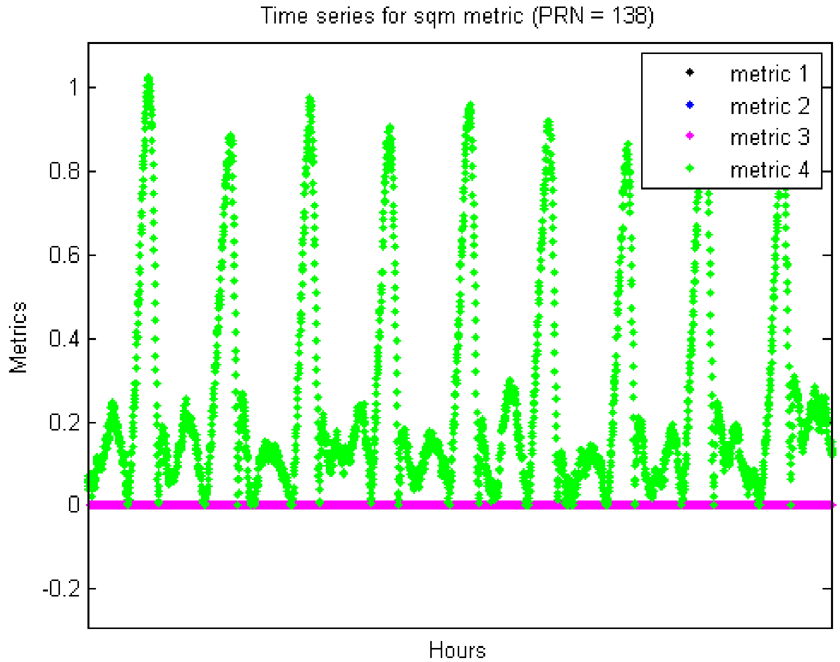


Figure 2.3-3 SQM time series for PRN 138 during trip

2.4 Satellite clock run-off analysis

2.5 Ionospheric Threat Model

2.5.1 Daily percentage of GIVE Chi^2 values > 1

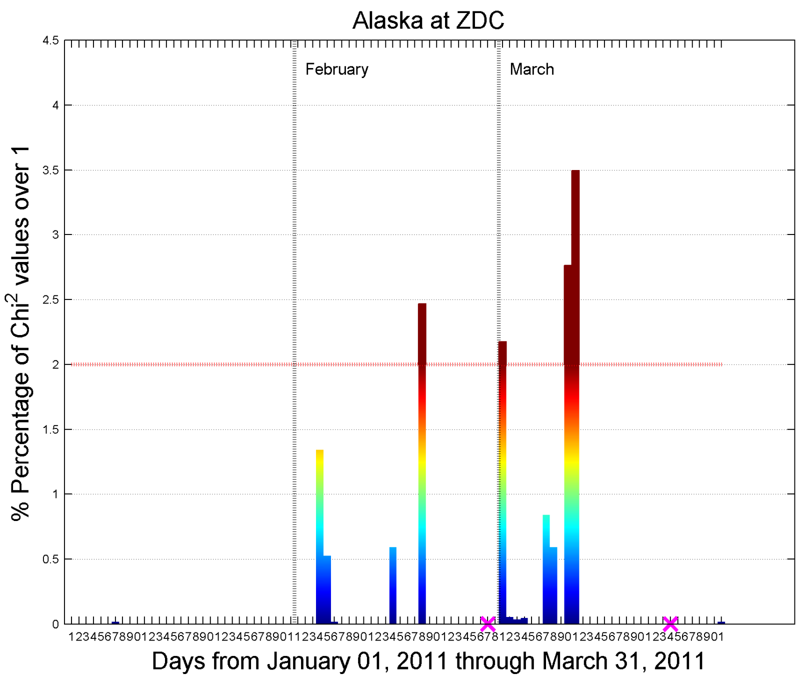


Figure 2.5-1 GIVE Chi^2 trips for Alaska Q1 2011 ZDC

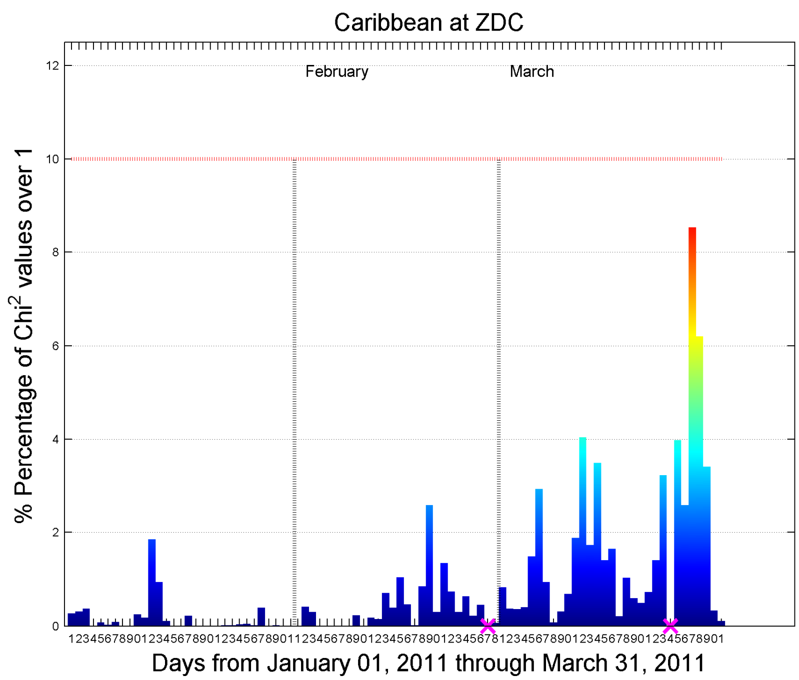


Figure 2.5-2 GIVE Chi^2 trips for the Caribbean Q1 2011 ZDC

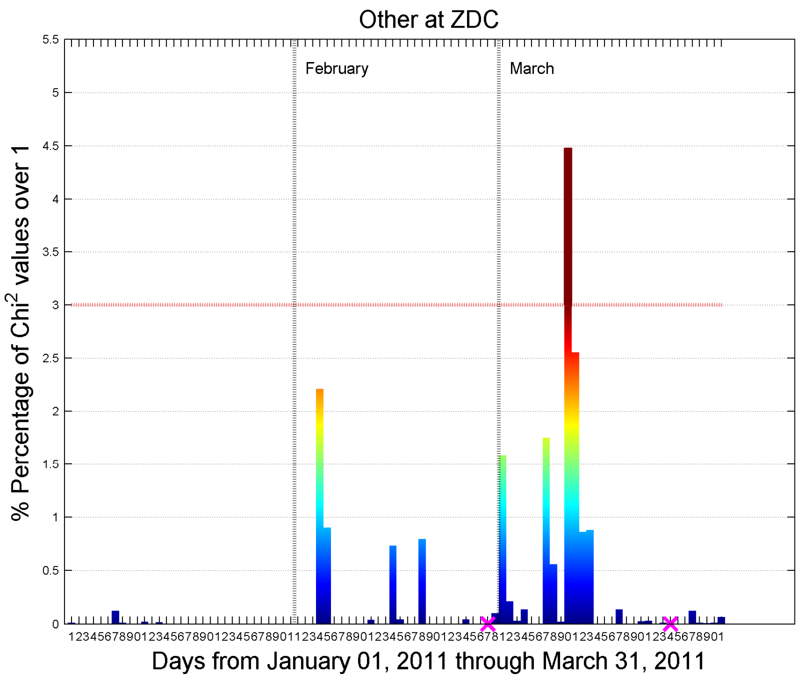


Figure 2.5-3 GIVE Chi^2 trips for Other region Q1 2011 ZDC

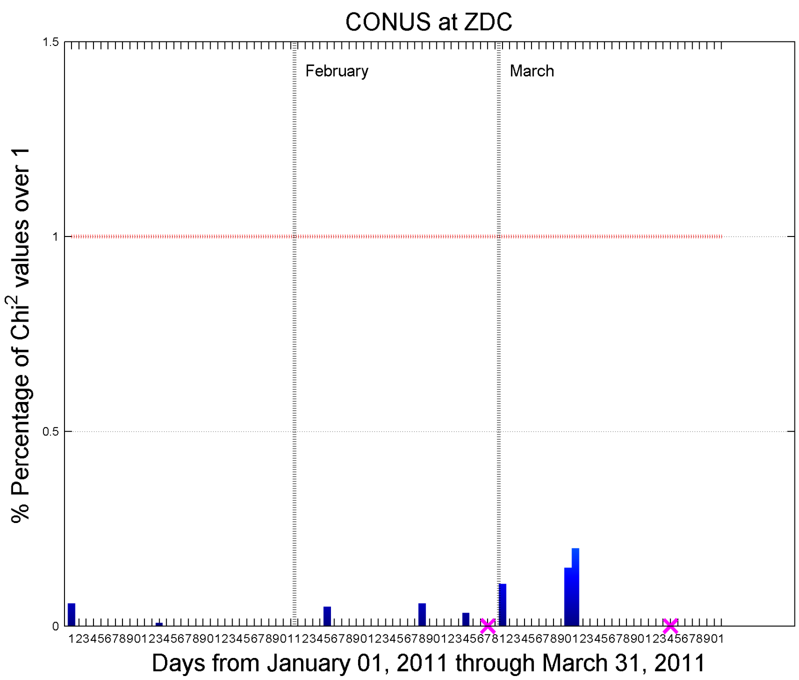


Figure 2.5-4 GIVE Chi^2 trips for CONUS Q1 2011 ZDC

2.5.2 Days of Interest

Table 2.5.2-1 Threat Model Days of Interest

	Region (threshold %)			
Date of Trip	Alaska (2%)	Caribbean (10%)	Other (3%)	CONUS (1%)
2/18/2011	2.40%			
3/1/2011	2.08%			
3/10/2011	2.58%		4.50%	
3/11/2011	3.56%			

2.6 L1L2 Bias Levels

See supplemental material section.

3 Availability Monitoring

3.1 Service Volume Model

3.2 System monitoring trips

Table 2.5.2-1 Reported Monitor trips for Q1 2011

Monitor Trips	ZDC	ZLA	ZTL
BMV	0	0	0
CCC	6	33	36
L1L2	19	17	18
RDM (Threshold)	0	0	0
SQM	2	2	2
UPM	0	0	0
WNT	0	0	0
WRE_BIAS	1	1	1

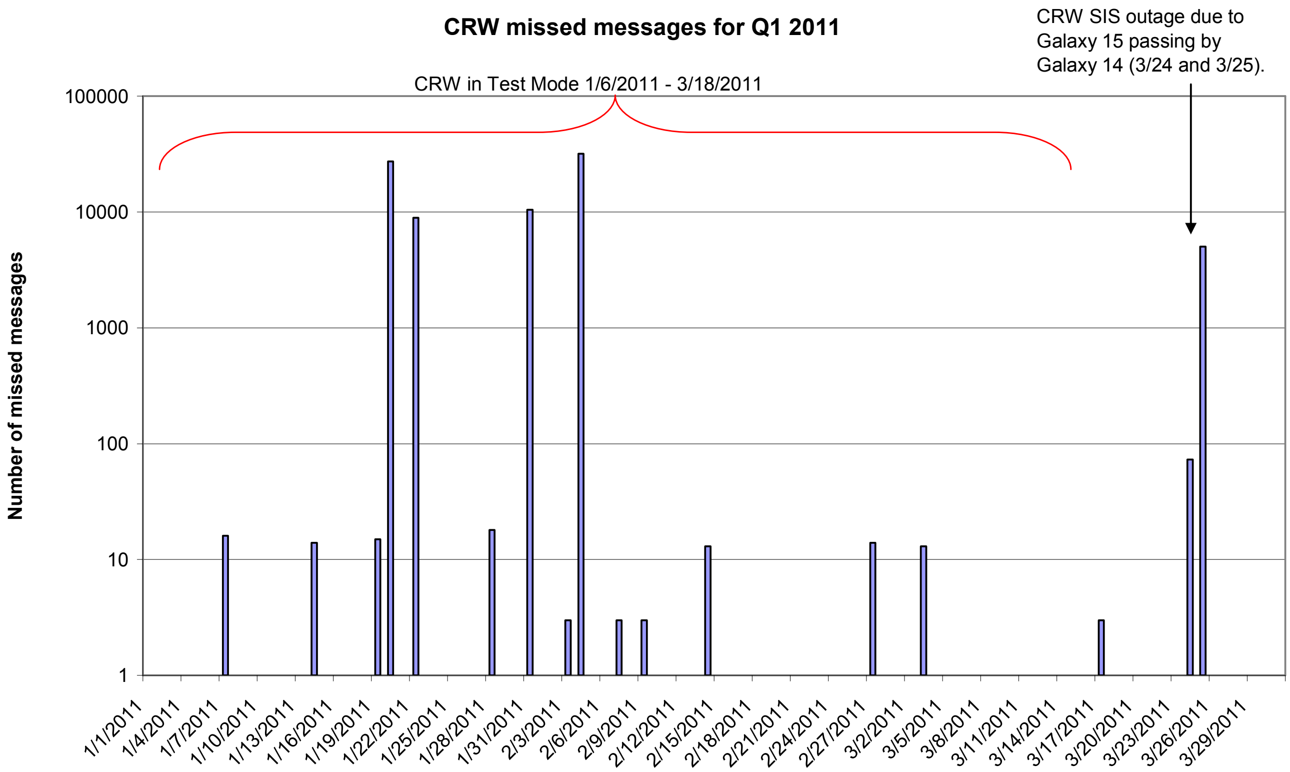
Table 2.5.2-2 Reported CCC Trips for Q1 2011

UTC Time	PRN		C&V	
2011-01-13 01:25:10	138	ZDC		
2011-01-18 18:24:00	138		ZLA	ZTL
2011-01-18 18:35:50	138		ZLA	ZTL
2011-02-02 16:40:58	138		ZLA	ZTL
2011-02-02 22:18:47	138	ZDC	ZLA	ZTL
2011-02-04 16:23:26	138		ZLA	ZTL
2011-02-04 17:53:30	138		ZLA	ZTL
2011-02-06 21:34:39	138		ZLA	ZTL
2011-02-10 05:01:59	138		ZLA	ZTL
2011-02-10 05:19:45	138		ZLA	ZTL
2011-02-13 05:20:37	138		ZLA	ZTL
2011-02-13 05:50:02	138		ZLA	ZTL
2011-03-02 08:02:27	138			ZTL
2011-03-02 16:37:21	138			ZTL

4 Continuity Monitoring

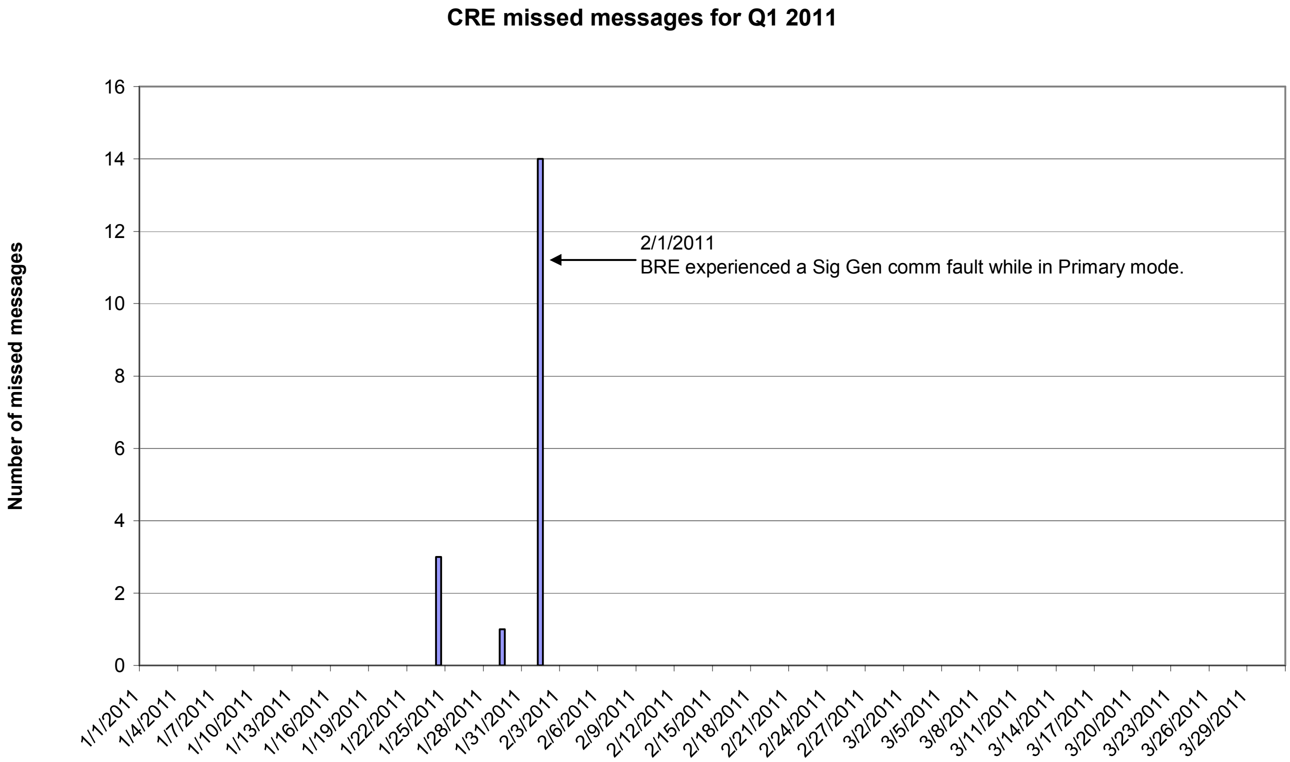
4.1 List of missed messages

The following histograms depict the missed messages categorized by GEO.



