

WIDE-AREA AUGMENTATION SYSTEM PERFORMANCE ANALYSIS REPORT

Report #3

April 30, 2002

**FAA/William J. Hughes Technical Center
NSTB/WAAS T&E Team
ACB 430
Atlantic City International Airport, NJ 08405**

Executive Summary

Since 1999 the Navigation Branch (ACB-430) at the William J. Hughes Technical Center has reported GPS performance as measured against the GPS Standard Positioning Service (SPS) Signal Specification. These quarterly reports are known as the PAN (Performance Analysis Network) Report. In addition to this report, the WAAS/NSTB Team is reporting on the performance of the Wide-Area Augmentation System (WAAS). This report is the third such WAAS quarterly report. This report covers WAAS performance during the period from January 1, 2002 to March 31, 2002.

During the reporting period the final two safety monitors of the WAAS were placed on the WAAS Signal in Space (SIS). These monitors do not have an effect on steady state WAAS performance, but are part of the system to protect against anomalous behavior of the GPS satellites.

The following table shows observations for accuracy and availability made during the reporting period. See the body of the report for results in the continuity, safety index, and range analysis. Please note that the results in the below table are valid when the Localizer Approach with Vertical Guidance (LPV) service is available. LPV service is available when the calculated Horizontal Protection Level (HPL) is less than 40 meters and the Vertical Protection Level (VPL) is less than 50 meters. See the body of the report for results when other service levels are available:

Parameter	Site/Maximum		Site/Minimum	
95% Horizontal Accuracy	Anchorage 1.799 meters		Greenwood 0.947 meters	
95% Vertical Accuracy	Anchorage 2.794 meters		Chicago 1.372 meters	
LNAV/VNAV Instantaneous Availability – HPL < 40 meters & VPL < 50 meters	Dallas 99.6%		CONUS Boston 96.0%	OCONUS Cold Bay 42.4%
95% HPL	CO NUS Los Angeles 26.2 meters	OCONUS Cold Bay 129.1 meters	CONUS Kansas City 15.0 meters	OCONUS Juneau 108.9 meters
95% VPL	CO NUS Boston 42.7 meters	OCONUS Cold Bay 189.7 meters	CONUS Kansas City 24.3 meters	OCONUS Juneau 161.7 meters

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1.0 Introduction

The FAA began monitoring GPS SPS performance in order to ensure the safe and effective use of the satellite navigation system in the NAS. The Wide Area Augmentation System (WAAS) adds more timely integrity monitoring of GPS and improves position accuracy and availability of GPS within the WAAS coverage area.

Objectives of this report are:

- a. To evaluate and monitor the ability of WAAS to augment GPS by characterizing important performance parameters.
- b. To analyze the effects of GPS satellite operation and maintenance, and ionospheric activity on the WAAS performance.
- c. To investigate any GPS and WAAS anomalies and determine their impact on potential users.

The WAAS data transmitted from GEO satellite PRN#122 (AORW) and PRN#134 (POR) were used in the evaluation. Table 1.1 and 1.2 listed the locations of the NSTB and WAAS reference station receivers used in the evaluation process with data transmitted from AORW and POR GEO, respectively. This report presents results from three months of data, collected between 01/01/2002 and 03/31/2002.

Table 1.1 NSTB and WAAS Reference Station Receivers - AORW

NSTB:	Number of Days Evaluated	Number of Samples
• Atlantic City, NJ	90	7,775,322
• Columbus, OH	90	7,773,909
• Denver, CO	86	7,455,595
• Grand Forks, ND	90	7,745,265
• Greenwood, MS	86	7,419,766
• Prescott, AZ	83	7,196,514
WAAS:		
• Atlanta, GA	87	7,474,122
• Billings, MT	84	7,224,994
• Boston, NH	78	6,767,083
• Chicago, IL	86	7,447,248
• Dallas, TX	78	6,706,816
• Kansas City, KS	87	7,485,671
• Miami, FL	84	7,237,248
• Oakland, CA	69	5,988,606
• Salt Lake City, UT	89	7,650,151
• Seattle, WA	63	5,480,167

Table 1.2 WAAS Reference Station Receivers - POR

WAAS:	Number of Days Evaluated	Number of Samples
• Anchorage, AK	86	7,462,553
• Cold Bay, AK	77	6,616,309
• Juneau, AK	73	6,265,891
• Los Angeles, CA	77	6,627,466

The report is divided to six performance categories listed below.

1. WAAS Position Accuracy
2. WAAS Operational Service Availability
3. LNAV/VNAV (APV-I) Coverage
4. Continuity
5. Integrity
6. WAAS Range Domain Accuracy

Table 1.3 lists the performance parameters evaluated for the WAAS in this report.

Table 1.3 WAAS Performance Parameters

Performance Parameter	Expected WAAS Performance
Accuracy Horizontal	≤ 7.6m error 95% of the time
Accuracy Vertical	≤ 7.6m error 95% of the time
Availability GLS*	Not Defined for Current WAAS phase
Availability APV-2*	Not Defined for Current WAAS phase
Availability LPV*	Not Defined for Current WAAS phase
Availability LNAV/VNAV*	Not Defined for Current WAAS phase
Coverage GLS	Not Defined for Current WAAS phase
Coverage APV-2	Not Defined for Current WAAS phase
Coverage LPV	Not Defined for Current WAAS phase
Coverage LNAV/VNAV	≥ 75% of CONUS
NPA Continuity of NAV	≥ 99.999% of the time
NPA Continuity of Fault Detection	≥ 99.999% of the time
LPV Continuity of Function	Not Defined for Current WAAS phase
LNAV/VNAV Continuity of Function	≥ 95% of the time
Integrity	≤ 4 X 10e-8 HMI's per approach
Accuracy Range Domain	≥ 99.9% of range error bounded by UDRE
Accuracy Ionospheric	≥ 99.9% of ionospheric error bounded by GIVE

* The availability referred is the instantaneous availability (i.e. Availability is calculated every second.)

1.1 Event Summary

Table 1.4 lists test events that occurred during the reporting period that affected WAAS performance or the ability to access the WAAS performance. These events include GPS or WAAS anomalies, relevant receiver malfunctions, and receiver maintenance conducted.

Table 1.4 Test Events

Date	Description
01/01/02 - 01/07/02	NSTB receiver failure at Prescott
01/01/02 - 01/02/02	NSTB receiver failure at Anderson
01/10/02	Ionospheric storm Kp = 5
01/11/02 - 01/16/02	Database station was under maintenance
01/16/02	WAAS S/W update. Loss availability for approximately 3 hours
01/31/02 - 02/01/02	NSTB receiver failure at Denver
01/28/02	GUS switchover - POR
02/02/02	Ionospheric storm Kp = 5
02/13/02 - 02/14/02	NSTB receiver failure at Denver
02/05/02 - 02/15/02	WAAS receiver Oakland was under maintenance
02/28/02	Ionospheric storm Kp = 5
03/12/02 - 03/15/02	NSTB receiver failure at Greenwood
03/06/02 - 03/13/02	WAAS receiver Seattle was under maintenance
03/19/02	Ionospheric storm Kp = 5
03/22/02	WAAS SIS outage. GUS Stress Test (AORW & POR)
03/24/02	Ionospheric storm Kp = 6
03/25/02 - 3/29/02	GUS Stress Test (POR). Data was not included in the evaluation
03/29/02 - 04/12/02	Transition period to the new WAAS message header

1.2 Report Overview

Section 2.0 provides the vertical and horizontal position accuracies from data collected, on a daily basis, at one-second intervals. The 95% accuracy index for the reporting period is tabulated. The daily 95% accuracy index is plotted graphically for each receiver. Histograms of the vertical and horizontal error distribution are provided for two receivers within the WAAS service area.

Section 3.0 summarizes the WAAS instantaneous availability performance, at each receiver, for three operational service levels during the reporting period. Daily availability is also plotted for each receiver evaluated.

Section 4.0 provides the percent of CONUS covered by WAAS at LNAV/VNAV operational service level on a daily basis. Monthly roll-up graphs presented indicate the portions of CONUS covered, and the percentage of time that WAAS was available.

Section 5.0 provides the percentage of time continuity requirements were met during the reporting period for each receiver.

Section 6.0 summarizes the number of HMI's detected during the reporting period and presents a safety margin index for each receiver. The safety index reflects the amount of over bounding of position error by WAAS protection levels.

Section 7.0 provides the UDRE and GIVE bounding percentage and the 95% index of the range and ionospheric accuracy for each satellite tracked by the NSTB receiver in Columbus.

Section 8.0 summarizes WAAS anomalies and problems identified during the reporting period, which adversely affect WAAS performance described in Table 1.3.

2.0 WAAS Position Accuracy

Navigation error data, collected from WAAS and NISTB reference stations, was processed to determine position accuracy at each location. This was accomplished by utilizing the GPS/WAAS position solution tool to compute a MOPS-weighted least squares user navigation solution, and WAAS horizontal and vertical protection levels (HPL & VPL), once every second. The user position calculated for each receiver was compared to the surveyed position of the antenna to assess position error associated with the WAAS SIS over time. The position errors were analyzed and statistics were generated for four operational service levels: WAAS GLS, WAAS APV-2, WAAS LPV, and WAAS APV-1 (LNAV/VNA), as shown in Table 2.1. For this evaluation, the WAAS operational service level is considered available at a given time and location, if the computed WAAS HPL and VPL are within the horizontal and vertical alarm limits (HAL & VAL) specified in Table 2.1.

Table 2.1 Operational Service Levels

WAAS Operational Service Levels	Horizontal Alert Limit HAL (meters)	Vertical Alert Limit VAL (meters)
GLS	40	12
APV-2	40	20
LPV (LOC/VNAV)	40	50
APV-1 (LNAV/VNAV)	556	50

Table 2.2 and 2.3 show the horizontal and vertical position accuracy maintained for 95% of the time at WAAS GLS, APV-2, APV1.5, and LNAV/VNAV operational service levels for period of the quarter. Note that WAAS accuracy statistics presented are compiled only when all WAAS corrections (fast, long term, and ionospheric) for at least 4 satellites are available. This is referred to as PA navigation mode. The percentage of time that PA navigation mode was supported by WAAS at each receiver is also shown in Table 2.2 and 2.3. A user is considered to be in NPA navigation mode if only WAAS fast and long term corrections are available to a user (no ionospheric corrections). Figures 2.1 and 2.2 show the daily horizontal and vertical 95% accuracy for LNAV/VNAV operational service level for the evaluated period. The spike occurred on 03/22/02 is caused by WAAS SIS outage (See Section 8 for more details). This event effects both accuracy and availability. Note the gap of data from 01/11/02 to 01/16/02 is due to the database station was under maintenance.