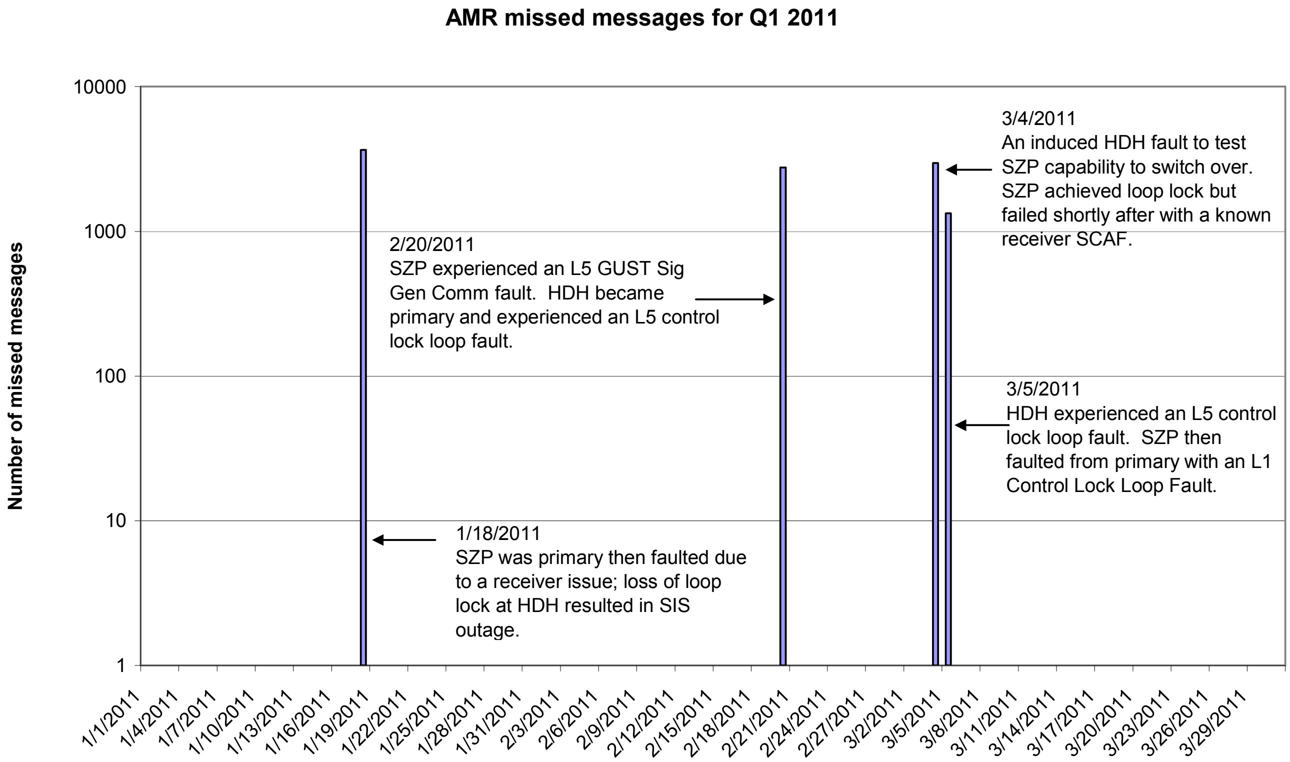
	1/3/11	1/7/11	1/14/11	1/18/11	1/19/11	1/20/11	1/21/11	1/22/11	1/24/11	1/28/11	1/29/11	1/31/11	2/1/11	2/3/11	2/4/11	2/7/11	2/9/11	2/14/11	2/17/11	2/20/11	2/27/11	3/3/11	3/4/11	3/5/11	3/7/11	3/17/11	3/24/11	3/25/11
CRW		16	14		15	27317	1	8929		18		10416		3	31891	3	3	13			14	13			1	3	73	5032

Figure 3.1-1 CRW missed messages Q1 2011



	1/3/11	1/7/11	1/14/11	1/18/11	1/19/11	1/20/11	1/21/11	1/22/11	1/24/11	1/28/11	1/29/11	1/31/11	2/1/11	2/3/11	2/4/11	2/7/11	2/9/11	2/14/11	2/17/11	2/20/11	2/27/11	3/3/11	3/4/11	3/5/11	3/7/11	3/17/11	3/24/11	3/25/11
CRE									3		1		14															

Figure 3.1-2 CRE missed messages Q1 2011



	1/3/11	1/7/11	1/14/11	1/18/11	1/19/11	1/20/11	1/21/11	1/22/11	1/24/11	1/28/11	1/29/11	1/31/11	2/1/11	2/3/11	2/4/11	2/7/11	2/9/11	2/14/11	2/17/11	2/20/11	2/27/11	3/3/11	3/4/11	3/5/11	3/7/11	3/17/11	3/24/11	3/25/11
AMR	1			3663															1	2756			2967	1337				

Figure 3.1-3 AMR missed messages Q1 2011

4.2 CNMP resets

4.3 CCC aggregate plots

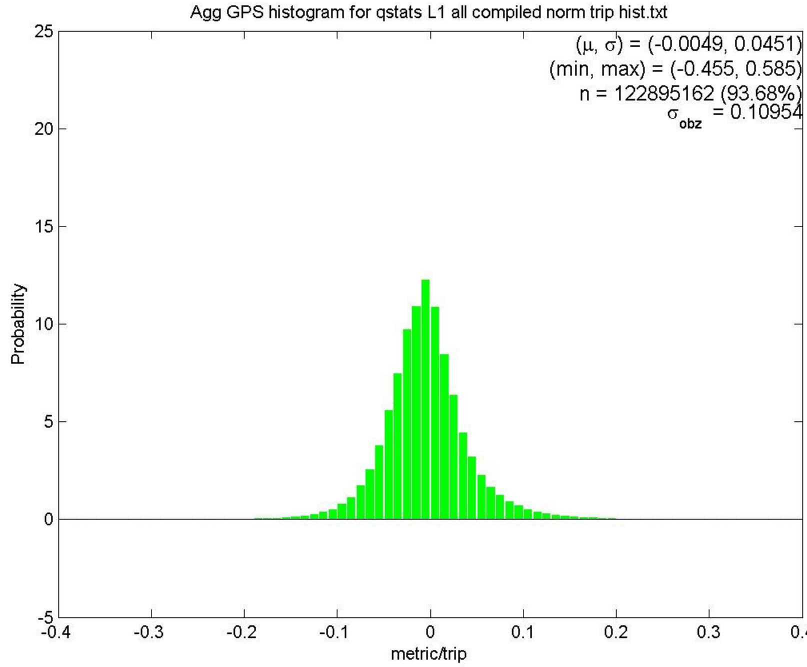


Figure 4.3-1 CCC GPS aggregate for L1

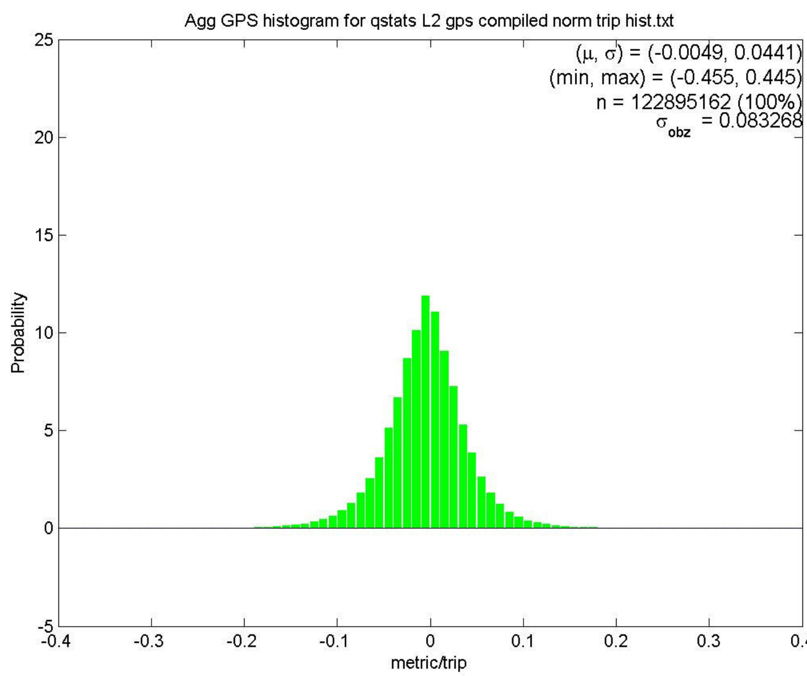


Figure 4.3-2 CCC GPS aggregate for L2

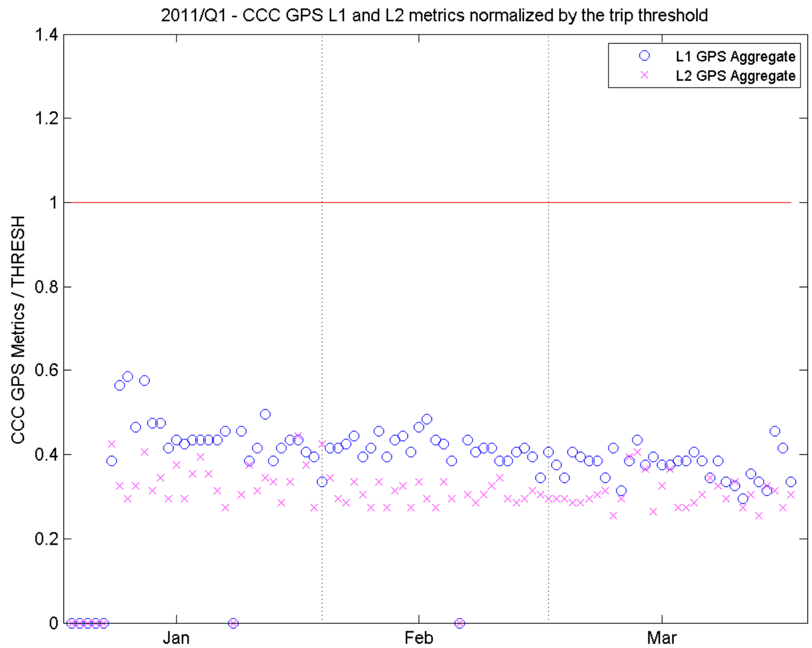


Figure 4.3-3 CCC GPS quarterly plot

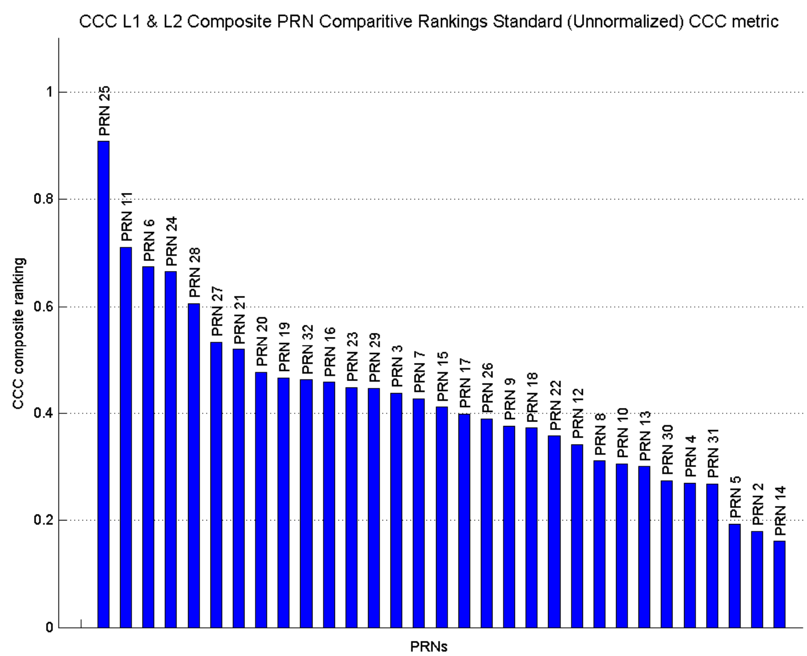


Figure 4.3-4 CCC GPS L1 L2 ranking plot

5 Accuracy Monitoring

To be added in a future revision.

6 External Monitoring

6.1 Antenna positioning

Results against CSRS-PPP indicate that all sites are less than 5 cm.

Results against WFO-R2 indicate that all sites are less than 5 cm.