During the evaluated period, the 95% horizontal and vertical accuracy at all evaluated sites are less than 7.6 meters for all WAAS operational service levels. The maximum horizontal and vertical LNAV/VNAV errors are 2.269 meters at Juneau and 2.794 meters at Anchorage, respectively. The minimum horizontal and vertical LNAV/VNAV errors are 0.955 meters at Greenwood and 1.372 meters at Chicago, respectively.

Figures 2.3 to 2.11 show the distributions of the vertical and horizontal errors in triangle charts and 2-D histogram plots for the quarter at three locations, Denver, Kansas City, and Juneau. The triangle charts show the distributions of vertical position errors (VPE) versus vertical protection levels (VPL) and horizontal position errors (HPE) versus horizontal protection levels (HPL). The horizontal axis is the position error and the vertical axis is the WAAS protection levels. Lower protection levels equate to better availability and the diagonal line shows the point where error equals protection level. Above and to the left in the chart, errors are bounded; below and to the right, errors are not bounded. The horizontal lines at various protection levels represent the various operational service levels as defined in Table 2.1. The 2-D histogram plots contain four histograms showing the distributions of vertical and horizontal error and normalized position errors. The left top and bottom histograms show the distributions of the actual vertical and horizontal errors. The horizontal axis is the position errors and the vertical axis is the total count of data samples (log scale) in each 0.1-meter bin. The right top and bottom histograms show the distributions of the actual vertical and horizontal errors normalized by one-sigma value of the protection level, vertical - (VPL/5.33) and horizontal - (HPL/6.0). The horizontal axis is the standard units and vertical axis is the observed distribution of

normalized errors data samples in each 0.1-sigma bin. Narrowness of the normalized error distributions shows very good observed safety performance.

Table 2.2 95% Horizontal and Vertical Accuracy

Location	Horizontal GLS/APV-2/-1.5 (HAL=40m) (meters)	Horizontal APV-1(LNAV) (HAL=556m) (meters)	Vertical GLS (VAL=12m) (meters)	Vertical APV-2 (VAL=20m) (meters)	Vertical APV-1.5/-1(VNAV) (VAL=50m) (meters)	Percentage in PA mode (%)
Kansas City	0.953	0.969	*	1.282	1.381	99.768
Chicago	0.973	1.010	*	1.268	1.372	99.766
Columbus	1.010	1.030	*	1.435	1.516	99.775
Denver	1.026	1.038	0.918	1.570	1.648	99.769
Salt Lake City	1.015	1.032	0.920	1.708	1.776	99.774
Greenwood	0.947	0.955	*	1.384	1.513	99.764
Billings	1.362	1.403	1.007	1.584	1.810	99.760
Atlanta	1.025	1.038	*	1.293	1.617	99.765
Seattle	1.442	1.520	0.894	1.353	1.784	99.689
Dallas	0.955	0.963	*	1.448	1.540	99.740
Atlantic City	1.058	1.134	*	1.602	1.827	99.775
Grand Forks	1.509	1.600	*	1.883	2.164	99.777
Prescott	1.178	1.190	*	1.054	1.470	99.743
Oakland	1.070	1.093	*	1.282	1.714	99.715
Boston	1.208	1.361	*	1.768	1.988	99.742
Miami	1.305	1.336	*	1.470	2.037	99.760
Los Angeles	1.137	1.148	*	1.071	1.447	99.751
Juneau	1.799	2.269	*	1.948	2.657	99.685
Anchorage	1.712	2.216	*	2.100	2.794	99.695
Cold Bay	1.540	2.051	*	*	2.297	99.414

* No data available at this operational service level

Figure 2.1 95% Horizontal Accuracy at LNAV/VNAV

LNAV/VNAV 95% Horizontal Accuracy

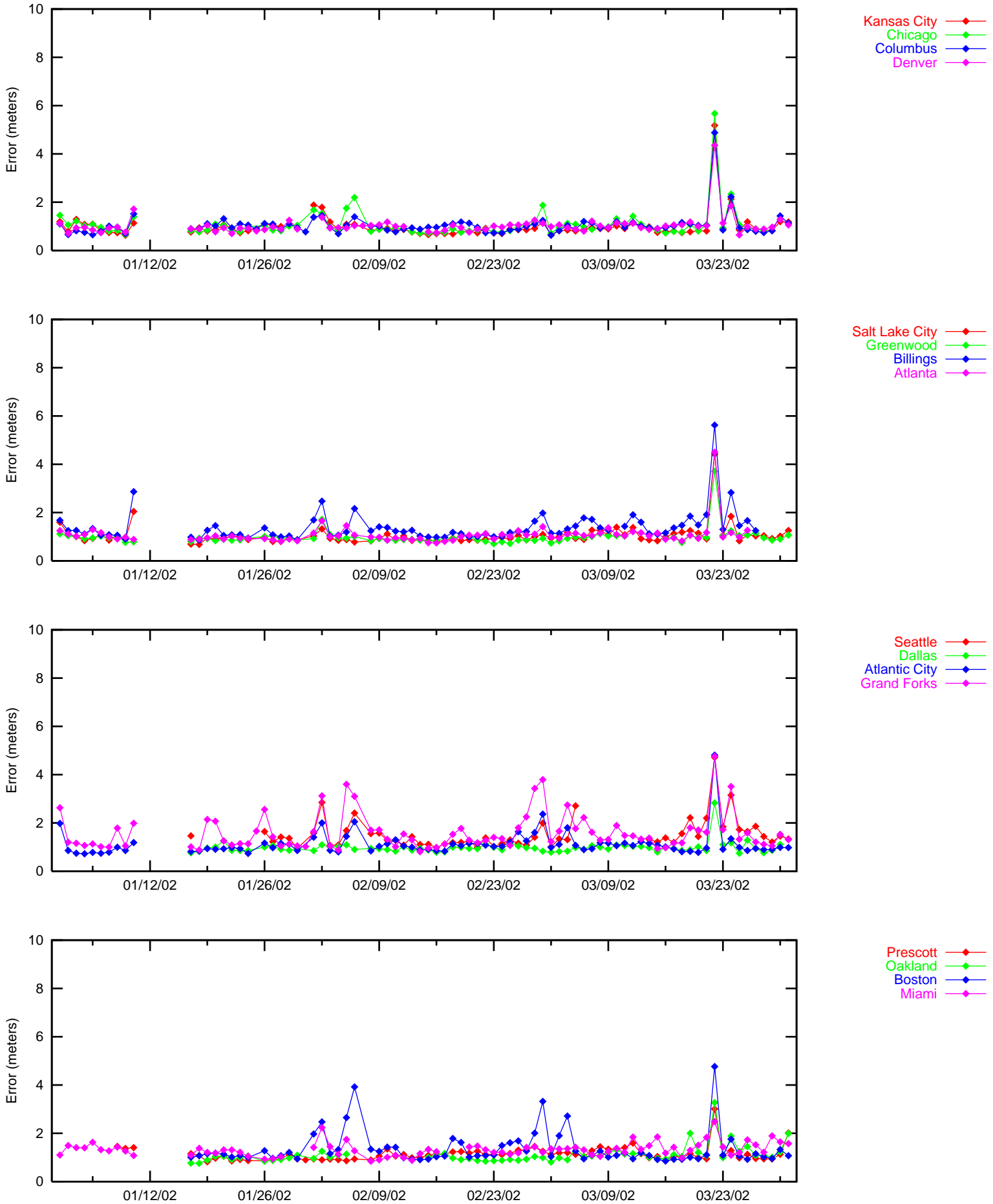
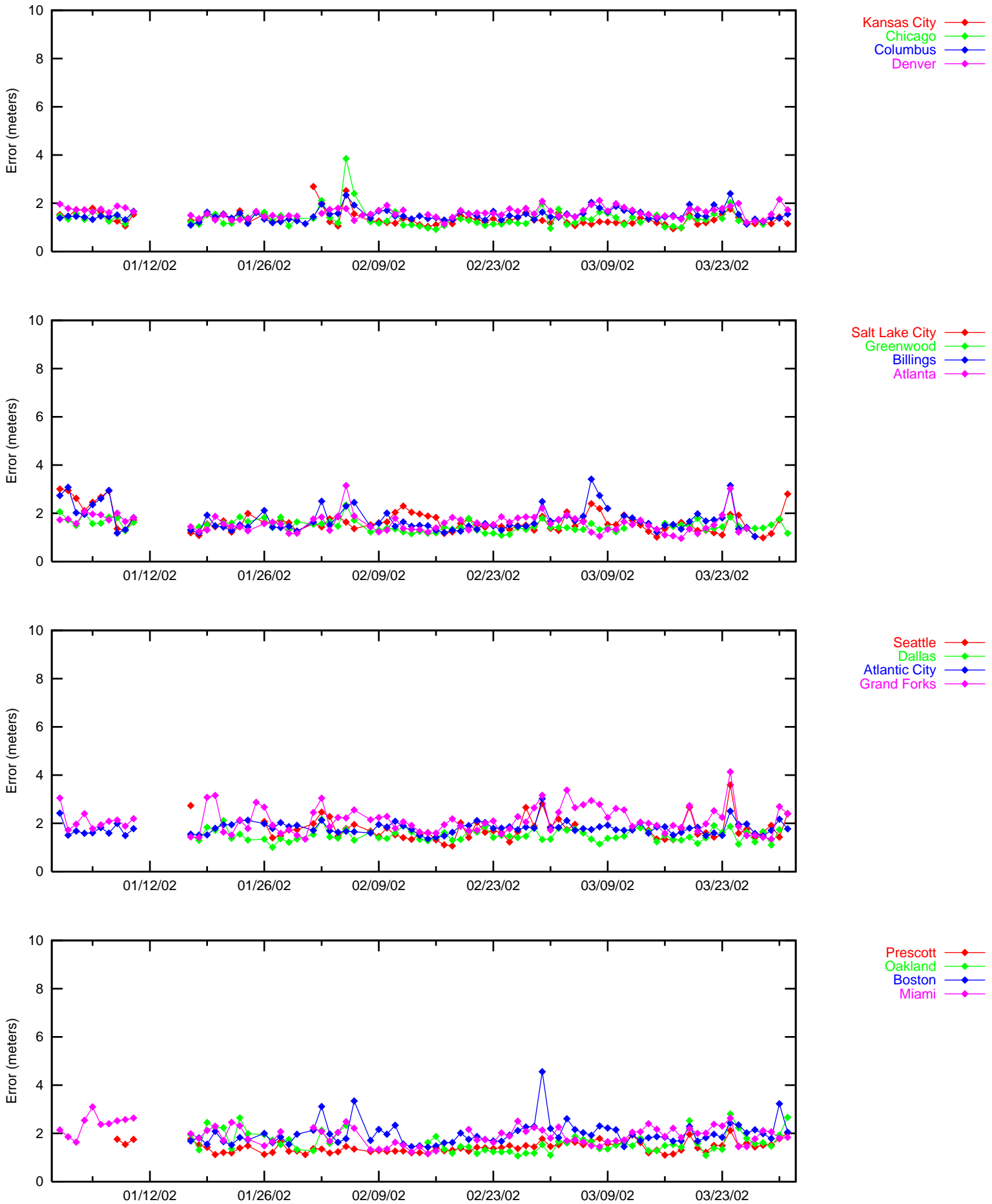


Figure 2.2 95% Vertical Accuracy at LNAV/VNAV

LNAV/VNAV 95% Vertical Accuracy



PA mode Unavailable(>556m)

Count: 0
0.000000 %
Mean: 0.00
StdDev: 0.00
Index95: 0.00

Figure 2.3 Horizontal Triangle Chart for Denver
Site: Denver Date: 01/01/02-03/31/02

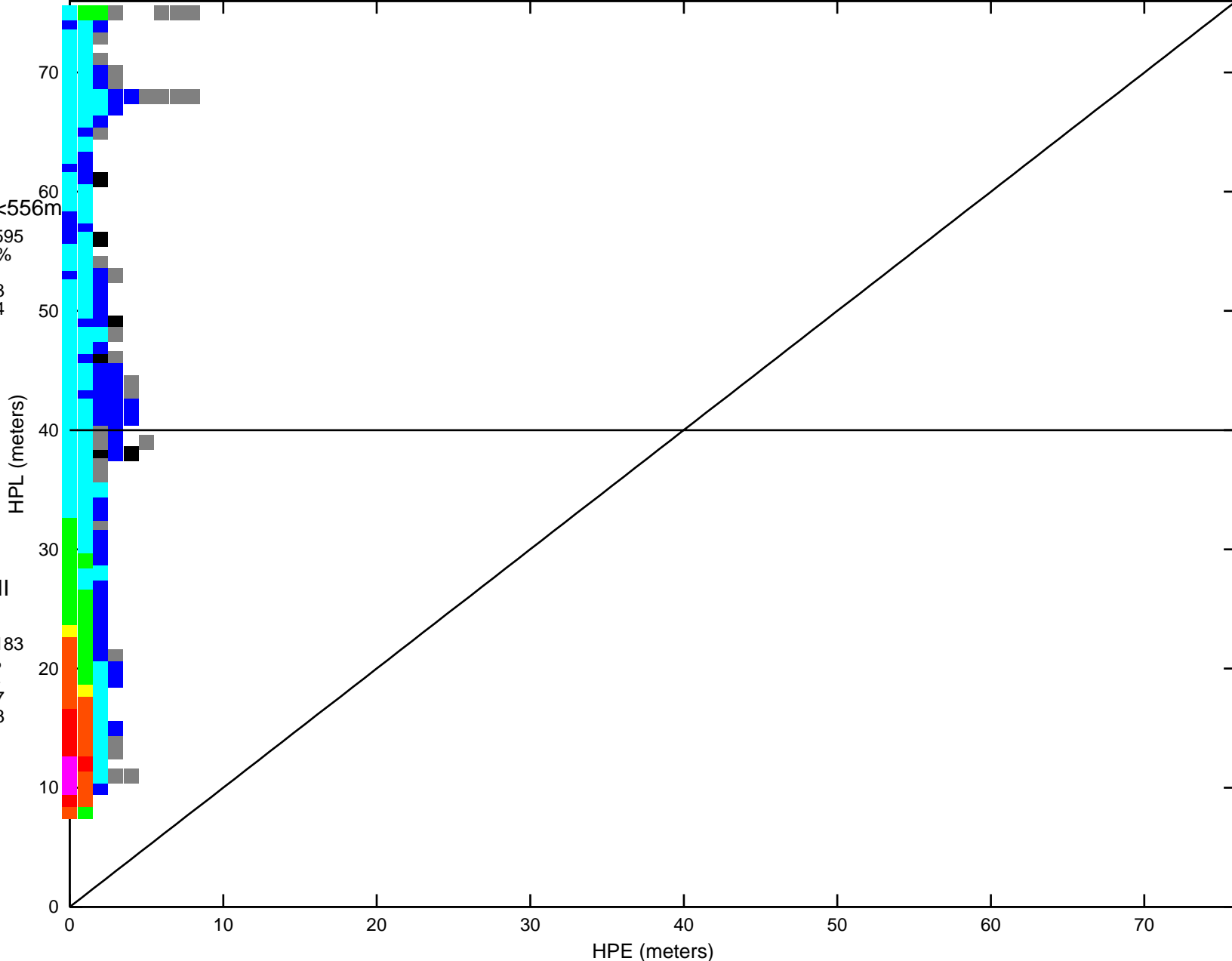
HPE vs HPL 3D PA Histogram

L/VNAV(= $\leq 556m$)

Count: 7455595
100.000000 %
Mean: 0.55
StdDev: 0.33
Index95: 1.04

GLS/APV-II
(= $\leq 40m$)

Count: 7412183
99.417725 %
Mean: 0.54
StdDev: 0.27
Index95: 1.03



- =1
- <10
- <100
- <1000
- <5000
- <10000
- <100000
- <1000000
- <10000000

Alarm Condition

Count: 0
0.000000 %
Mean: 0.00
StdDev: 0.00
Index95: 0.00

Samples: 7455595
Mean: 0.55
StdDev: 0.33
Index95: 1.04

PA Samples: 7438377
Mean: 0.55
StdDev: 0.28
Index95: 1.03

Not PA Samples: 17218
Mean: 3.04
StdDev: 2.67
Index95: 7.99

PA mode Unavailable(>50m)

Count: 35630
0.477896 %
Mean: -0.53
StdDev: 2.15
Index95: 4.01

Figure 2.4 Vertical Triangle Chart for Denver
Site: Denver Date: 01/01/02-03/31/02