6.2 Ephemerides monitoring

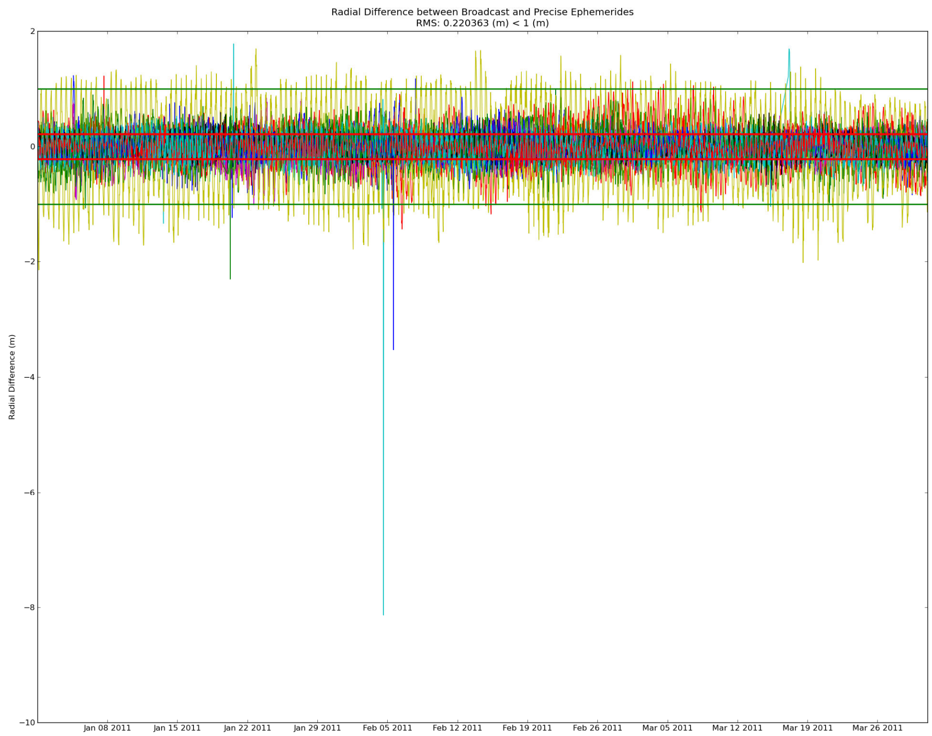


Figure 6.2-1Radial ephemeris

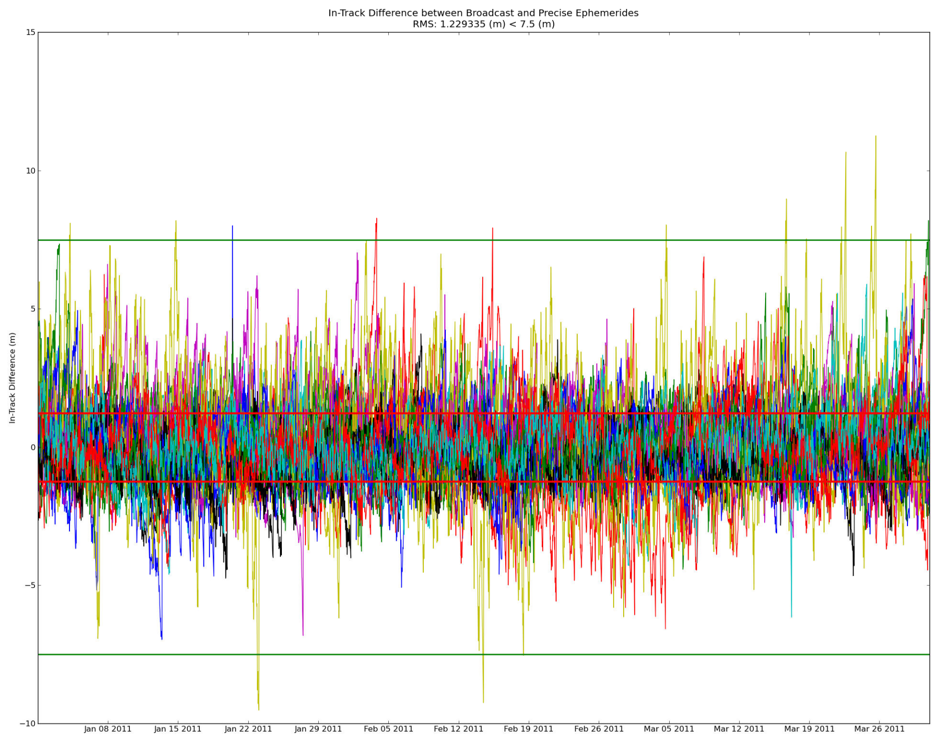


Figure 6.2-2 In-track ephemeris

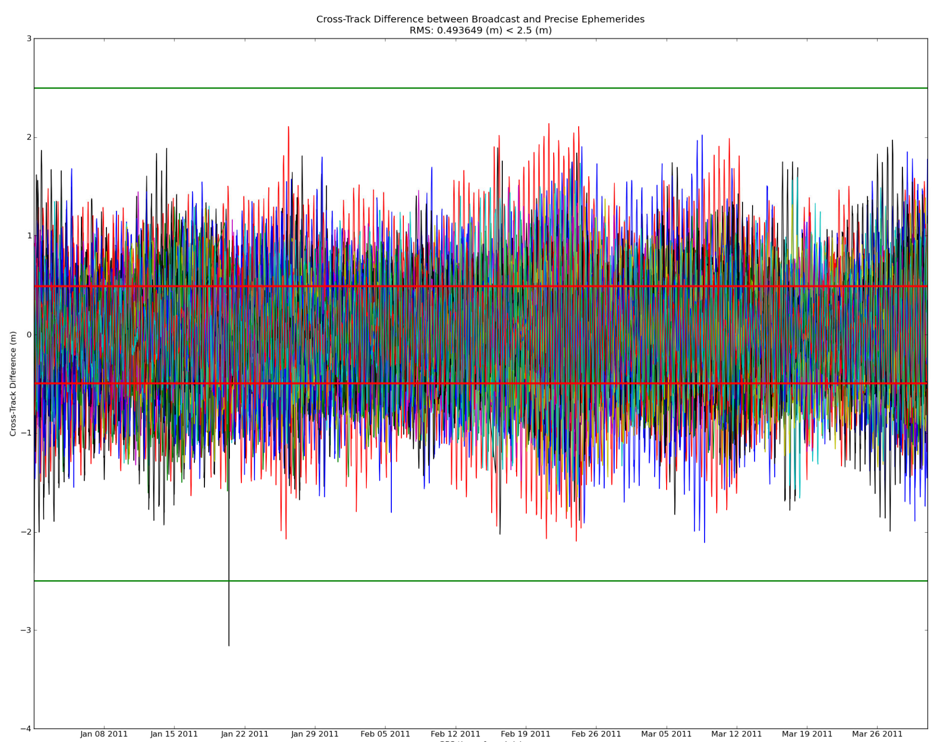


Figure 6.2-3 Cross-track ephemeris

Table 2.5.2-1 RIC outliers

PRN	R	I	C
1	0	0	0
2	0	0	0
3	24	3	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	2	1	0
9	4	4	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	9	0	0
16	0	0	0

PRN	R	I	C
17	0	12	0
18	0	0	0
19	0	0	0
20	0	0	0
21	0	0	1
22	0	0	0
23	0	0	0
24	15	0	0
25	23	0	0
26	2	0	0
27	1537	86	0
28	0	0	0
29	3	0	0
30	4	0	0
31	0	0	0
32	0	0	0

6.3 Space Weather monitoring

6.3.1 Daily A-indices

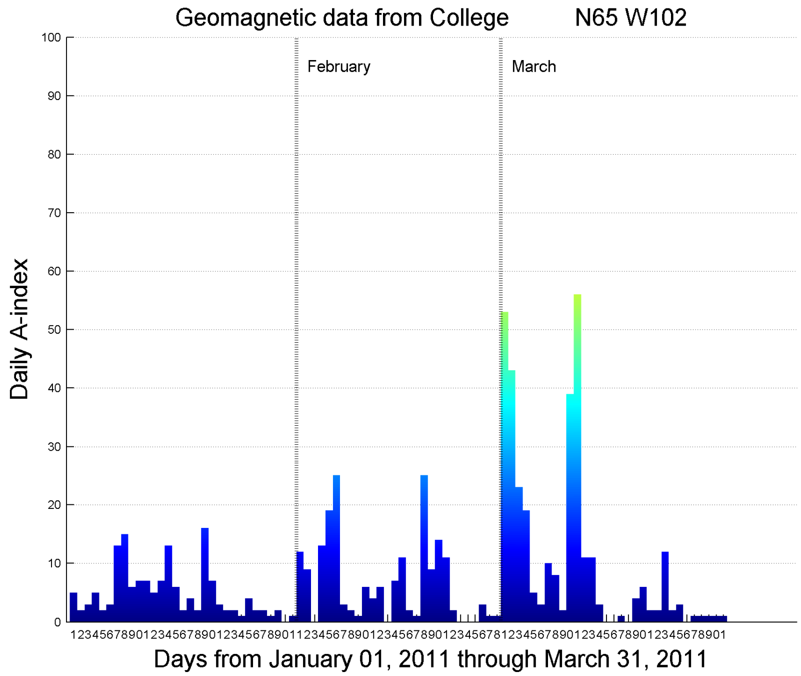


Figure 6.3-1 Daily A-index from College, Canada

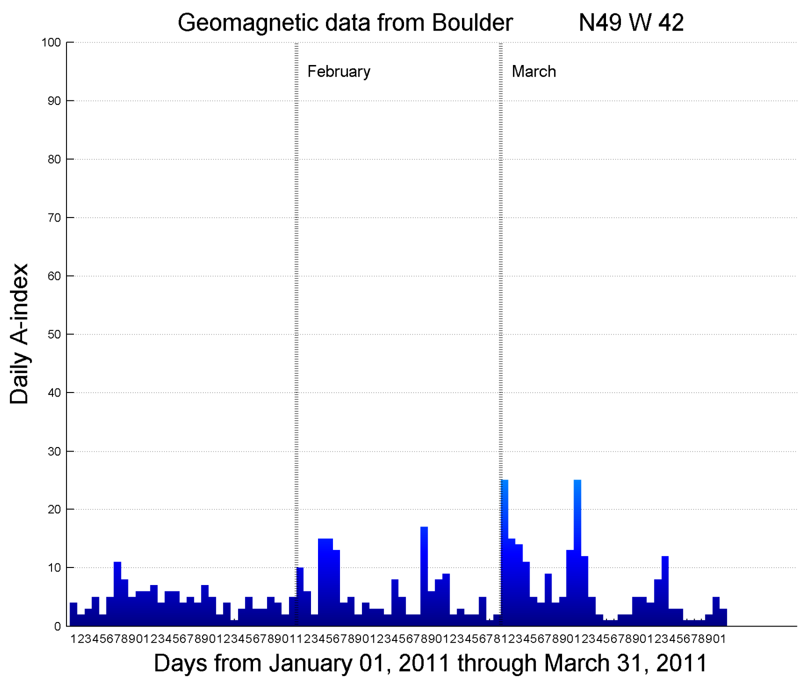


Figure 6.3-2 Daily A-index from Boulder, Colorado

6.3.2 Maximum daily K-indices

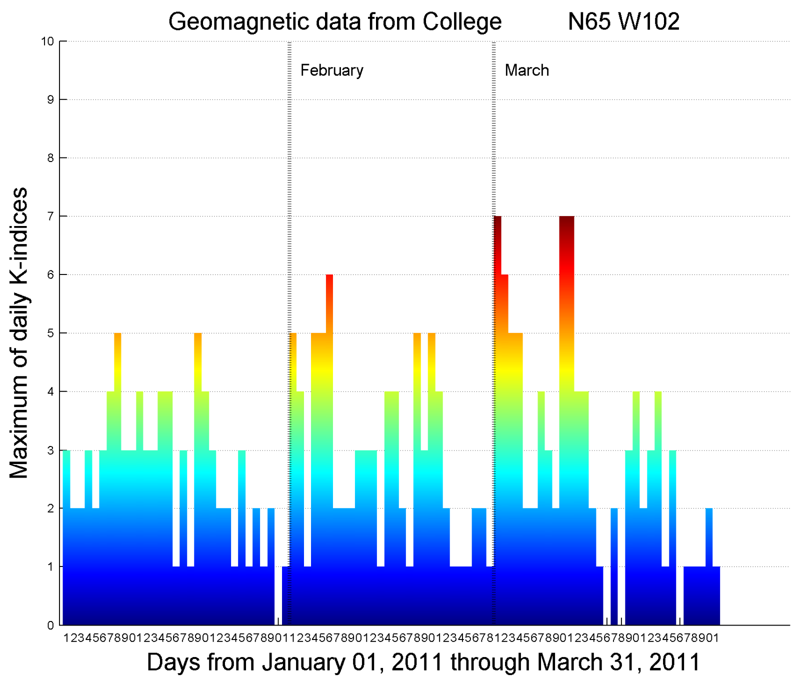


Figure 6.3-3 Maximum daily K-index from College, Canada

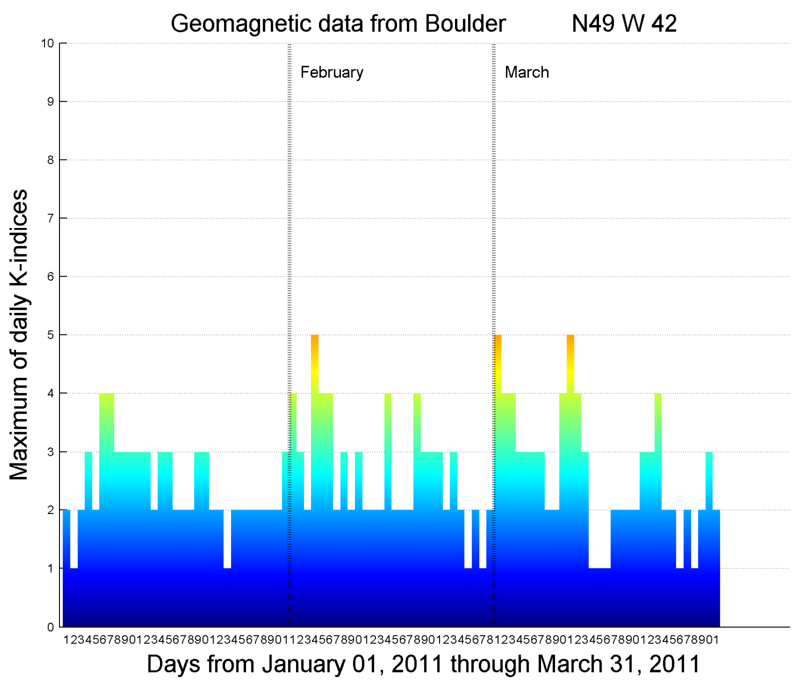


Figure 6.3-4 Maximum daily K-index from Boulder, Colorado

6.4 GEO CCC signal quality analysis (SQA)

A fly-by of CRW on March 4th apparently affected measurements of both CRE and CRW for several days. A different type of elevated noise occurred within several days of the fly-by. This was apparently related to Dopplar crossing of PRN 135 and 138. It was noted that not every Doppler crossing had an associated elevated noise at every site. There is still no explanation available for this anomalous behaviour.

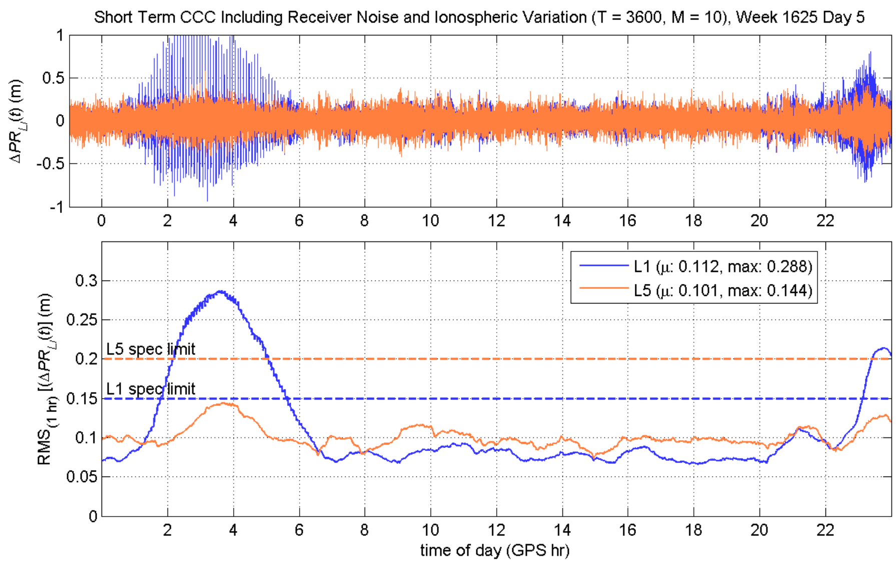


Figure 6.4-1 Elevated PR noise for PRN 135

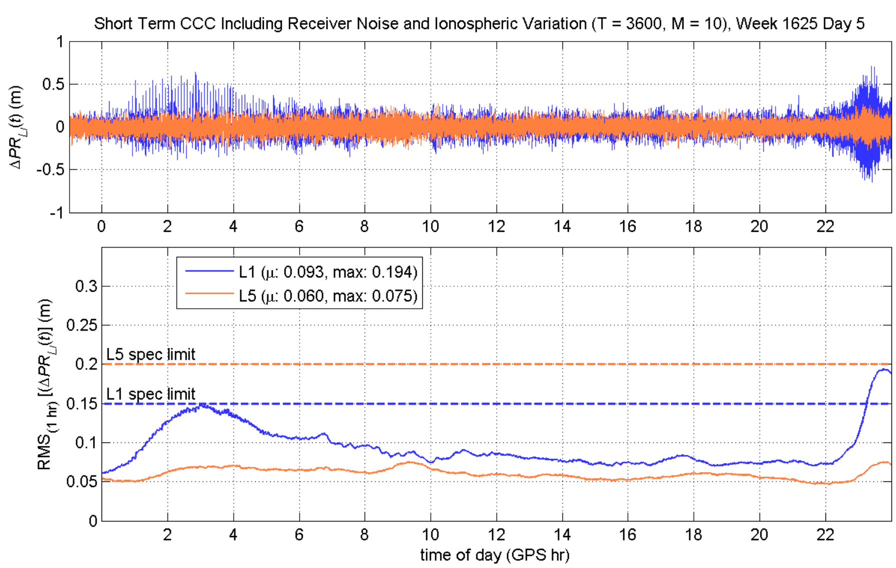
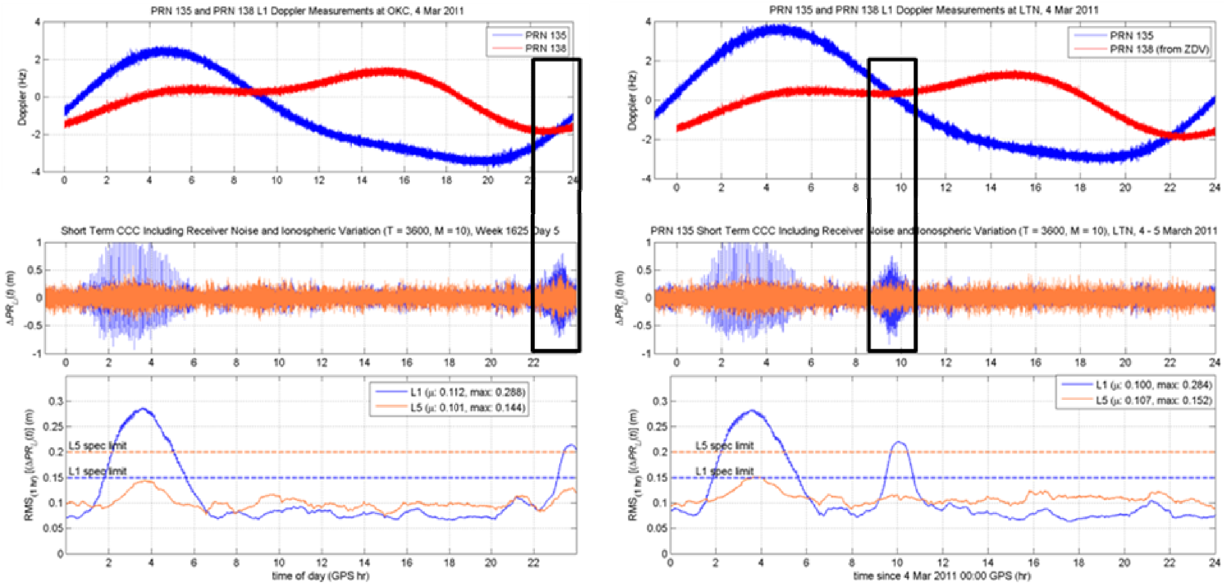