VPE vs VPL 3D PA Histogram

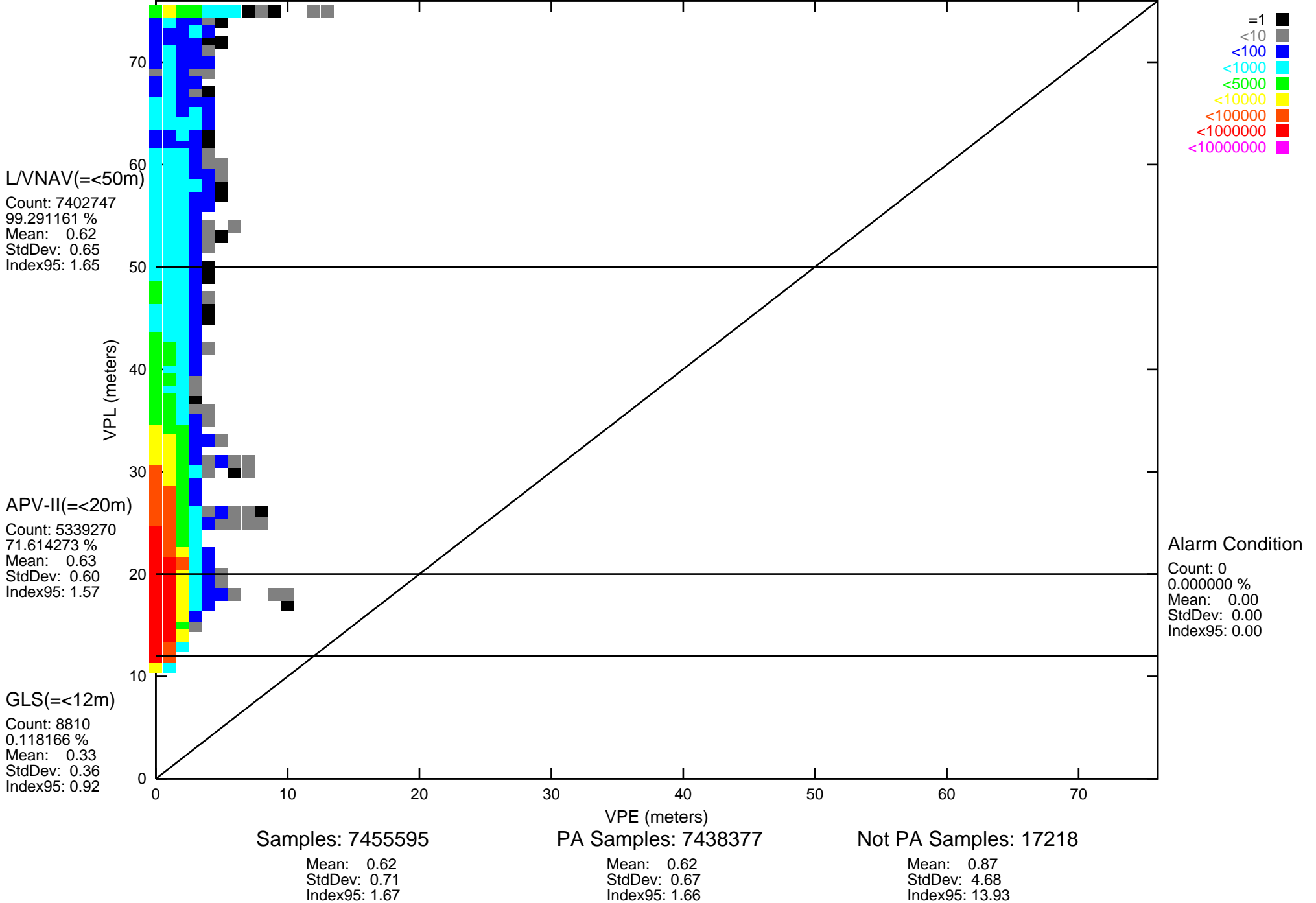
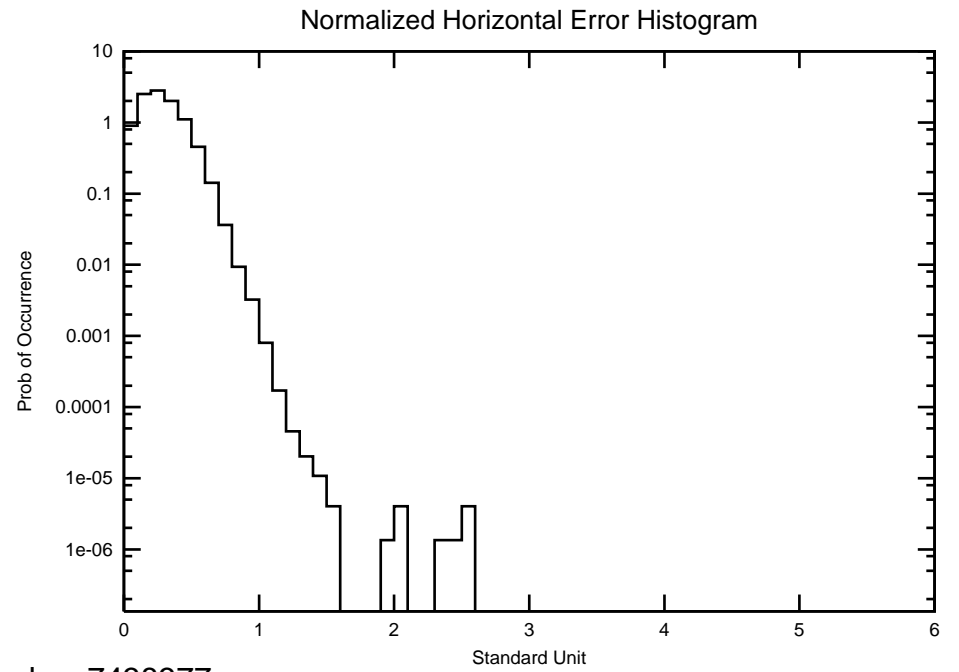
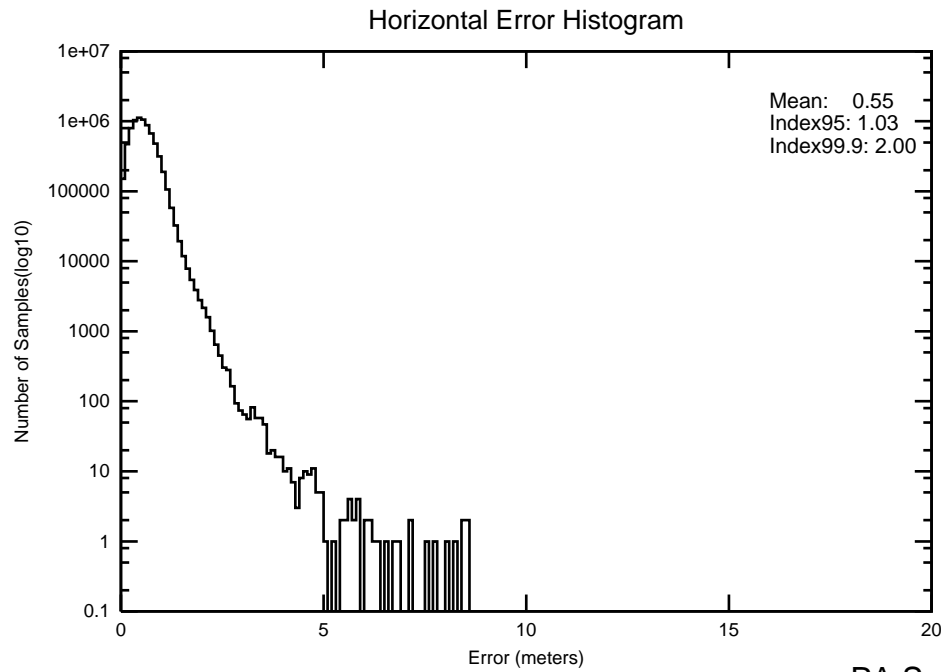
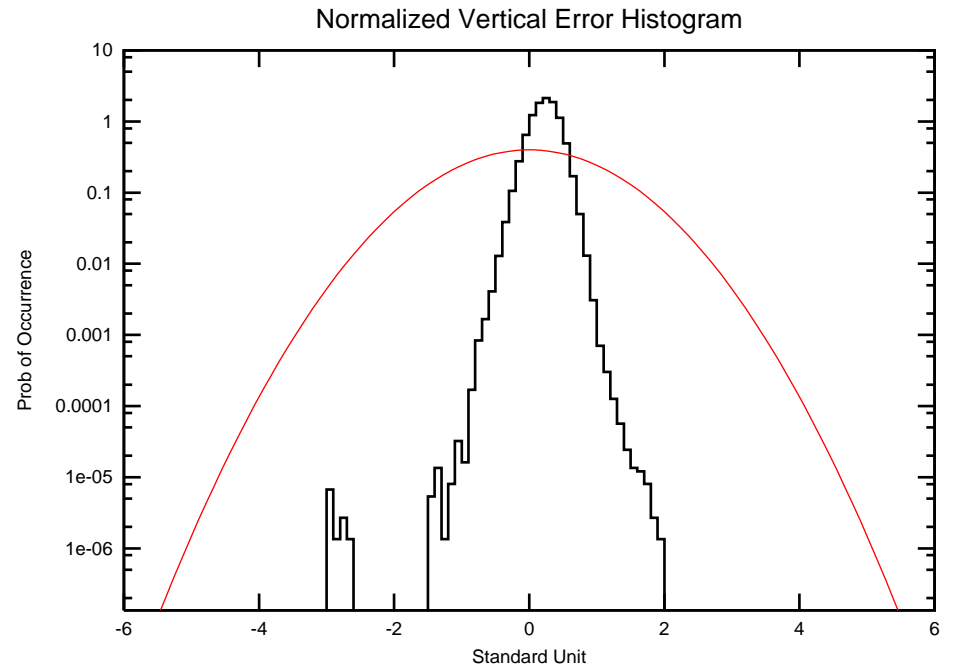
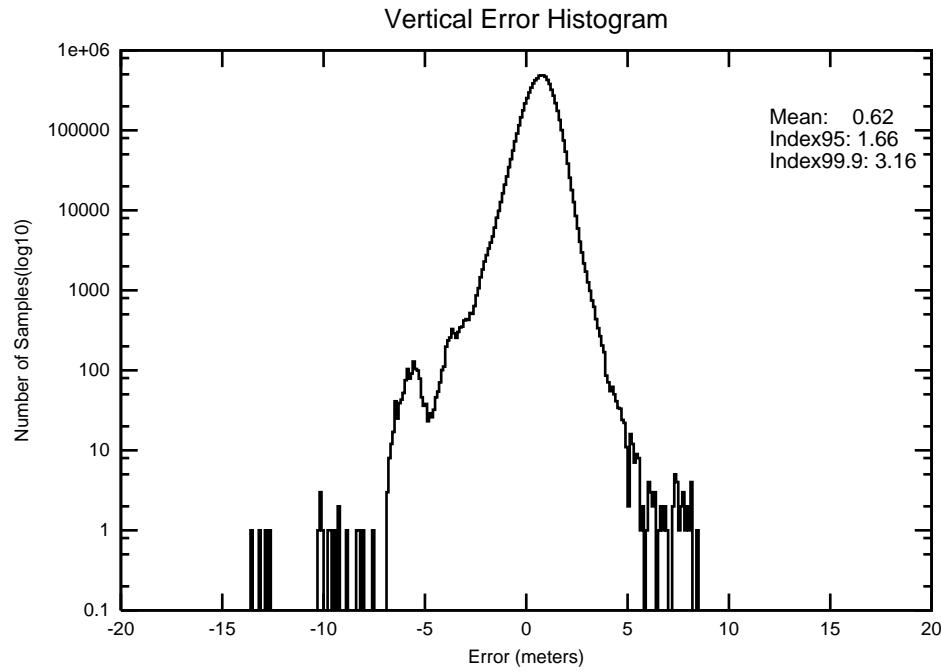


Figure 2.5 2-D Histogram for Denver

Site: Denver

Date: 01/01/02-03/31/02



PA Samples: 7438377

PA mode Unavailable(>556m)

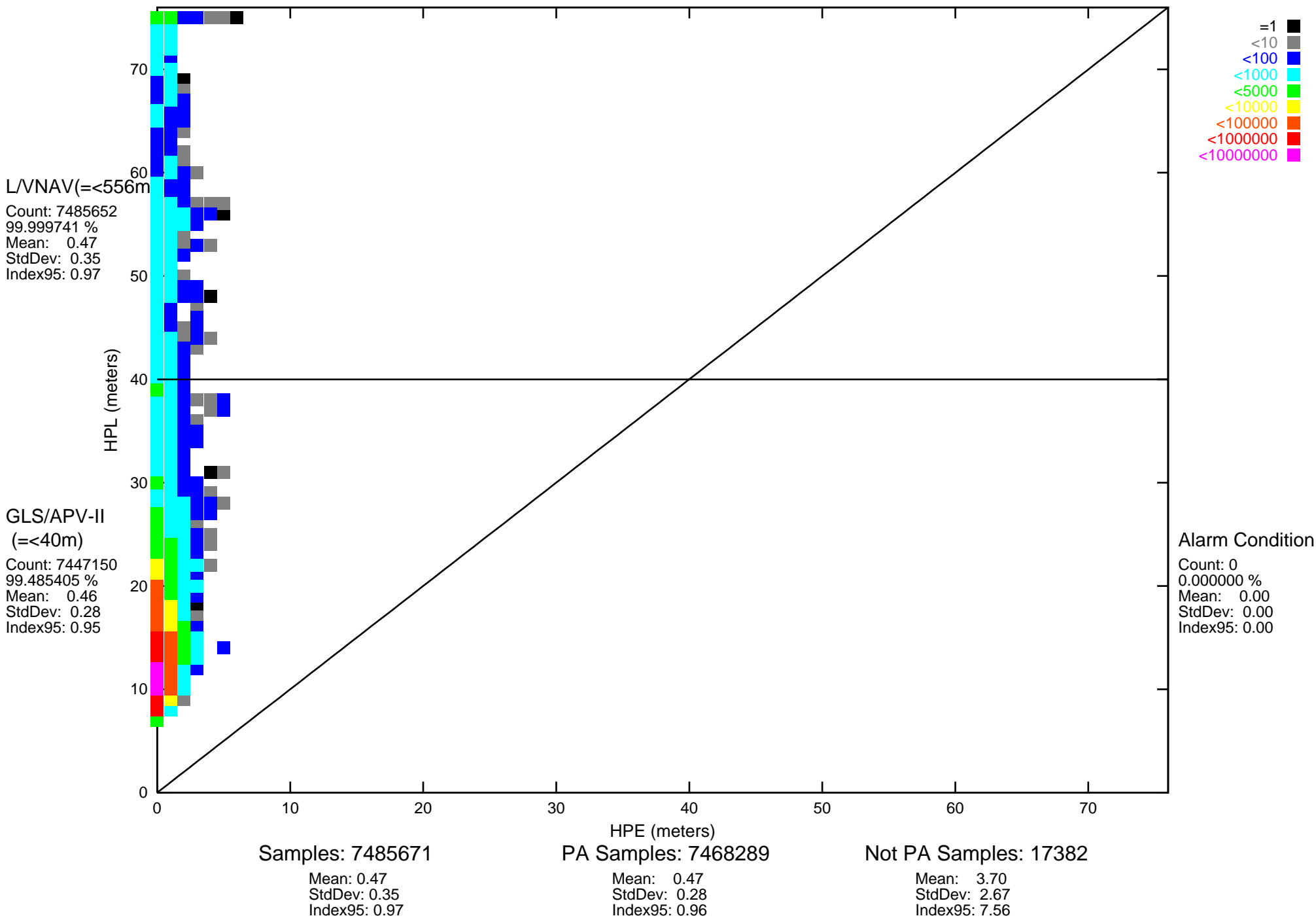
Count: 0
0.000000 %
Mean: 0.00
StdDev: 0.00
Index95: 0.00

Figure 2.6 Horizontal Triangle Chart for Kansas City

Site: Kansas_City

Date: 01/01/02-03/31/02

HPE vs HPL 3D PA Histogram



PA mode Unavailable(>50m)

Count: 30058
0.401540 %
Mean: -1.32
StdDev: 2.11
Index95: 4.93

Figure 2.7 Vertical Triangle Chart for Kansas City

Site: Kansas_City

Date: 01/01/02-03/31/02

VPE vs VPL 3D PA Histogram

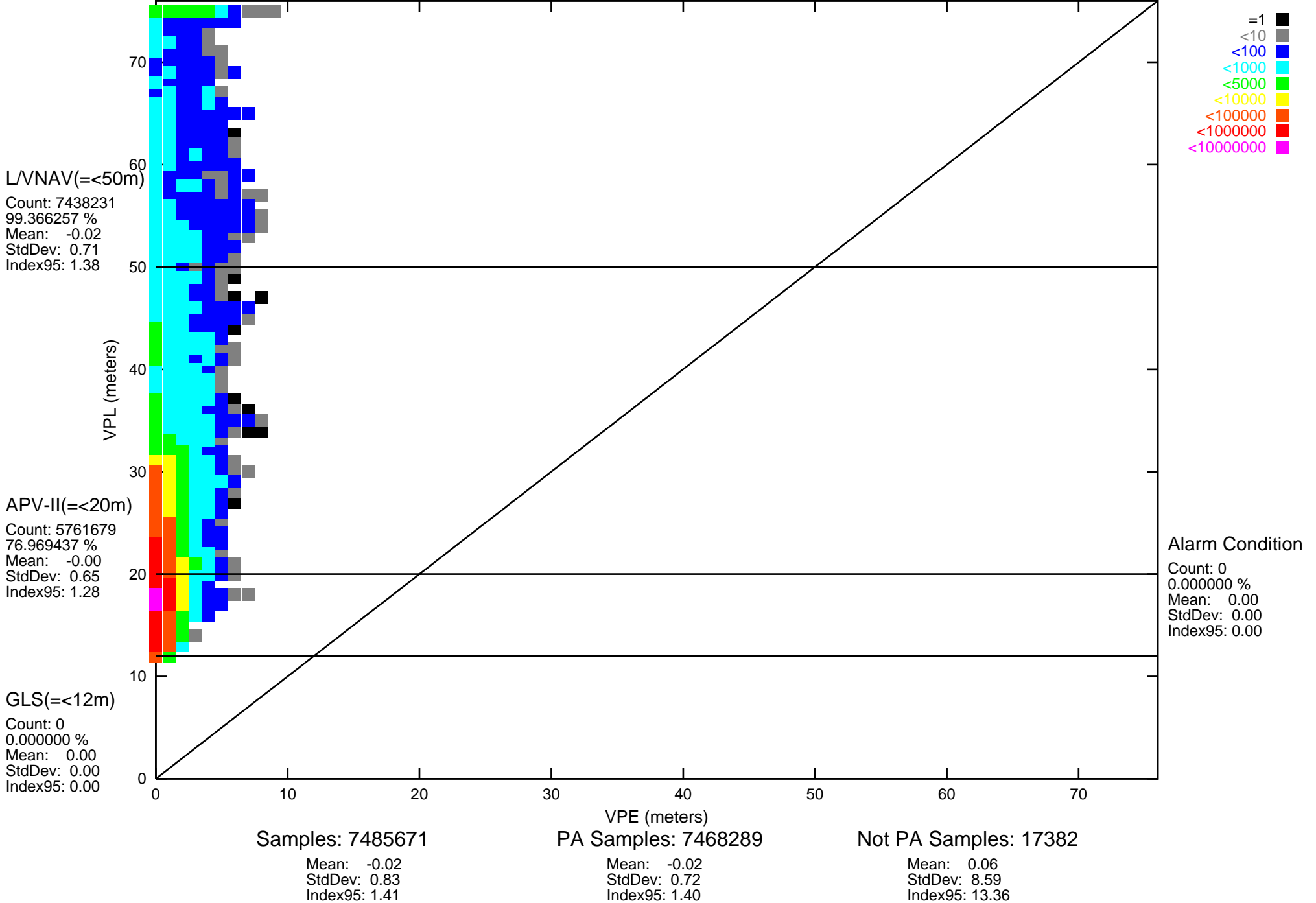
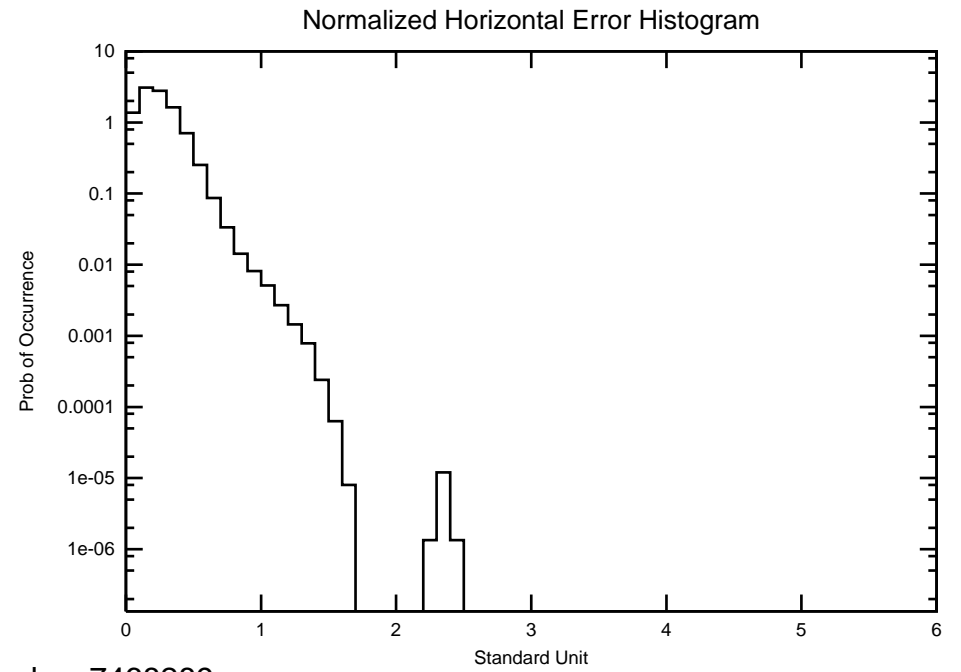
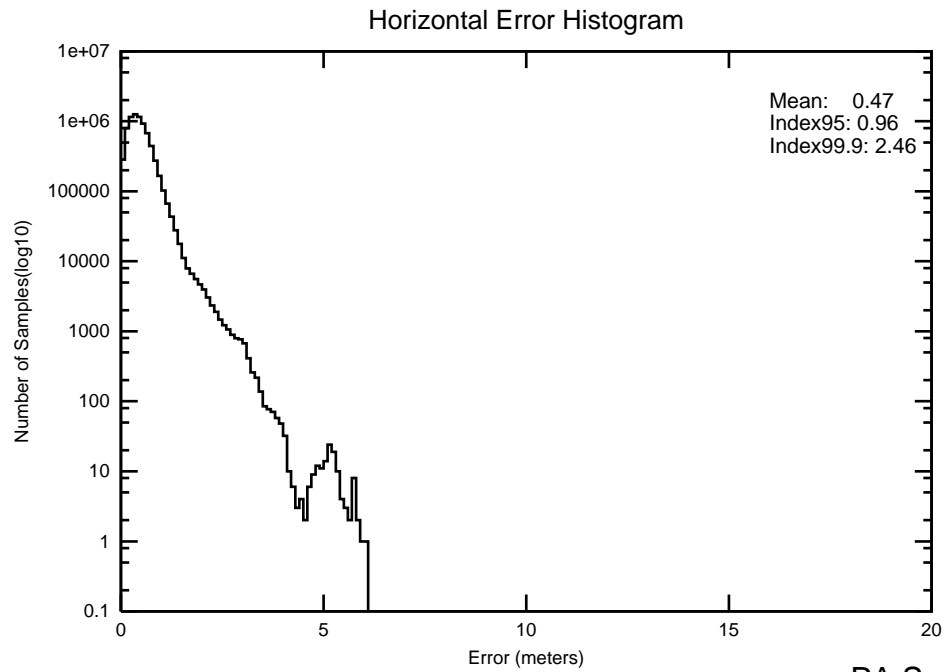
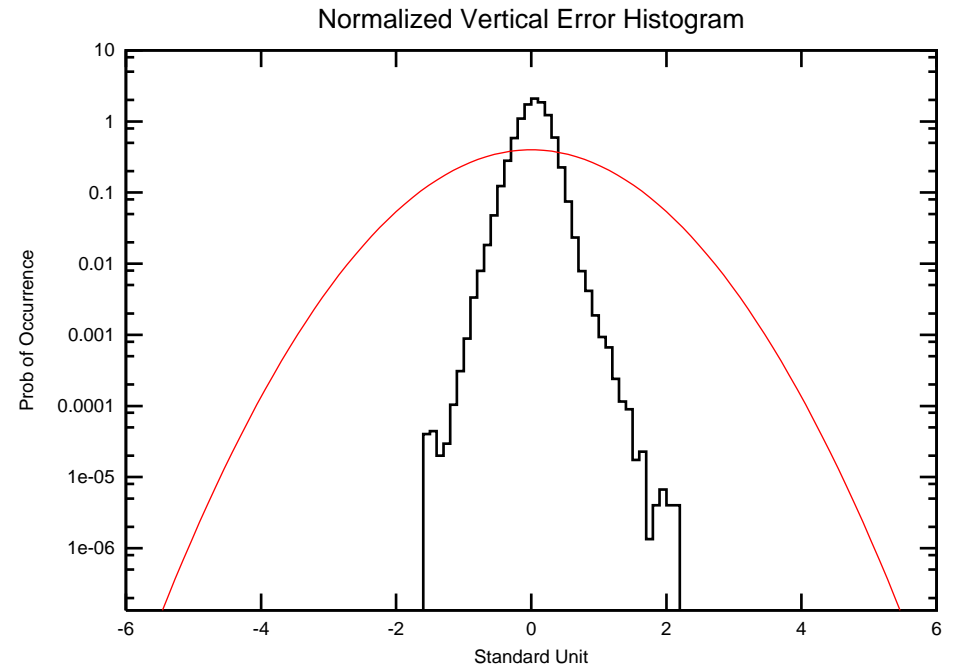
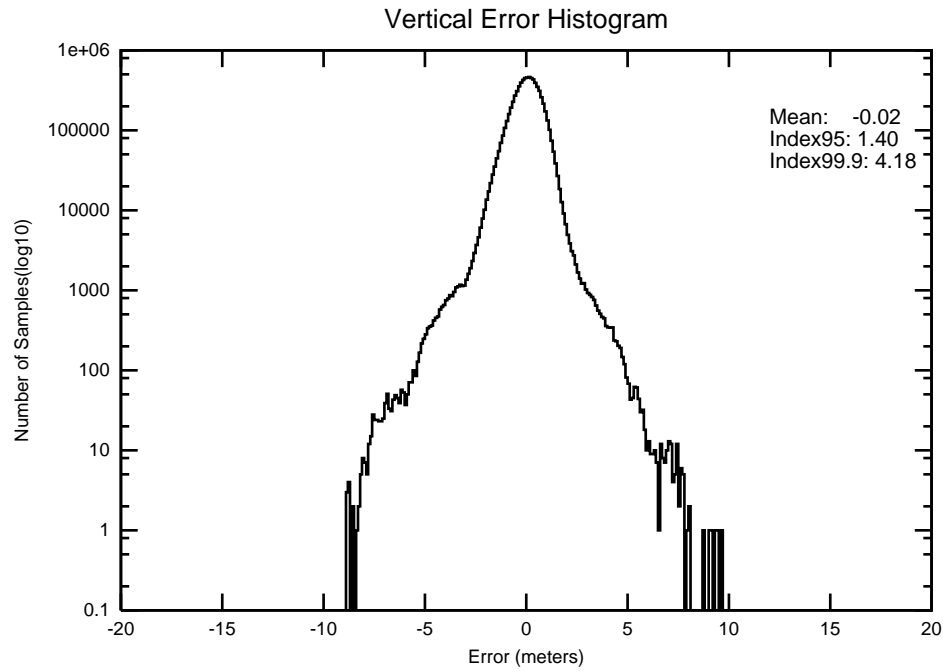