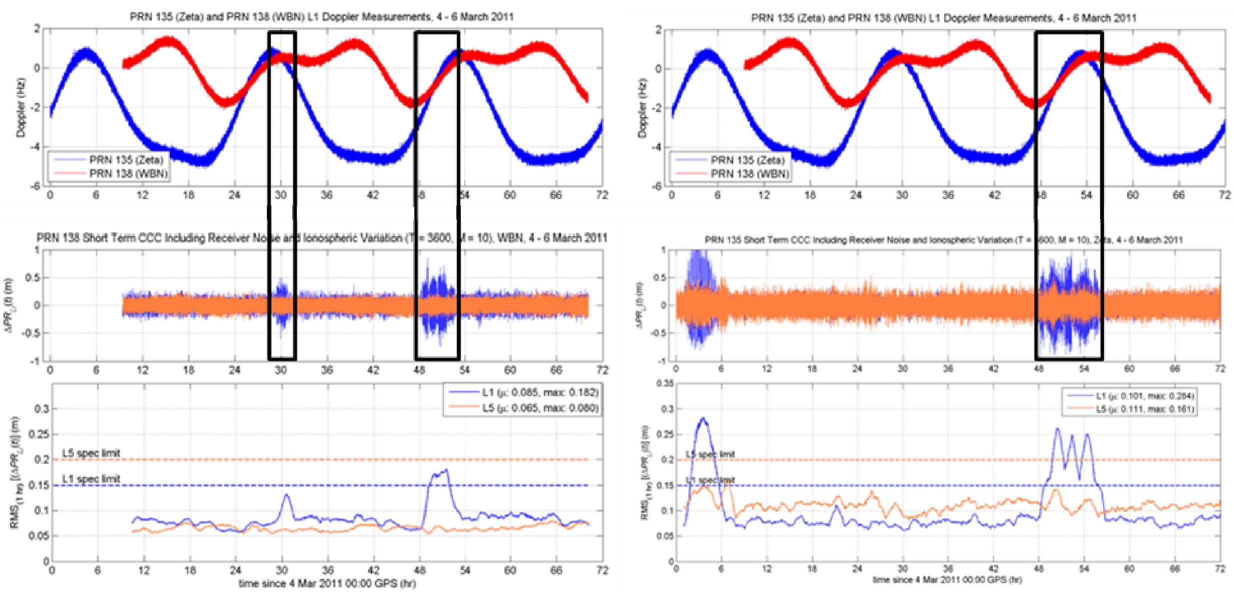
Figure 6.4-2 Elevated PR noise for PRN 138



PRN 135 OKC

PRN 135 LTN (Backup)

Figure 6.4-3 Doppler crossing noise: OKC and LTN



PRN 138 WBN (Backup)

PRN 135 Zeta

Figure 6.4-4 Dopplar crossing noise: WBN and Zeta

7 Anomaly Investigations

7.1 Paumalu AMR SIS Outages

Three major AMR SIS outages resulted early in 2011 after the Primary AMR GUST faulted. Those faults and times are shown in Table 6.1.

Anomaly	Faulted GUST	Time	Root Cause	SIS Outage Duration
WAAS00004125	SZP	01/18/2011 03:22:18	Known receiver issue where receive stops outputting RXSECSTATUS logs	61 Minutes
WAAS00004222	SZP	02/10/2011 18:44:11	L1 Signal Generator Communication fault	12 Minutes
WAAS00004316	SZP	02/20/2011 12:51:46	L5 Signal Generator Communication fault	46 Minutes

Table 6.1: AMR SIS Loss Anomalies

The sequence of events for these anomalies was very similar. The receiver at the backup GUST (HDH) continued to track the signal with good RANGE log parity indication for 3 to 4 seconds after the fault. During this continued tracking, the measured pseudorange diverged from the Kalman Filter range estimate and the filter subsequently failed its Innovation Test. Kalman filter convergence to a low, OSP-defined value is a prerequisite to achieving initial loop lock. The new Primary GUST was unable to achieve loop lock in the allowed 80 minutes and subsequently faulted. Figure 6.1 shows the Kalman Filter divergence and subsequent fault of HDH on 01/18/2011.

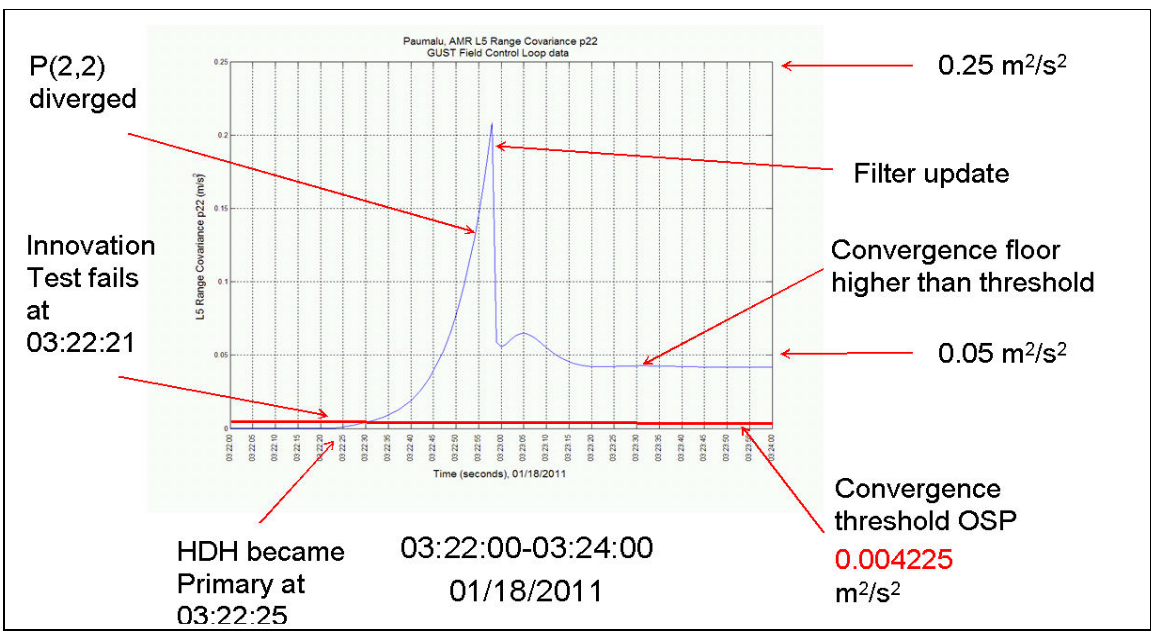


Figure 6.1: 2011-01-18 HDH Range (Courtesy P. Hsu – Raytheon Corp.)

The cause of the large erroneous receiver pseudorange measurements during continued tracking after a GUST fault is believed to be related to low C/No at HDH. Figure 6.2 shows a long term HDH Average L5 C/No plot. As indicated in the plot, the 3 anomalies where erroneous pseudorange measurements caused filter divergence occurred when the C/No was well below the nominal value of about 62 dB-Hz. This time period of low C/No is due to interference from the CRW-135 GEO drifting west toward its final location at 133W longitude.

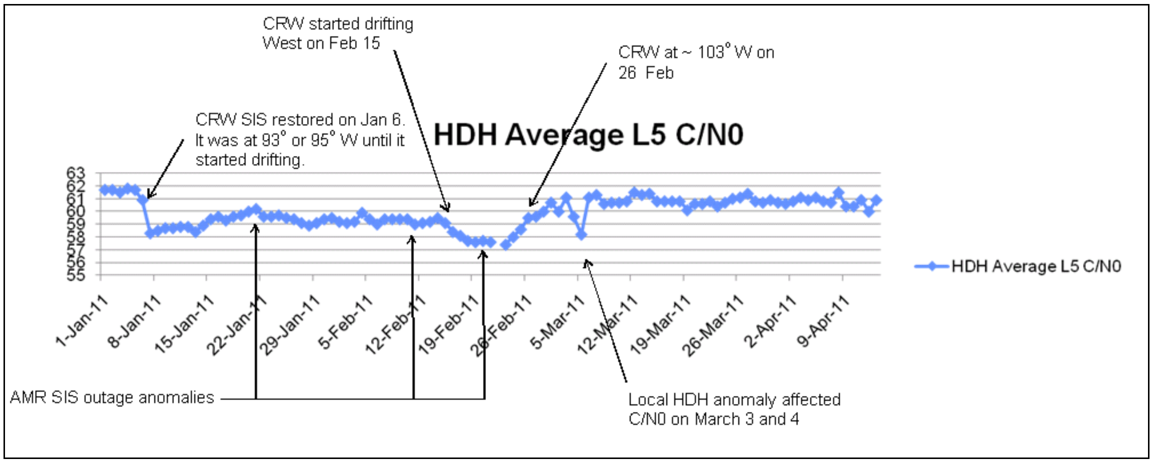


Figure 6.2: Long Term HDH Average L5 C/No (Courtesy L. Cheung – Raytheon Corp.)

Subsequent analysis by Zeta Associates found a correlation between range parity errors and low values of C/No. The range parity flag is likely to incorrectly indicate valid L5 parity following loss of signal when L5 C/No is less that 20 dB above the tracking threshold. The L5 tracking threshold is currently configured to 40 dB. Therefore, this analysis suggests that an L5 C/No of less than 60 dB may result in errors when switching to HDH as the Primary GUST. The L-band downlink antenna at HDH is fixed and not located on the large C-band dish. All of the other GUST sites have the L-band downlink antennas mounted on the large dish and therefore track the GEO by either ephemeris or C-band beacon as the satellite moves throughout the day. Due to its fixed antenna, HDH L5 C/No drops below 60 dB-Hz on a daily basis.

AMR GUST Switchover Testing was conducted on 04/13/2011 beginning at 20:41:04 UTC and continued into 04/14/2011 with the last switchover at 01:55:19 UTC. The testing included 2 induced faults and 2 operator initiated switchovers at both SZP and HDH. Figure 6.3 shows a log of the testing activities.

Testing Activity:

SZP induced L5 SIGGEN Comm Fault at 20:41:04
HDH GUS Primary @ 2011-04-13 20:41:12 UTC
SZP GUS Faulted @ 2011-04-13 20:41:04 UTC
HDH Initial Loop Lock at 2011-04-13 20:42:28 UTC
HDH Achieved Full Loop Lock at 2011-04-13 21:41:12 UTC
58 Minutes between Initial and Full LL at HDH

HDH induced Fault at 22:30:34
HDH GUS Faulted @ 2011-04-13 22:30:34
SZP GUS Primary @ 2011-04-13 22:30:42
SZP Initial Loop Lock at 2011-04-13 22:31:28 UTC
SZP Full Loop Lock at 2011-04-13 23:30:42 UTC
59 Minutes between Initial and Full LL at SZP
SZP back to Degraded LL at 2011-04-13 23:46:52 UTC
SZP achieved Full LL again at 2011-04-14 00:27:59 UTC

First operator initiated switchover to HDH at 2011-04-14 00:34:11 UTC
HDH Achieved Initial Loop Lock at 2011-04-14 00:38:41 UTC
HDH Achieved Full Loop Lock at 2011-04-14 01:34:11 UTC

Figure 6.3: 04/13/2011 AMR Switchover Testing Activities

The testing was conducted when C/No levels had returned to near normal levels after CRW had completed its drift back to 133W longitude. In each case where HDH was brought into Primary it achieved Full LL within the allowed 80 minutes. A significant observation of this testing was that the L5 parity flag changed to invalid about 1 second after each GUST fault. This prevented large errors in pseudorange and successful acquisition of loop lock. Figure 6.4 shows these parity observations.

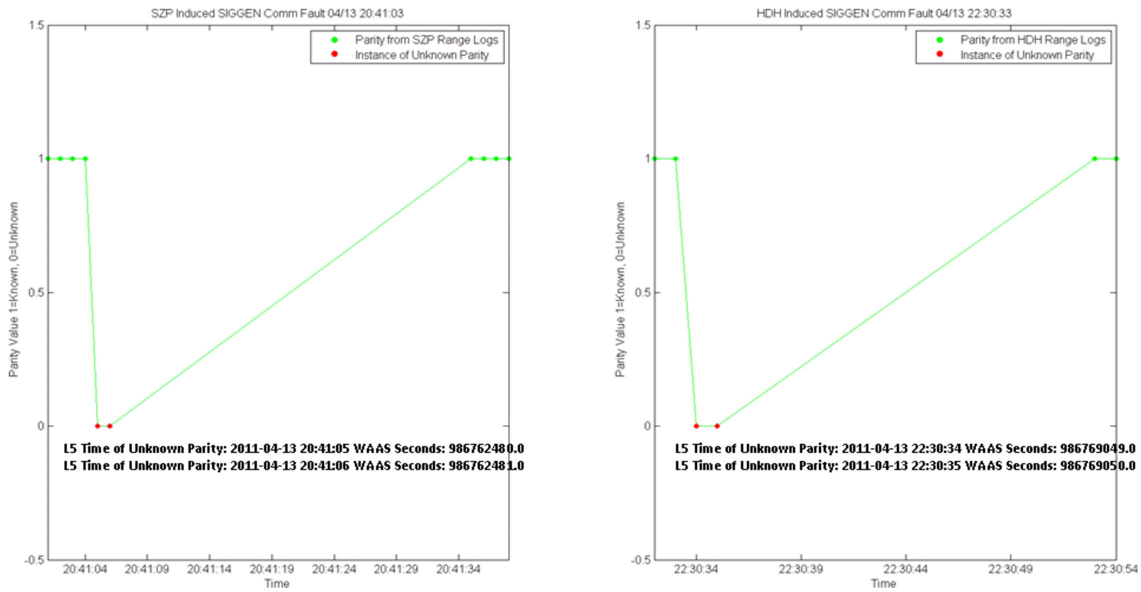


Figure 6.4: 04/13/2011 AMR Switchover Testing Parity Observations

CRW proximity to AMR did contribute to the AMR SIS outages caused by anomalies WAAS00004125, WAAS00004222, and WAAS00004316 in January and February 2011. The daily average HDH L5 C/No was approximately 2 dB lower than normal when CRW was within 5 degrees of AMR. GUST Switchovers involving HDH were normally successful prior to CRW operation near the AMR GEO. Successful switchover testing in mid-April showed L5 parity indicators declared invalid about 1 second after a GUST fault, preventing large pseudorange measurement errors and convergence of the GUST range filters. These types of AMR GUST faults involving large pseudorange errors have not occurred since February since CRW was restored at 133W longitude in early March 2011.

Anomalies WAAS00004401 and WAAS00004430 document 2 additional AMR SIS outages in the first quarter of 2011. Those anomalies, along with a description, are shown in Table 6.2.

A fault was induced at HDH on 03/04 to support AMR switchover testing. The GUST processor at HDH was faulted to test switchover capability from HDH to SZP. After the switchover SZP successfully attained initial loop lock. Several minutes later, SZP faulted with a known receiver SCAF. HDH was still down from the induced fault and therefore was not a viable backup GUST. This caused a SIS outage for 49 minutes but was not related to the GUST faults on Jan 18, Feb 10, and Feb 20, 2011.

Anomaly	Faulted GUST	Time	Root Cause	SIS Outage Duration
WAAS00004401	**SZP**	**2011-03-04 08:15:10**	**HDH was purposely faulted to support AMR switchover testing. SZP changed to Primary and achieve initial loop lock but faulted a few minutes later with a receiver SCAF. HDH had just been purposely faulted and was not a viable backup GUST**	**49 Minutes**
WAAS00004430	**SZP**	**2011-03-05 16:37:19**	**SZP GUST faulted from Primary (ZLA SS) with SE 131 L1 Control Lock Loop Fault. HDH had just faulted so SIS was lost until SZP was put back into Primary @16:59:15.**	**22 Minutes**

Table 6.2: AMR SIS Outages on 03/04 and 03/05/2011

HDH faulted on 03/05/2011 with an L5 control lock loop fault. GUST RANGE logs show that the Carrier Phase Standard Deviation at HDH had been very noisy for the entire day. The data further indicated that the error source was at HDH, at some point after the Signal Generator output. Both the range and carrier Kalman filters diverged resulting in loss of L5 loop lock several times throughout the day. The GUST faulted after 80 minutes of continuous loss of loop lock.

During normal operation, the control loop at the Backup GUST remains active in order to be ready for a switchover. SZP was in Backup and built up large pseudorange errors due to HDH broadcasting erroneous signals. The SZP range filter diverged for a long period of time. When SZP transitioned to Primary, the range error exceeded 1 million meters and the GUST faulted 120 seconds after the switchover. The GUST is designed to fault when the range control loop error exceeds 60 km for 60 seconds. The root cause for anomaly WAAS00004430 is a noisy uplink signal from HDH RFU.

7.2 Data drop from prototype during Dec. 16th to Jan. 6th 2011

WPR 118188

Originator Description:

The GPS data for the CCC monitor was missing for an extended period of time from the prototype outputs. The 110203 version of the prototype was run on snoop file taken from SOS for the 2010 Q4 Offline Monitoring Report for the entire quarter of 2010 (October 1st to December 31st). On the 77th day of the quarter (December 16th, 2010) the GPS portion of the CCC monitor was disabled (i.e., the data was not being printed) and the data file was smaller because approximately 17 hours into the day, the data stopped. This continued for several weeks, and reappeared after the 1st of the year.

Root Cause:

CRW (geo_index 0) was out from December 16, 2010 until early January. The prototype prints CCC statistics for geo_index 0 only, singe the data is the same for all 3 geo_inidex. Since the data structures for geo_index 0 were not populated, then only the default values (Don't Use) for GPS UDREs existed. Because the GPS UDREs were DU, then the CCC statistic prints were skipped for GPS. They did not get skipped for GEOs, since GEO UDREs were still updated for geo_index 0.

The fielded system is not affected, since this problem affects prototype prints only.

Resolution: Fix logical error so that GPS data prints from prototype as long as at least one GEO is not in a DNU state.

8 Materials and Methods

This is where an engineer can look to see how he/she can re-run everything that was performed in this study. This should include which tool was run, flags set, build number, data files used, any pre-processing done, etc.

8.1 Antenna Positioning

Sites were surveyed on 2011-01-28 and cross compared against the following:

- CSRS-PPP
- WFO-R2
- Coordinates projected to six months beyond WFO WFO Release 3, that is, 2012-05-01

8.2 Clock Runoff

8.2.1 Monitoring approach

- Events typically result in a fast correction that exceeds 256 meters
- When this occurs, the satellite is set Do Not Use until the correction reaches a reasonable size
- Events where the satellite is set Do Not Use from excessively large fast corrections while the satellite is healthy are recorded

8.3 Ionospheric Threat Model

8.3.1 Monitoring approach

- Monitor for Chi^2 values greater than 1 in the four regions, including:
    - CONUS > 1%
    - Alaska > 2%
    - Caribbean > 10%
    - Other > 3%

8.4 Ephemeris

Compared broadcast vs precise in HCL to ensure sigmas are less than 1m, 2.5m, 7.5m for Radial, Cross Track, and In Track.

8.5 GEO Signal Quality Analysis

8.5.1 Data

Used MATLAB to compile data inside the Geotest2 shared directory on the SQA server. GPS dates for Q4 range from 1603_5 to 1616_5. Files compiled were 1603_5_00_GUST_S[1 2]_???.GPS to 1616_5_00_GUST_S[1 2]_???.GPS.

8.5.2 Tools

Ran MATLAB plotting code on SQA machine.

9 Supplemental Material

9.1 Ionospheric Threat Model

9.1.1 Monitoring regions

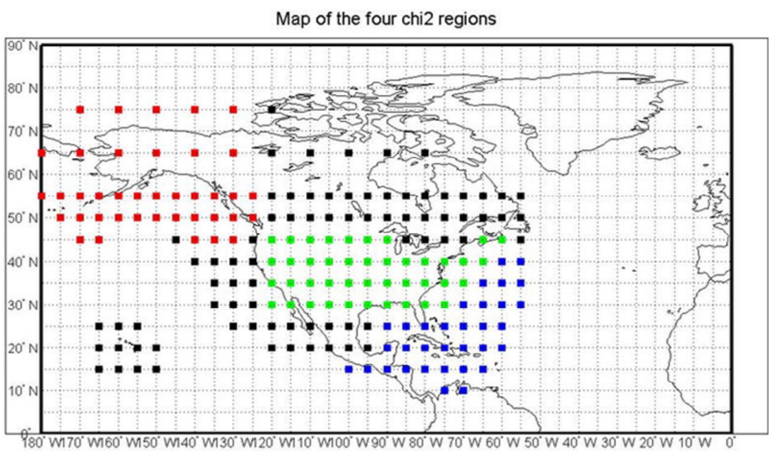


Figure 9.1-1 Map of the four Chi^2 regions

9.2 CNMP

9.2.1 Analysis on poor performing sites

- The cable on MSD-A was replaced on 2011-07-08. An full analysis of the change with the new cable will be presented at the next WIPP.

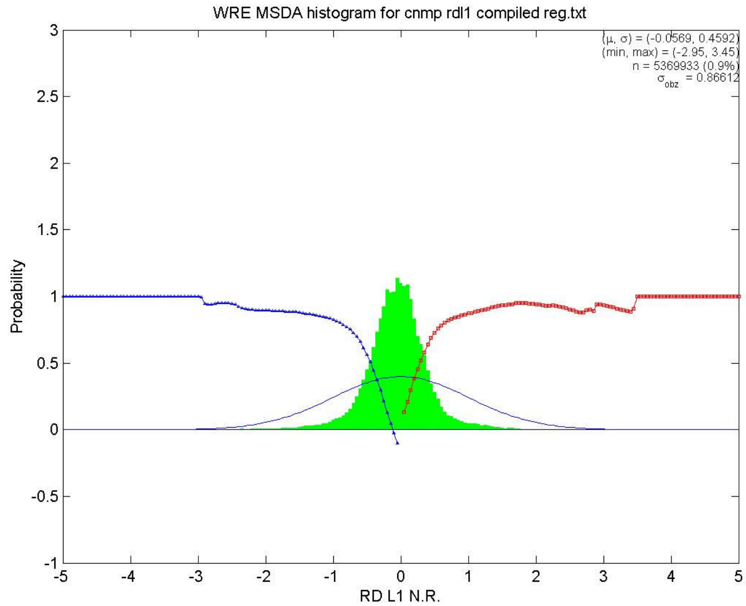


Figure 9.2-1 MSD-A Poor CNMP Performance

Sliced by WRE Legend: - = passed X = did not pass WRE #, WRE Name	L1				IFPR				Delay			
	μ	σ	|max|	pass/ fail	μ	σ	|max|	pass/ fail	μ	σ	|max|	pass/ fail
102, MSD_A	-0.056	0.46	3.45	-	-0.017	0.44	3.05	-	-0.002	0.43	2.95	-
27, Houston_A	-0.031	0.36	3.20	-	0.0	0.31	1.95	-	-0.014	0.33	1.85	-
37, Kansas_City_B	0.008	0.31	2.15	-	0.028	0.31	2.95	-	-0.034	0.31	3.2	-
29, Houston_C	0.041	0.45	3.15	-	0.063	0.46	2.60	-	-0.067	0.45	2.7	-
28, Houston_B	0.017	0.40	3.00	-	0.060	0.42	2.45	-	-0.075	0.43	2.5	-