Figure 2.8 2-D Histogram for Kansas City

Site: Kansas_City

Date: 01/01/02-03/31/02



PA Samples: 7468289

PA mode Unavailable(>556m)

Count: 39
0.000622 %
Mean: 6.33
StdDev: 3.85
Index95: 13.00

Figure 2.9 Horizontal Triangle Chart for Juneau

Site: Juneau Date: 01/01/02-03/31/02

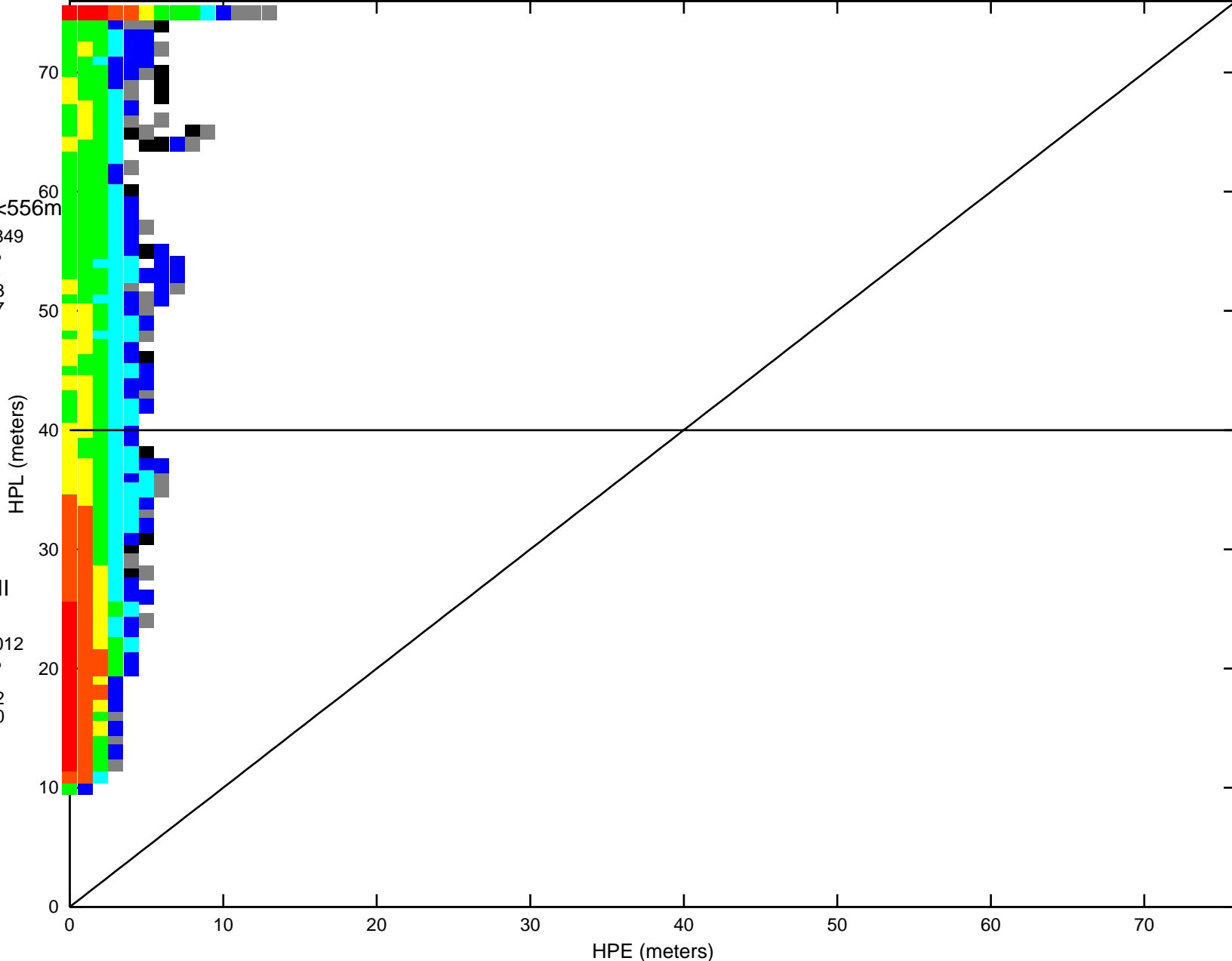
HPE vs HPL 3D PA Histogram

L/VNAV(= $\leq 556m$)

Count: 6265849
99.999329 %
Mean: 0.93
StdDev: 0.73
Index95: 2.27

GLS/APV-II
(= $\leq 40m$)

Count: 5196012
82.925346 %
Mean: 0.78
StdDev: 0.52
Index95: 1.80



- =1
- <10
- <100
- <1000
- <5000
- <10000
- <100000
- <1000000
- <10000000

Alarm Condition

Count: 0
0.000000 %
Mean: 0.00
StdDev: 0.00
Index95: 0.00

Samples: 6265891

Mean: 0.93
StdDev: 0.73
Index95: 2.27

PA Samples: 6246169

Mean: 0.92
StdDev: 0.72
Index95: 2.24

Not PA Samples: 19722

Mean: 3.11
StdDev: 1.76
Index95: 5.69

PA mode Unavailable(>50m)

Count: 1204057
19.216055 %
Mean: 0.59
StdDev: 2.28
Index95: 4.71

Figure 2.10 Vertical Triangle Chart for Juneau
Site: Juneau Date: 01/01/02-03/31/02