Table 9.2.1-1 CNMP results from poor performing WRE slices

9.3 GEO Signal Quality Analysis

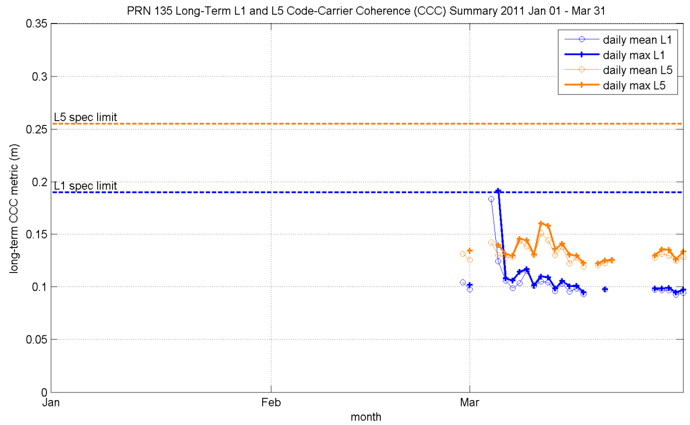


Figure 9.3-1 long-term CCC PRN135

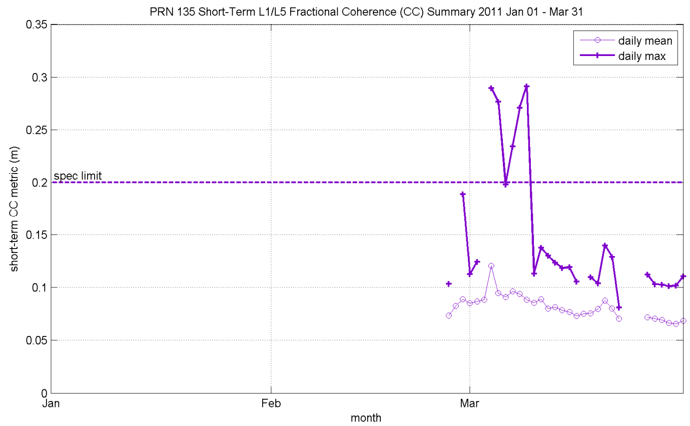


Figure 9.3-2 PRN 135 short-term CC

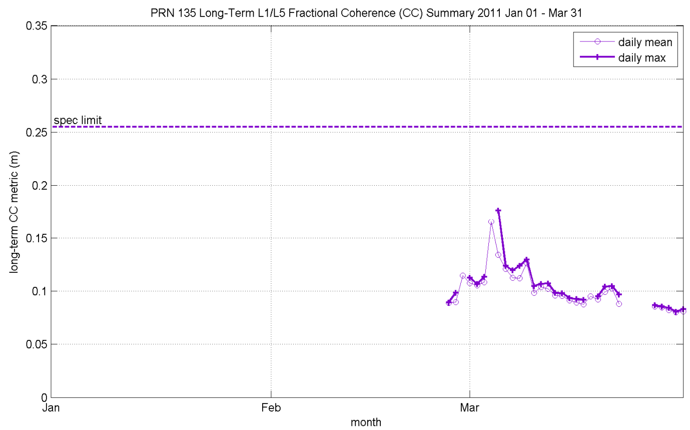


Figure 9.3-3 PRN 135 long-term CC

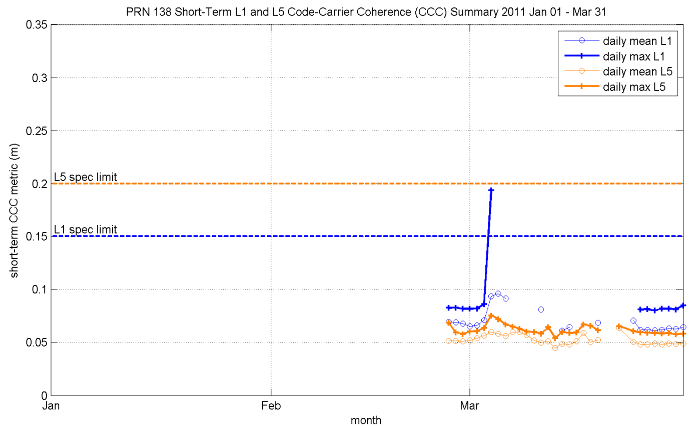


Figure 9.3-4 PRN 138 short-term CCC

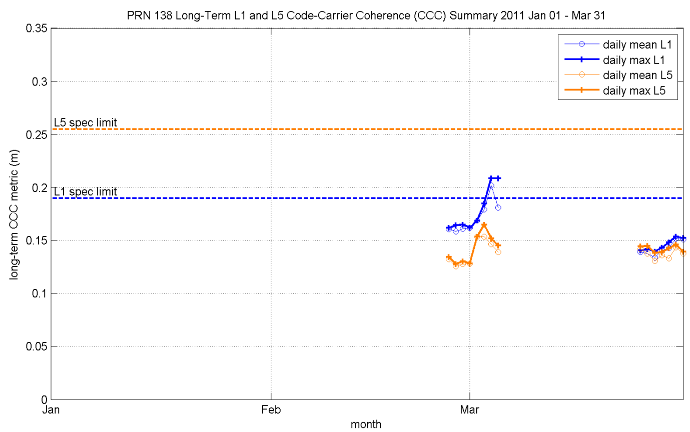


Figure 9.3-5 PRN 138 long-term CCC

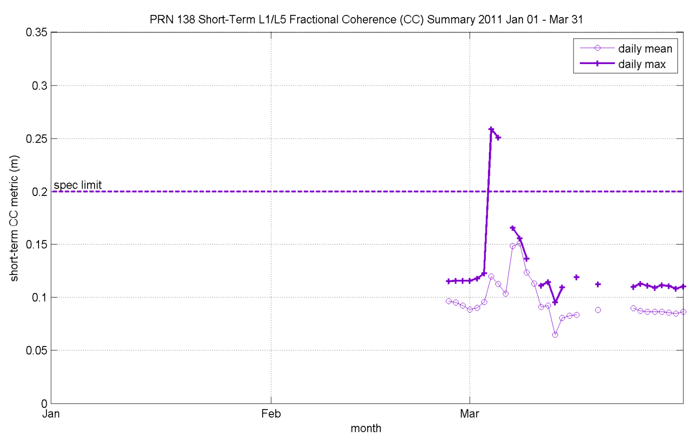


Figure 9.3-6 PRN 138 short-term CCC

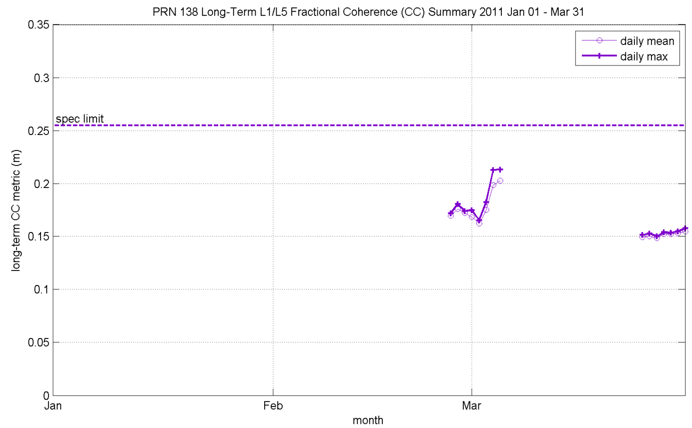


Figure 9.3-7 PRN 138 long-term CC

9.4 Space Weather Monitoring

9.4.1 Data from Fredericksburg, Virginia

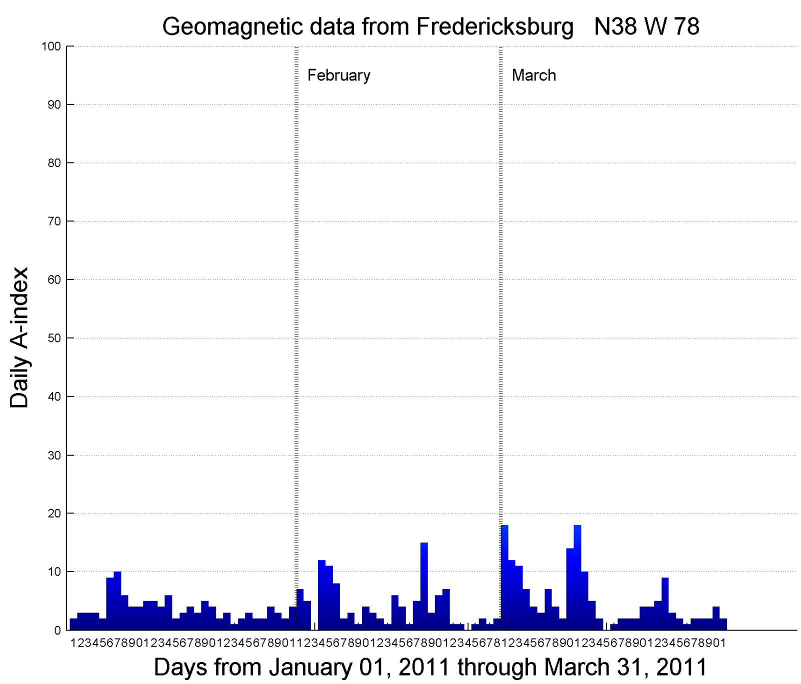


Figure 9.4-1 Daily A-index from Fredericksburg, Virginia

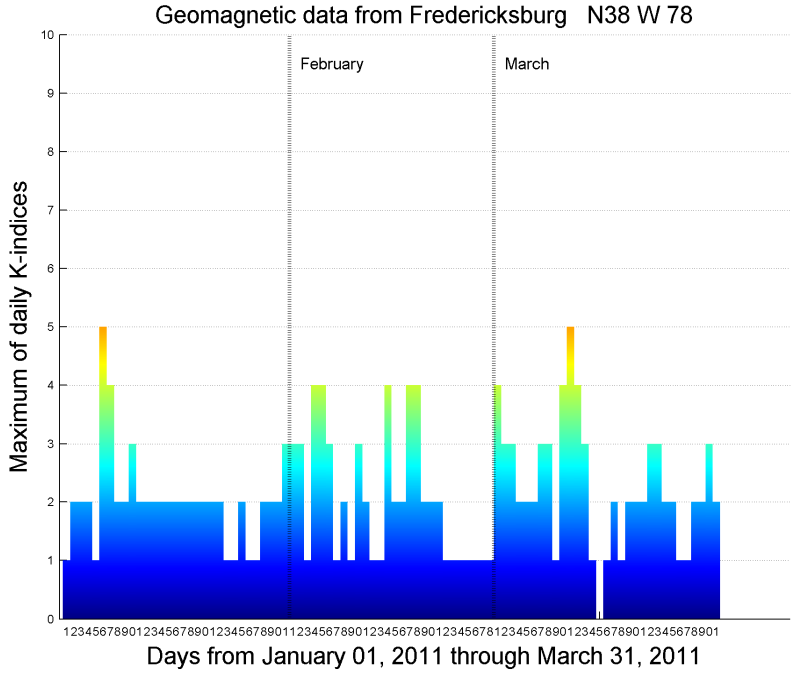


Figure 9.4-2 Maximum daily K-index from Fredericksburg, Virginia

9.5 L1L2 Bias Levels

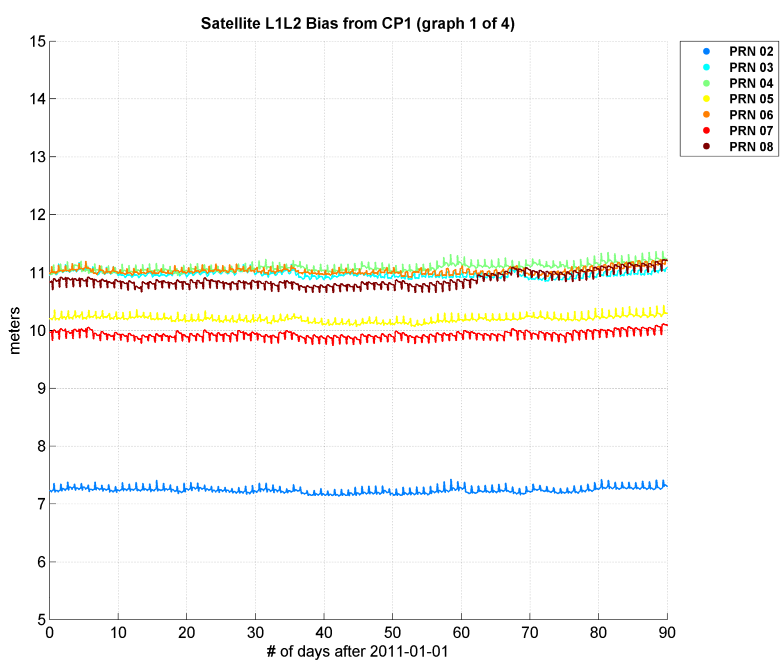


Figure 9.5-1 PRN2-8 L1L2 bias from CP1

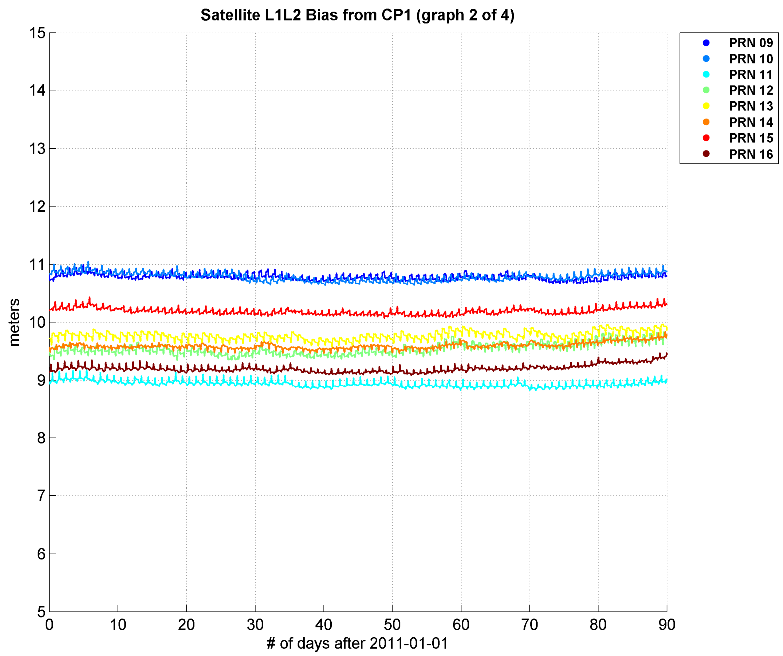


Figure 9.5-2 PRN9-16 L1L2 Bias from CP1

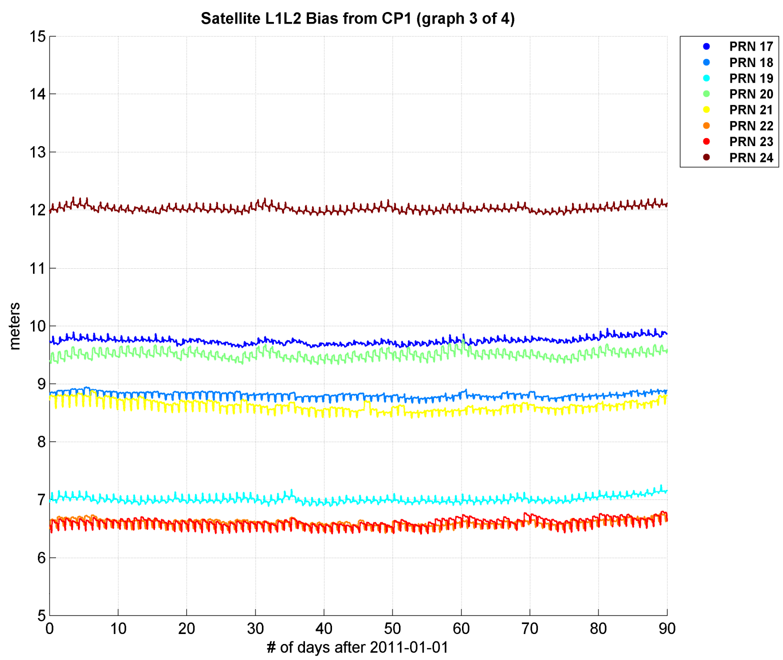


Figure 9.5-3 PRN17-24 L1L2 Bias from CP1

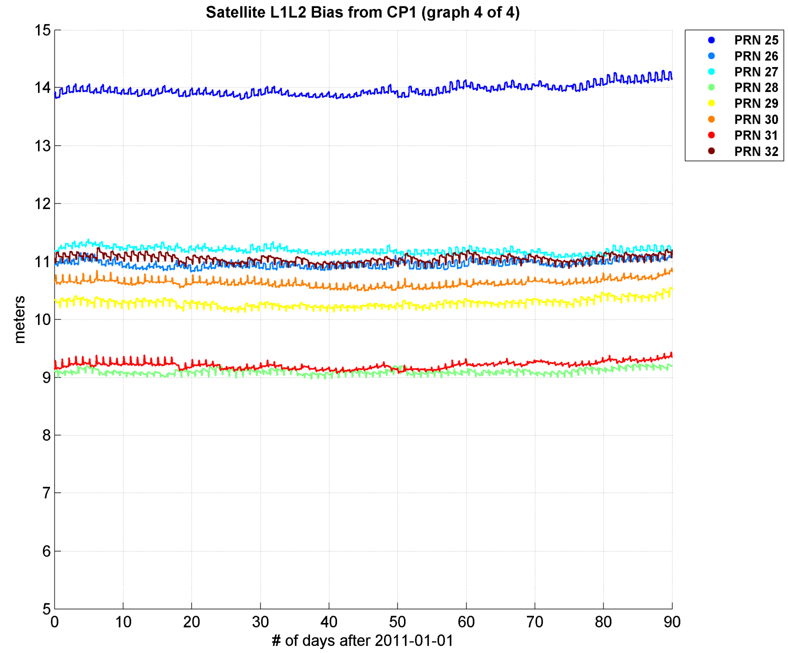


Figure 9.5-4 PRN25-32 L1L2 Bias from CP1

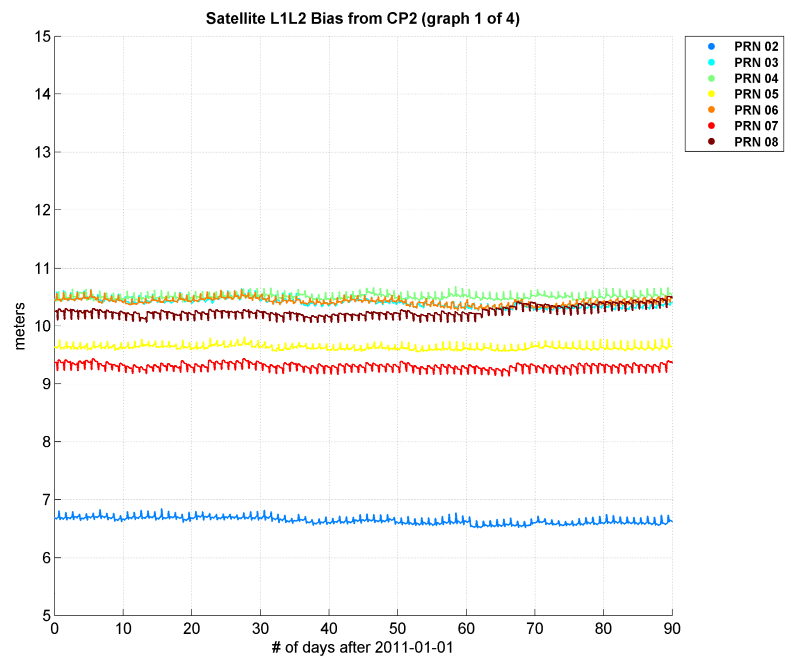


Figure 9.5-5 PRN2-8 L1L2 Bias from CP2

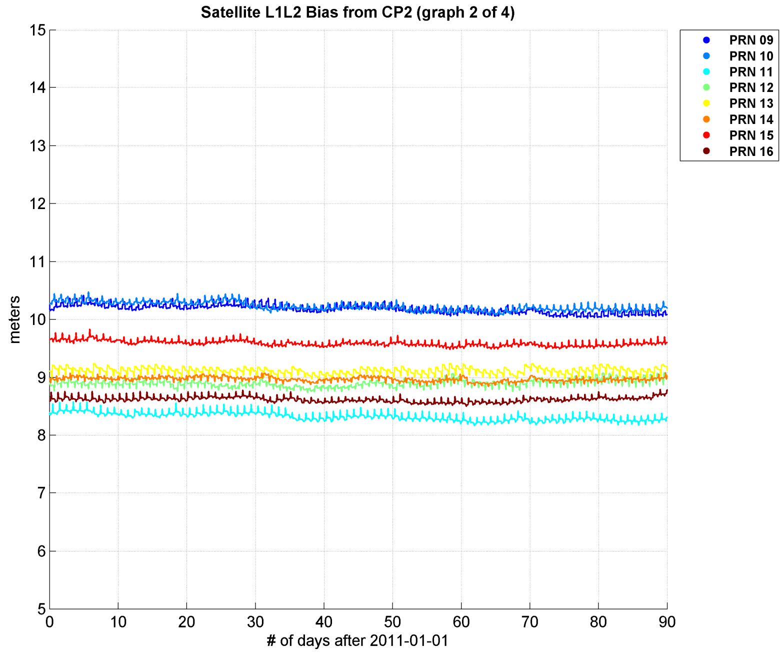


Figure 9.5-6 PRN9-16 L1L2 Bias from CP2

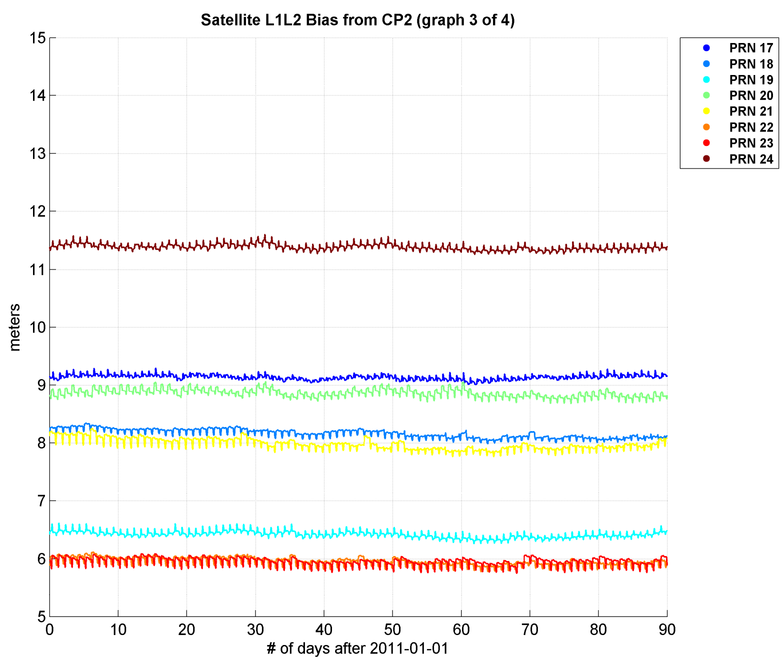


Figure 9.5-7 PRN17-24 L1L2 Bias from CP2

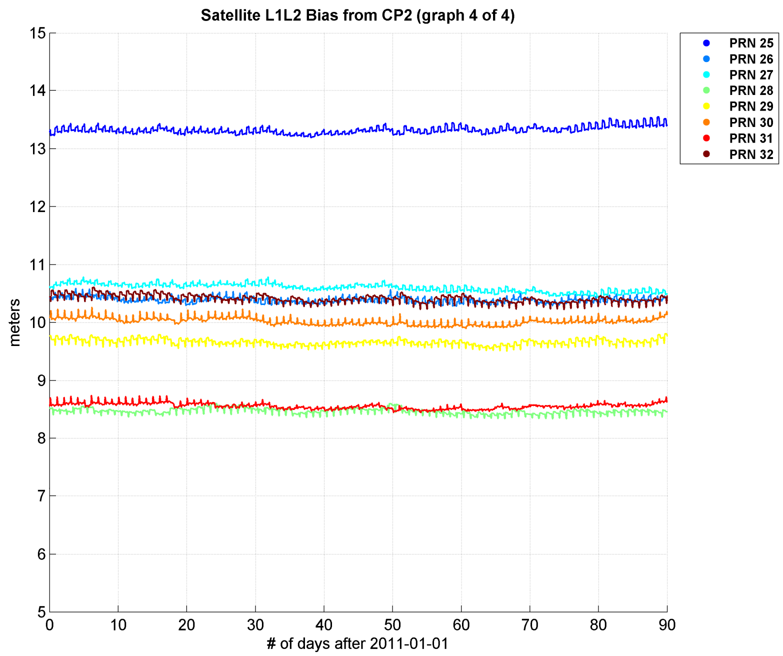


Figure 9.5-8 PRN25-32 L1L2 Bias for CP2

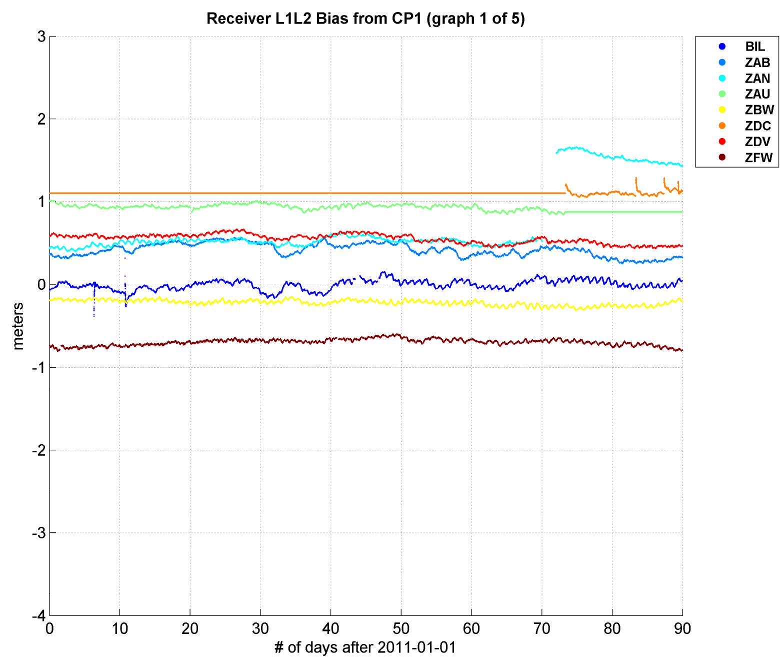


Figure 9.5-9 Receiver L1L2 Bias from CP1 (1 of 5)

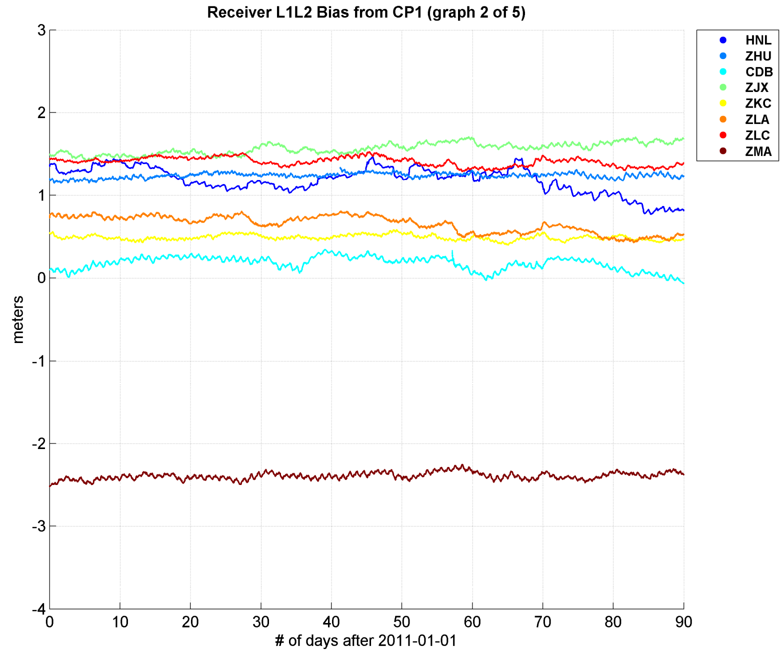


Figure 9.5-10 Receiver L1L2 Bias from CP1 (2 of 5)

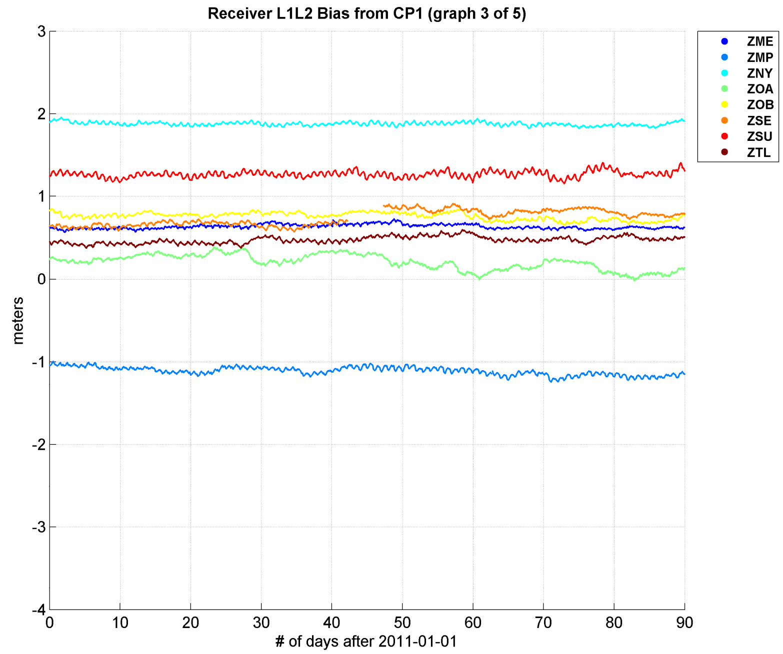


Figure 9.5-11 Receiver L1L2 Bias from CP1 (3 of 5)

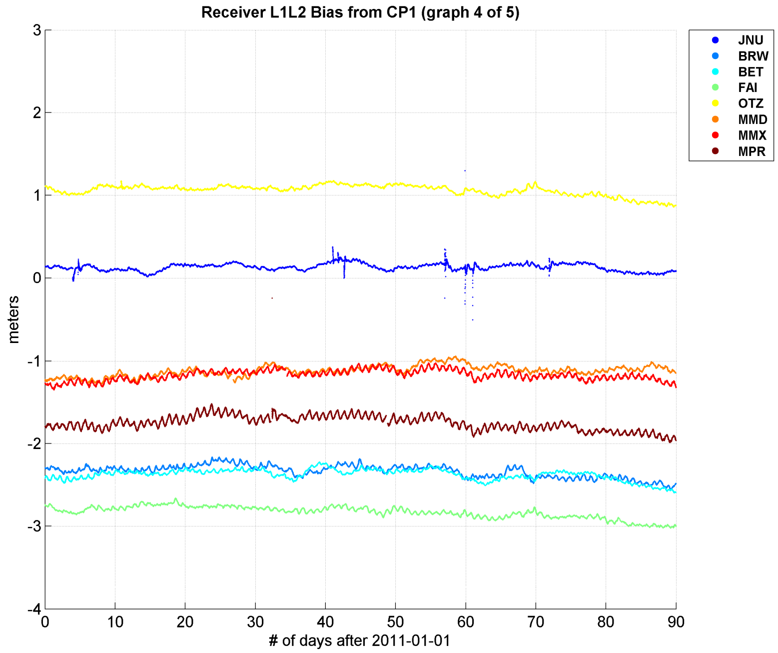


Figure 9.5-12 Receiver L1L2 Bias from CP1 (4 of 5)

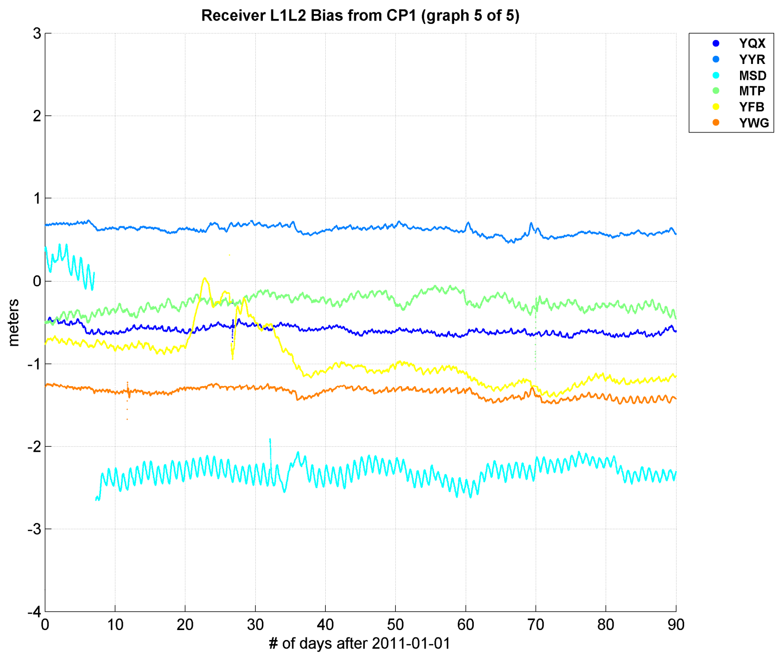


Figure 9.5-13 Receiver L1L2 Bias from CP1 (5 of 5)

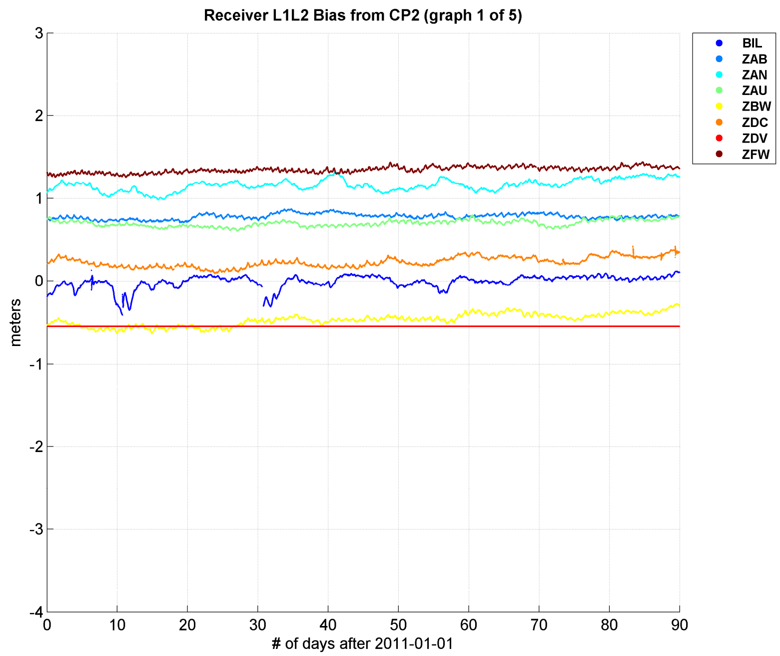


Figure 9.5-14 Receiver L1L2 bias from CP2 (1 of 5)

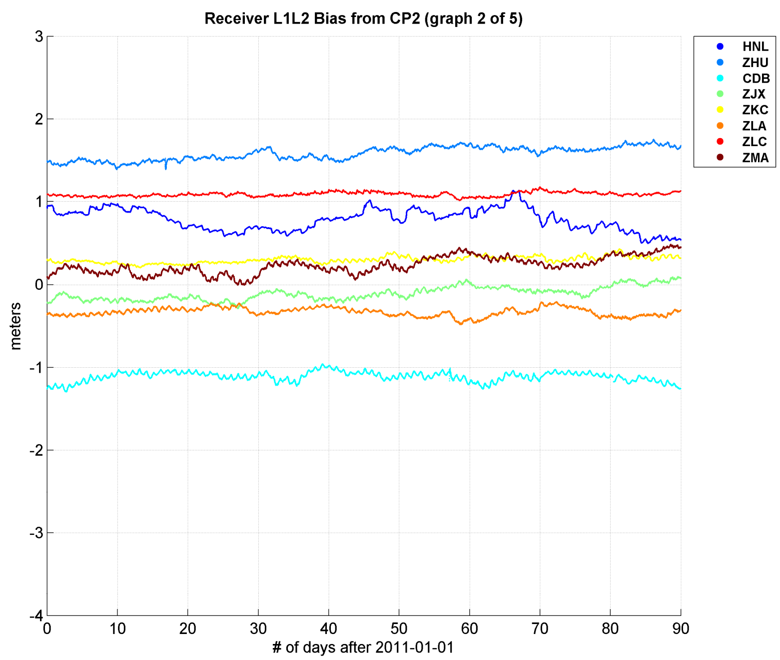


Figure 9.5-15 Receiver L1L2 bias from CP2 (2 of 5)

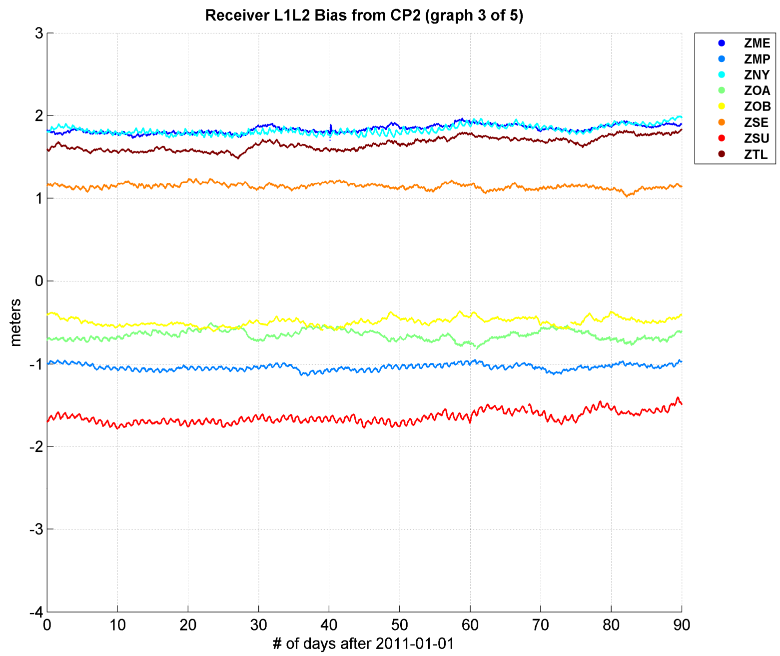


Figure 9.5-16 Receiver L1L2 bias from CP2 (3 of 5)

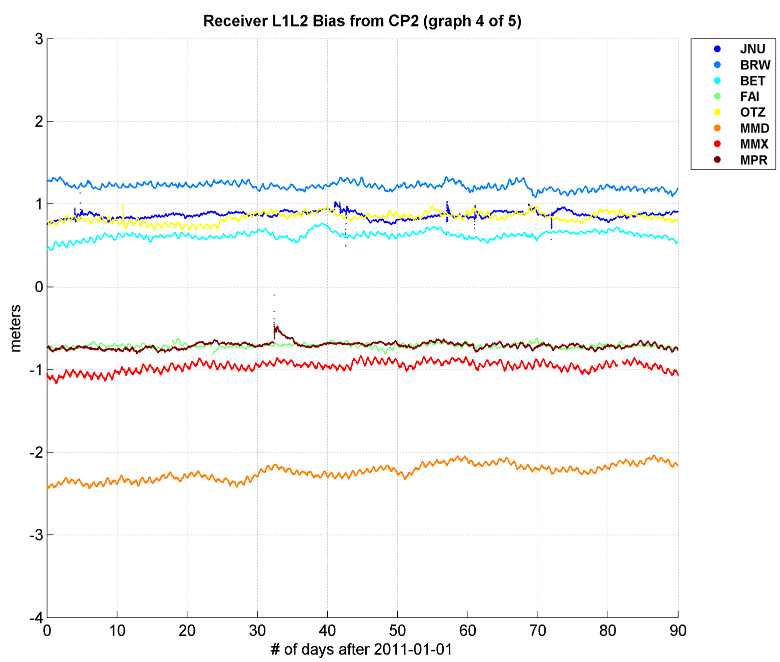


Figure 9.5-17 Receiver L1L2 bias from CP2 (4 of 5)

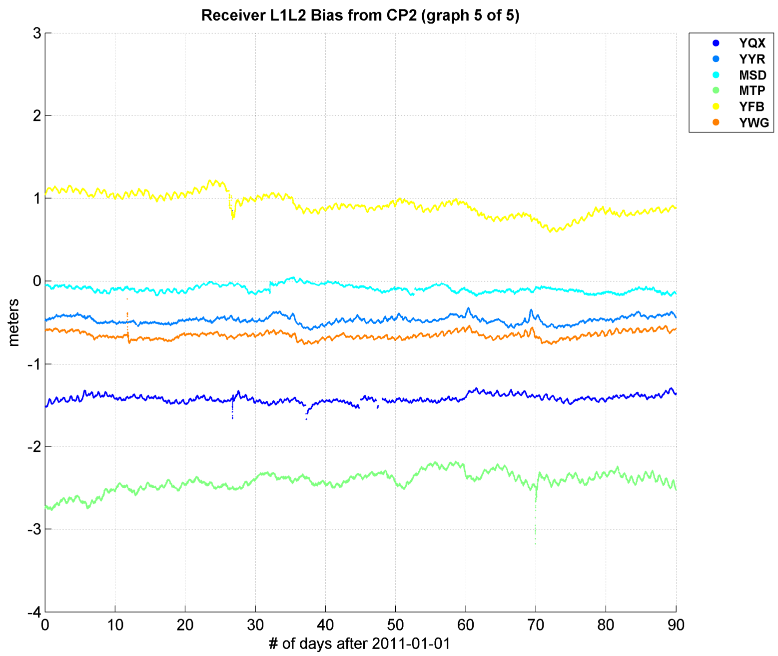


Figure 9.5-18 Receiver L1L2 bias from CP2 (5 of 5)

10 Appendix

10.1 Equations

10.1.1 CNMP

The cumulative density function (CDF) is defined as:

$$\Phi^R(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2/2} dt$$

Equation 10.1-1 : Cumulative Density Function (CDF)

$$\Delta(x) = \begin{cases} \dfrac{\Phi^R_{theory}(x) - \Phi^R_{data}(x)}{\Phi^R_{theory}(x)} & x \geq 0 \\ \dfrac{\left[1 - \Phi^R_{theory}(x)\right] - \left[1 - \Phi^R_{data}(x)\right]}{\left[1 - \Phi^R_{theory}(x)\right]} & x < 0 \end{cases}$$

Equation 10.1-2

CNMP passes for $\Delta x > 0$ for all $|x| > 0.25$

The number and/or complexity of equations will be limited in the main body and will be put here.