VPE vs VPL 3D PA Histogram

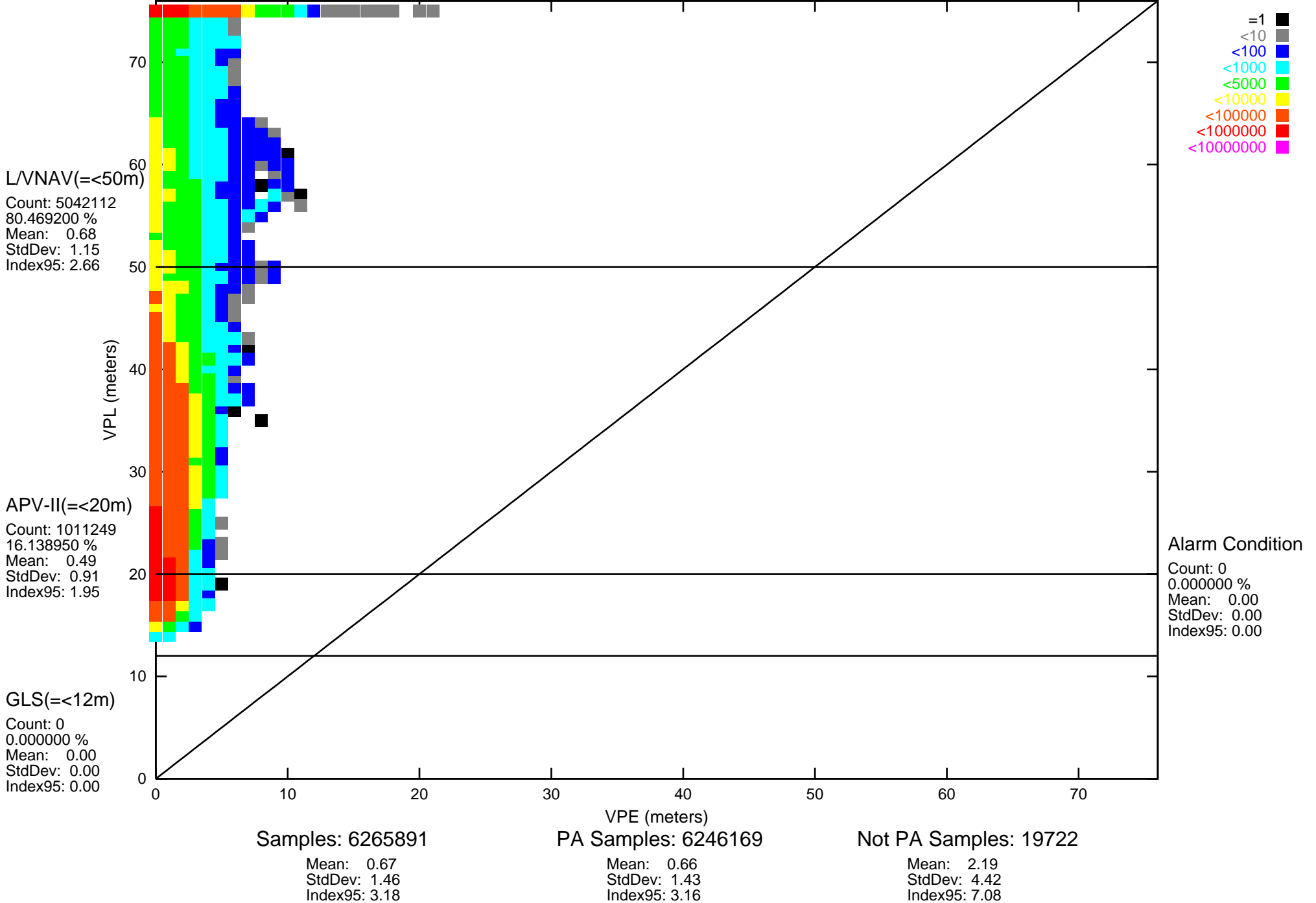
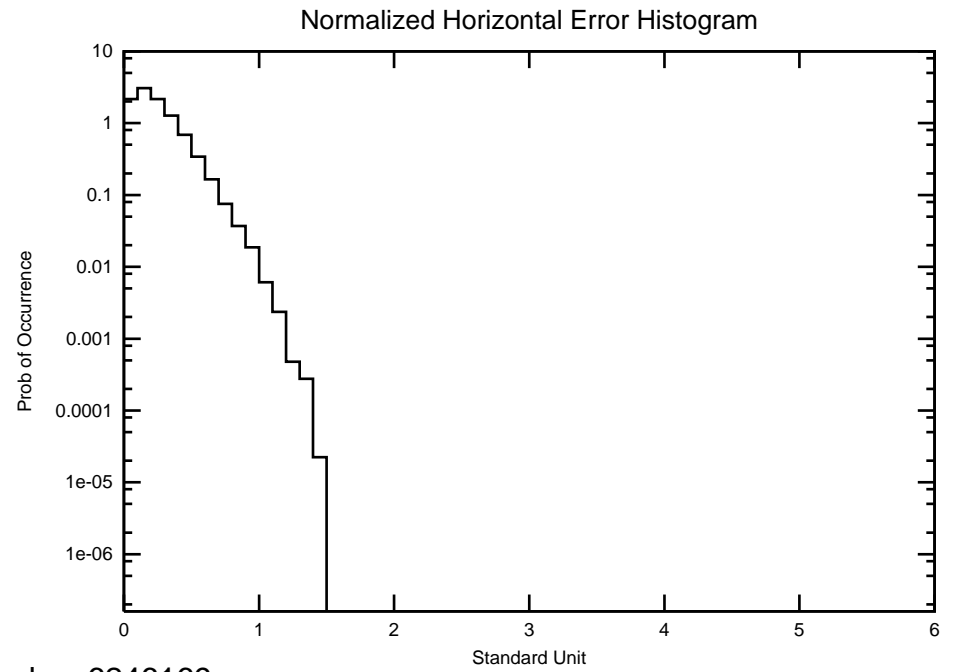
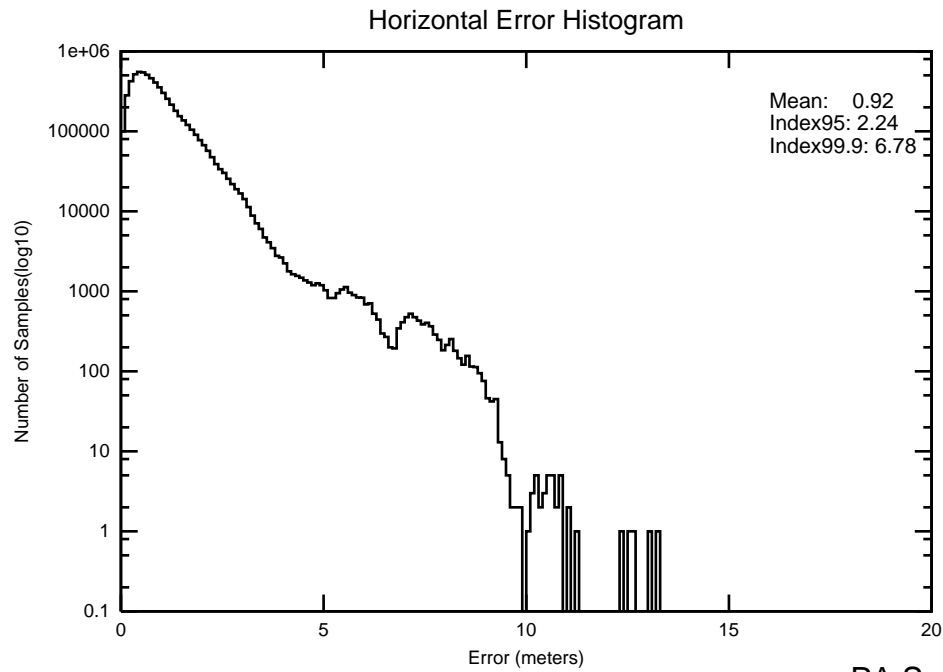
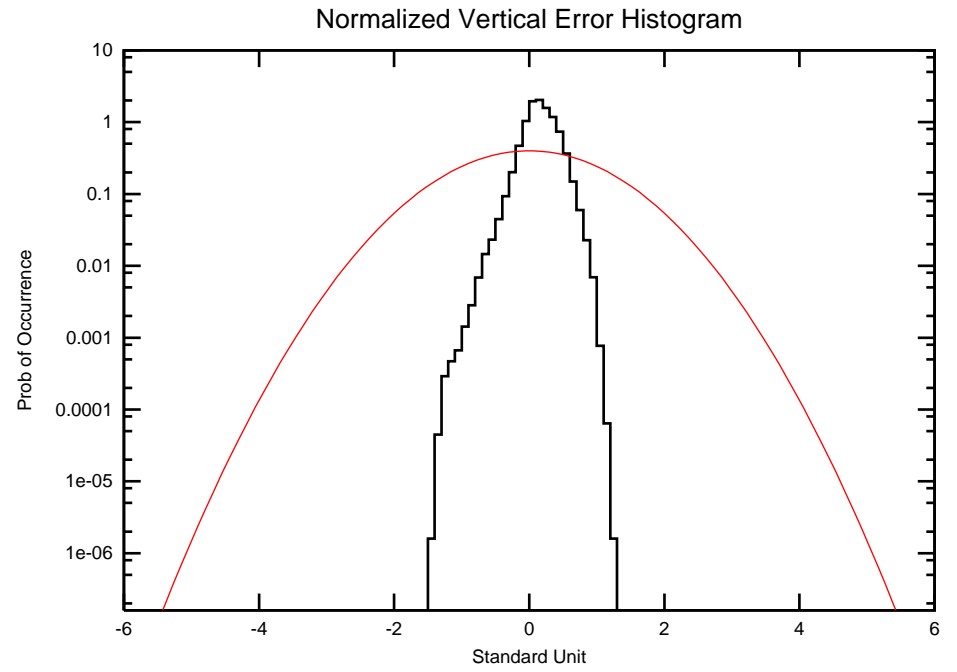
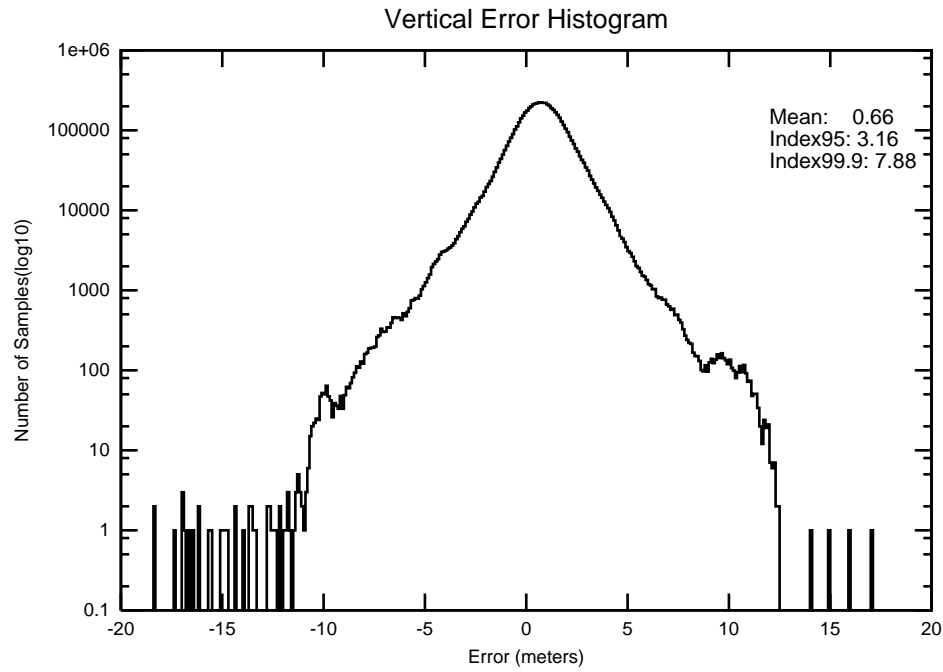


Figure 2.11 2-D Histogram for Juneau

Site: Juneau

Date: 01/01/02-03/31/02



PA Samples: 6246169

3.0 Availability

WAAS availability evaluation estimates the probability that the WAAS can provide Operational Service Levels (GLS, APV-2, LPV, and APV-1(LNAV/VNAV)) defined in Table 2.1. At each receiver, the WAAS message, along with the GPS/GEO satellites tracked, were used to produce WAAS protection levels in accordance with MOPS. Table 3.1 shows the protection levels that were maintained for 95% of the time for each receiver location for the quarter. The table also included the percentage in PA mode as described in section 2.0. Table 3.2 presents the percentage of time that WAAS operational service levels were available at each receiver location.

The geographic location of each receiver evaluated is depicted in Figure 3.1, along with the 95% VPL value, the WAAS LPV and APV-1(LNAV/VNAV) instantaneous availability percentage at each location for the quarter.