10.2 References

References to external material and journal articles go here.

10.3 Assertions

10.3.1 Code Carrier Coherence

The *a priori* probability of a CCC failure is less than 1x10-4 per set of satellites in view per hour for GPS satellites and 1.14x10-4 for GEO satellites.

10.3.2 CNMP

The Code Noise and Multipath (CNMP) error bound is sufficiently conservative such that the error in linear combinations of L1 and L2 measurements is overbounded by a Gaussian distribution with a sigma described by the Root Sum Square (RSS) of L1 and L2 CNMP error bounds except for biases, which are handled separately.

10.3.3 Antenna Monitoring

The position error (RSS) for each WAAS reference station antenna is 10 cm or less when measured relative to the ITRF datum for any given epoch. (Mexico City is allowed 25cm). The ITRF datum version (realization) is the one consistent with WGS-84 and also used for positions of the GPS Operational Control Segment monitoring stations.

10.3.4 Ephemeris

The CDF of GPS ephemeris errors in a Height, Cross-track, and Along-track (HCL) coordinate system is bounded by the CDF of a zero-mean Gaussian distribution along each axis whose standard deviations are σosp-ephh, osp-ephc, and ▯osp-ephl. The probability that a satellite's position error is not characterized by this a priori ephemeris model is less than 10-4 per hour.

10.3.5 Ionospheric Threat Model

The values of $\sigma_{decorr\_undersampeled}$ and ε_{iono} adequately protect against worst case undersampled ionosphere over the life of any ionospheric correction message, when the storm detectors have not tripped.

10.4 Coding standards and guidelines

The standards and guidelines for the Offline Monitoring effort are recorded here. "Standards" represent a "rule" that is assumed to be "enforceable", that is, it has been agreed to by the stakeholders and recorded as official. PCRs can (but not necessarily will) be blocked due to lack of upholding a standard. Furthermore, standards can certainly have exceptions, but these are dealt with on a case-by-case basis and recorded as such. "Guidelines", on the other-hand, are not enforceable. Guidelines represent good ideas and common engineering practices across the group. PCRs cannot be blocked as a result of not following a guideline.

Transitioning from a guideline to a standard is a done on a case-by-case basis. While there is no hard and fast rule for how this is done, the steps for this usually contain an initial agreement by the stakeholders (which included management and engineers) that a standard ought to be adopted, a resource (with associated level of effort) assigned, and an initial assessment as to how much work is involved (estimated end date, etc). The process of transitioning from a guideline to a standard is known as refactoring, and the practice is encouraged as long as stakeholder buy in is considered at each step.

The standards and guidelines are differentiated by the words "shall" and "should".

10.4.1 Integrity standards for MATLAB

The integrity standards for MatLab were developed during the WAAS FLP Release 6/7 time frame. These standards represent rules that, if broken, could lead to incorrect or erroneous results (not necessarily a tool crash but actual incorrect output). These are documented in the WAAS HMI document (in section 4.3.3 of that document) and are repeated here in their condensed form. More detail can be found in the WAAS HMI document. Note that these standards are enforced by use of the CD_STD_CHK tool which parses the files/scripts line by line checking for breaches.

- MATLAB Calling Ambiguity:
  - Ensure that no MATLAB keywords are used as function names.
  - Use functions, not scripts.
  - Function name and filename being the same is required.
  - One function per file required.
- Functions should not be influenced by anything other than inputs:
  - No **global** variables.
  - No **persistent** variables.
- MATLAB Functionality Ambiguity:
  - The **squeeze** function shall not be used.
- Windows Ambiguity:
  - The **exist** function shall not be used.
- Coding Clarity:
  - The **eval** command shall not be used.
- Consistency Check:
  - OSP consistency must be addressed.
  - Critical parameters need to not be hardcoded in the tools
- Repeatability:
  - The actual scripts that were used to generate the data, tables and plots need to be captured along with the outputs, as well as a mapping to the actual data set used.

10.4.2 Offline Monitoring Coding Standards

Along with the Integrity standards described in section 9.4.1, there exist several "Offline Monitoring" coding standards. These are coding standards which are attached to the running of the Offline Monitoring code and which have been identified as required for the processing of the offline monitoring data. Currently, there are five standards

- All open files shall be closed

  - This requirement should be applied over all tools for all Offline Monitoring scripts. This requirement is simple, as it just requires that any file which is opened be appropriately closed in the same script that opens it.
- In MatLab, the "figure" command needs to always have a file ID associated with the open figure
  - The MatLab coding language allows the user to create "figures" without assigning a file id variable. Closing the specific figure is then impossible in general, and the figure must be closed either by keeping track of the "current" figure ID, or by applying the "close all" command. Neither of these is desired, and as such, each figure must have a unique file ID in memory.
- In MatLab, the "close all" command shall not be used.
  - The close all command is issued to close all figures with or without a file ID. As standards are in place to assign a file ID for all figures, this line of code is unnecessary and should not be used.
- All open figures should have the option to be closed
  - The MatLab tools should not leave open figures after the analysis is run (by default). For particular tools, it may be desirable to keep the plots up on the screen, but the option to close them should be implemented
- Use cs_saveplot for saving plots in MatLab
  - The cs_saveplot function is a common script which saves figures to results directories. There are several options when saving a plot, as using this function allows one place to modify the saving requirements.

10.4.3 File naming conventions

While no complete convention exists, there are standard "pieces" which shall be enforced for the Offline Monitoring effort. These refer to the labels inside the actual name of the tool which refer to information in the data file. The requirements are listed below.

- There shall be no more than one "." in a file name
- Text files shall end with the suffix ".txt"
- Filenames shall use lowercase letters, integers, underscores and dashes.
- Files which contain data for a particular PRN shall have a six-character label of the form "prnDDD" where DDD are the three digits referring to the PRN number. PRNs less than 100 shall have a leading zero, and PRNs less than 10 shall have two leading zeros.
- Files which contain data for a particular WRE shall have a six-character label of the form "wreDDD" where DDD are the three digits referring to the WRE number. WREs less than 100 shall have a leading zero, and WREs less than 10 shall have two leading zeros. Also note that WREs start counting at 0, so for a 38-station system, the WRE number range from 0 to 113.
- Files which contain data for a particular UDREI shall have a seven-character label of the form "udreiDD" where DD are the two digits referring to the UDRE index. UDREIs less than 10 shall have a leading zero. Also note that UDREIs start counting at 0, so UDREIs range from 0 to 15.
- Files which contain data for a particular GIVEI shall have a seven-character label of the form "giveiDD" where DD are the two digits referring to the GIVE index. GIVEIs less than 10 shall have a leading zero. Also note that GIVEIs start counting at 0, so GIVEIs range from 0 to 15.

10.4.4 Histogram slicing and bin requirements

For many of the analyses, histograms are used to show compliance to particular requirements. As there is inherent averaging in the creating an aggregate histogram, the concept of slicing was introduced early in the WAAS analysis process. This requires that data from (potentially) different error sources are not averaged into a single histogram, but are examined separately. In order to compile results across multiple days (and data sets), both the bin centers and the number of columns for each type of slice needs to be fixed. Modifying these requirements at a later date would make long term trending difficult, if not impossible.

Table 4.4.3-1 below shows the bin requirements for the data files which are to be histogrammed by one or more of the Offline Monitoring analyses. Note that the minimum and maximum data cutoffs are defined to be the bin EDGES, not the bin centers. Thus, the bin centers are in between the edges defined in table 4.4.3-1.

Table 10.4.4-1 Data histogram bin requirements

Data Description	Data file	Data min	Bin width	Data max	Units
Raw CCC metric (L1 and L2)	Qstats*	-8.0	0.01	8.0	meters
CCC metrics normalized by trip threshold	Qstats*	-3.0	0.01	3.0	None
CCC metrics normalized by MERR	Qstats*	-2.0	0.001	2.0	None
Max SQM metric	SQM_reduced	0	0.001	2.0	None

Table 4.4.3-2 below shows the slicing requirements, i.e., the number of columns (and their designations) for each type of slice.

Table 10.4.4-2 Slicing requirements

Slice Description	# columns	Column Description
Aggregate	1	This is the histogram of the entire metric. There is always one column, no more.
UDRE index	16	Columns 1 through 14 represent the data associated with a UDREI of one less than the column, i.e., UDREIs of 0 through 13. The last two columns represent satellites which are NM and DU respectively.

Slice Description	# columns	Column Description
PRN	44	The PRN slices come in a few sets. The first set is the first 32 PRNs. The second set is 10 columns devoted to past, current and future GEOs. The first five GEO columns are the GEO PRNS of 122, 133, 134, 135, and 138. The next five columns are reserved for future GEO PRNS. Finally, the last two columns are the aggregate of the GPS data ns the aggregate of the GEO data respectively. This order is maintained.

10.4.5 OLM file formats

Standard file formats have been defined for four types of files, listed below. These represent standards, and are enforceable requirements.

10.4.5.1Histogram files

The number of columns in a histogram file shall be one more than the sum of the number of slices. For example, is a histogram file contained an aggregate histogram, slices by UDREI and slices by PRN (both GEO and GPS), there would be 1+1+16+44 = 62 columns. The first column is the bins, the second column is the aggregate, columns 3 through 18 are the 16 UDRE slices (with columns 17 and 18 being NM and DU), columns 19 through 50 are the 32 GPS PRNs, columns 51 through 60 are the GEO PRNS (which the last five being held in reserve), column 61 is the aggregate GPS histogram and column 62 is the aggregate GEO histogram.

- Histogram files are stored as raw counts, not probabilities and the bins are recorded as bin centers.
- Histogram files can be daily or compiled into a report.
- The histogram file shall have a header which has column headings lined up with the columns of the data.

10.4.5.2Statistics files

Each statistic in the statistics file shall be defined to be able to be computed using bins (either centers or edges) and the raw counts, and each column in the histogram file shall have all statistics computed for it. Thus, the dimensions of a statistics file shall be as such.

- The number of rows is the same as the number of statistics
- The number of columns shall be the same as the number of slices

In order to account for the column of bins, a statistic index is placed there, so that each column in a histogram file corresponds to the same column in the statistic file. There are currently fifteen descriptive statistics computed for each histogram file:

1. Counts
2. Mean
3. Standard Deviation
4. Minimum
5. Maximum

6. Absolute Maximum
7. Sigma Over-bound (Zero-centered)
8. Sigma Over-bound (Mean-centered)
9. 1st Quartile
10. Median (2nd Quartile)
11. 3rd Quartile
12. Mean of Absolute Value
13. Standard Deviation of Absolute Value
14. RMS
15. Variance

The statistics file shall have a header which has column headings lined up with the columns of the data, as well as the list of statistics represented in the file.

Statistics files can be daily or compiled into a report.

10.4.5.3 Time Series files

Time series files represent a quantity which evolves over time. These can be any quantity, but currently only satellite quantities are created. Thus, the file naming convention for PRN (described in 4.4.2) are utilized.

The time series files have as the first three columns three different representation of time. The first is WAAS time, the second is UTC in ISO-8601 format (HHMMSS) and the third is seconds in the day.

After the first three columns, more columns can be added. The intent of the time series file is to have all of the data which a plot would require in the subsequent columns.

Time series files are only attached to daily quantities, but several time series files could be concatenated together to create a multi-day files (and plot).

10.4.5.4 Quantity files

Quantity files contain two dimensional slices of a particular quantity. For example, creating a UDREI/ GPS PRN slice for the absolute maximum of the CCC metric would allow a user to see which satellite have issues at which UDREIs. As both dimensions are used, only one statistic per file can be represented.

Quantity files are currently only daily files, but they could be created for a compiled data for some statistics.

10.4.5.5 Quarterly files

Quarterly files are the files which are plotted over the period of the quarter. Thus, the first column is the number of the day in the quarter and the second (and subsequent) columns are data to be plotted. The data set can be customized for the particular plot.

10.5 Offline Monitoring Process and Procedures

10.5.1 Schedule and Meetings

The offline monitoring group will meet approximately twice a quarter. One set of meetings is to be set for the first week of the new quarter to go over plans for that quarter. The second set of meetings is to be set for shortly before the WIPP. For both meetings, the general purpose is to plan for the next WIPP or the next OLM report, as the case may be. At the meetings, task lists with priorities and resources are created, to be reviewed at the next set of meetings.

The offline monitoring document is release once a quarter. The analyses should be running during the quarter, and should be being reviewed on a periodic basis. Once the quarter ends, three dates are pertinent.

- Two weeks after the quarter ends – All analyses complete
- Four weeks after the quarter ends – Draft document released
- Six weeks after the quarter ends – Final document completed

10.5.2 Data Processing

The data processing strategy for the Offline Monitoring document is to currently run the safety processor prototype on blocks of snoop files, approximately one week long. The blocks are then run in succession to create a “quarters” worth of data, which spans the three months of the quarter in question. The blocks of data are usually a week long, but due to data issues, as well as week VS month cutoff issues, the lengths of the individual blocks may vary.

Standard processing is applied across the analyses for the individual days. This includes the creation of histogram files, histogram statistics files, time series files, and two dimensional quantity files. There are associated plots as well for each of the above mentioned plots. In addition to the standard processing, analyses specific to the tool are also run for each day. In this way, analysis specific data reduction and results are generated on a daily basis.

Once the daily analyses have been run, the results are compiled into a “report” directory. This includes the accumulation of histogram data, and the plotting of statistics across the quarter.

10.5.3 Tool Strategy

Tool builds created at SOS are valid, and need to have proper versioning attached to them. All of the results from a single quarter should come from one version of a tool, and this version should be recorded in the OLM document.

Both regression testing and coding standards checking are as automated as possible, and both have tools associated with them. For the regression testing, the “reg” MatLab tool has been created. This tool is stored in the OLM repository, and runs the regression tests for the MatLab tools in an automated way (from reg_go). The coding standards are checked via the CODE_STD_CHK tool. There is one standard which checks that all of the scripts are in the top-level directory, followed by the ten integrity standards, followed again by the five OLM coding standards.

As is often the case, tools (old and new) do not comply with the coding standard at the outset. As such, a “refactoring” approach is adopted. By “refactoring”, it is mean that some way to assess the level of non-compliance is required (either by manual review or via automation) before work commences on fixing the issue across the tool set. Once this is assessed, the work commences as is best seen fit by the group, and the standard is enforced for future tools.

An example of the current coding standards plot is shown below. As can be seen, the SQM tool is the only tool which does not have all of its scripts in the top level folder. Thus, it is not possible to assess any other issues until that first issue has been worked. For the other tools, the ten integrity standards are all met, and then several of the OLM standards are in a state of non-compliance. As of the writing of this document, PCRs are in place to fix the issues. Note that two other standards (which have to do with SLOC count and complexity) are also listed. The plot below just serves as an example.