Table 3.1 95% Protection Level

Location	95% HPL (meters)	95% VPL (meters)	Percentage in PA mode
Kansas City	15.004	24.322	99.768
Chicago	16.074	25.993	99.766
Columbus	15.803	25.073	99.775
Denver	16.232	25.829	99.769
Salt Lake City	16.428	26.087	99.774
Greenwood	15.294	25.481	99.764
Billings	18.076	27.931	99.760
Atlanta	15.203	26.529	99.765
Seattle	24.366	35.318	99.689
Dallas	16.004	26.139	99.740
Atlantic City	19.311	32.047	99.775
Grand Forks	25.564	34.750	99.777
Prescott	23.286	36.965	99.743
Oakland	25.522	37.544	99.715
Boston	25.374	42.746	99.742
Miami	25.511	37.514	99.760
Los Angeles	26.152	38.527	99.751
Juneau	108.846	161.678	99.685
Anchorage	117.084	180.227	99.695
Cold Bay	129.102	189.714	99.414

Table 3.2 Instantaneous Availability Statistics

Location	GLS (HAL = 40 m VAL = 12 m) % of time	APV-2 (HAL = 40 m VAL = 20 m) % of time	LPV (HAL = 40 VAL = 50 m) % of time	LNAV/VNAV (HAL = 556m VAL = 50 m) % of time
Kansas City	*	0.769694	0.993386	0.993663
Chicago	*	0.747301	0.985136	0.985744
Columbus	*	0.733274	0.990016	0.990602
Denver	0.001182	0.716143	0.992578	0.992912
Salt Lake City	0.001244	0.710558	0.992925	0.993076
Greenwood	*	0.652954	0.996531	0.996827
Billings	0.000998	0.668680	0.985276	0.986950
Atlanta	*	0.650228	0.994815	0.995321
Seattle	0.000126	0.539471	0.970499	0.972845
Dallas	*	0.552350	0.996981	0.997071
Atlantic City	*	0.448888	0.976270	0.978291
Grand Forks	*	0.316964	0.969761	0.971815
Prescott	*	0.294945	0.987477	0.988337
Oakland	*	0.242496	0.984519	0.985802
Boston	*	0.225954	0.960532	0.961438
Miami	*	0.182188	0.979321	0.982497
Los Angeles	*	0.233496	0.986176	0.987573
Juneau	*	0.161390	0.799214	0.804692
Anchorage	*	0.041446	0.700160	0.706150
Cold Bay	*	*	0.424830	0.483970

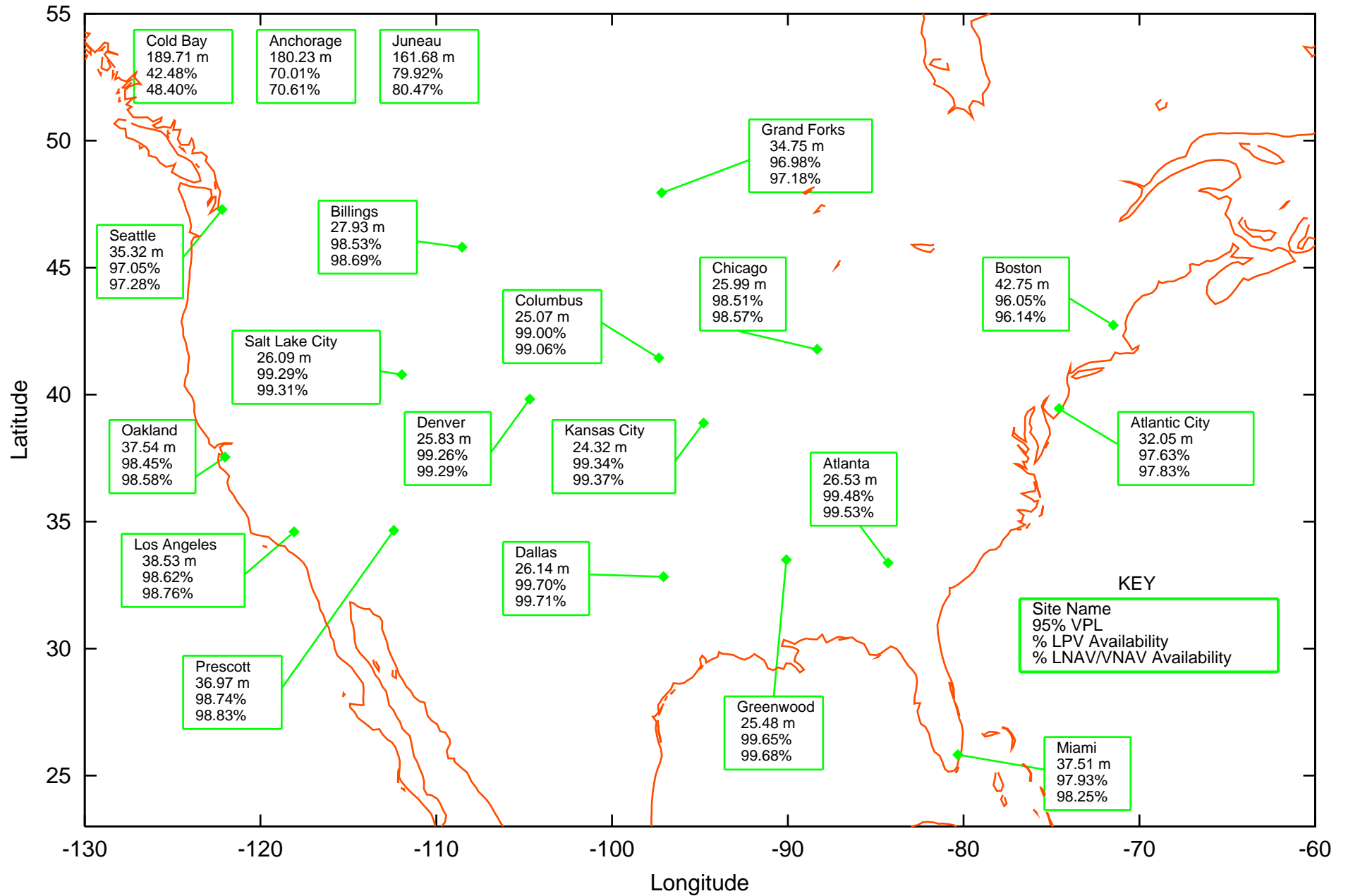
* No data is available at this operational service level.

During the evaluated period, the maximum 95% HPL and VPL for CONUS sites are 26.152 meters at Los Angeles and 42.746 meters at Boston, respectively. The minimum 95% HPL and VPL for CONUS sites are 15.004 meters and 24.322 meters at Kansas City. For CONUS sites, LNAV/VNAV instantaneous availability ranges between 96.14% and 99.71%. For the Alaska sites, LNAV/VNAV instantaneous availability ranges between 48.40% and 80.47%.

Figure 3.1 95% VPL, LPV, and LNAV/VNAV Availability

95% VPL, LPV and LNAV/VNAV Availability

January 01 to March 31, 2002



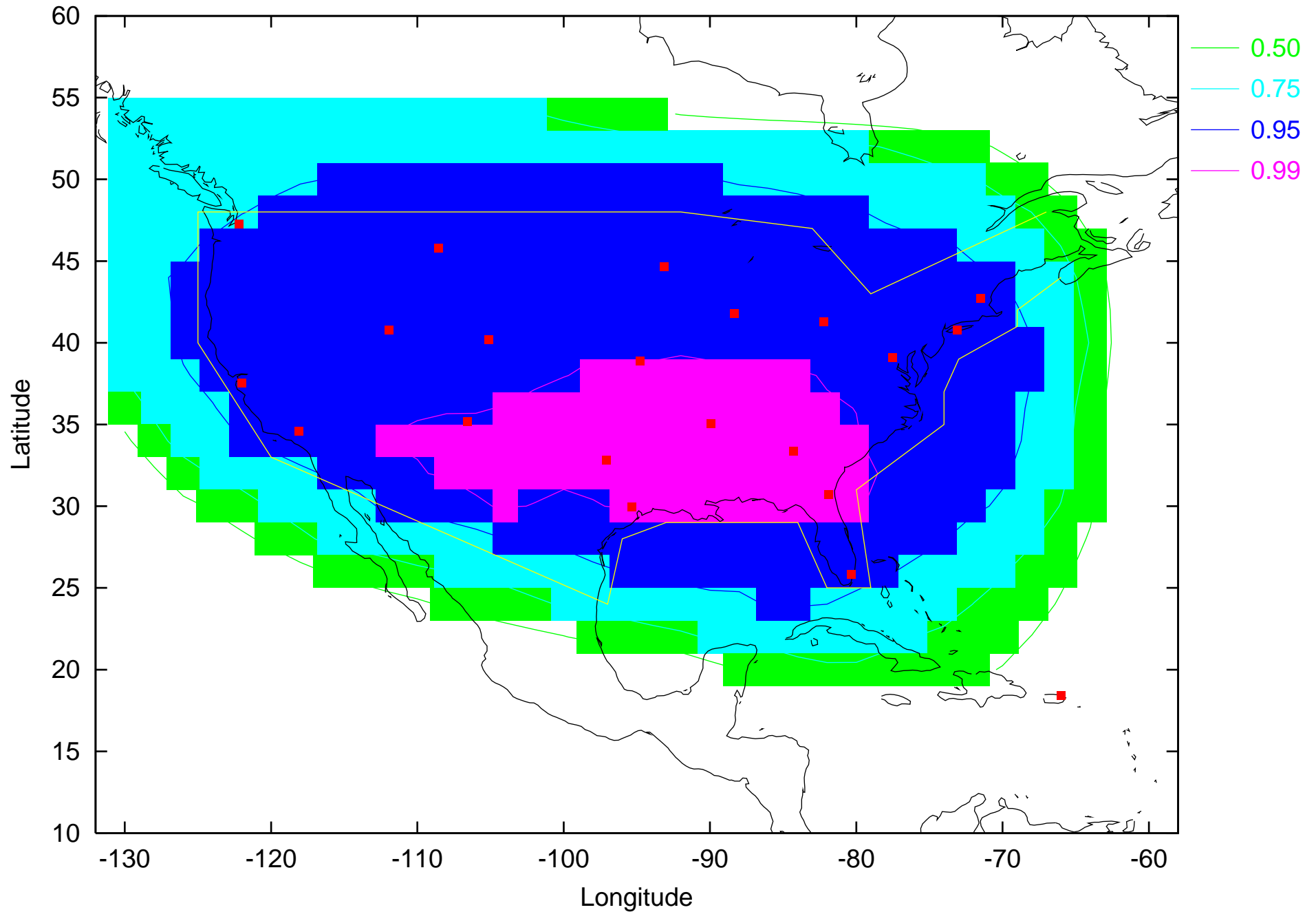
4.0 Coverage

WAAS Coverage area evaluation estimates the percent of CONUS where WAAS is providing LNAV/VNAV service. The WAAS message, along with GPS/GEO satellite status, is used to determine WAAS availability across North America at an array of locations that are spaced two degrees apart. If the protection levels at a given location meet LNAV/VNAV alert limits (VAL = 50 and HAL = 556) 95% of the time, then the location is considered to be available.

Figures 4.1 to 4.3 show the WAAS coverage area of each month for this quarter. The portion of CONUS, where WAAS provides LNAV/VNAV service, is included in the 95% availability area colored in blue, and 99% availability area colored in purple. Figure 4.4 shows the daily WAAS LNAV/VNAV coverage and Ionospheric Storm Kp index values for this quarter. Note the LNAV/VNAV coverage is 0% for 01/16/02 and 03/22/02. The drop in coverage for 01/16/02 is caused by WAAS setting GPS SVs to not monitored and for 03/22/02 is caused by WAAS SIS outage. During both days WAAS availability at all NSTB and WAAS receiver location dropped to approximately 90%.

WAAS Coverage LNAV/VNAV

January 2002

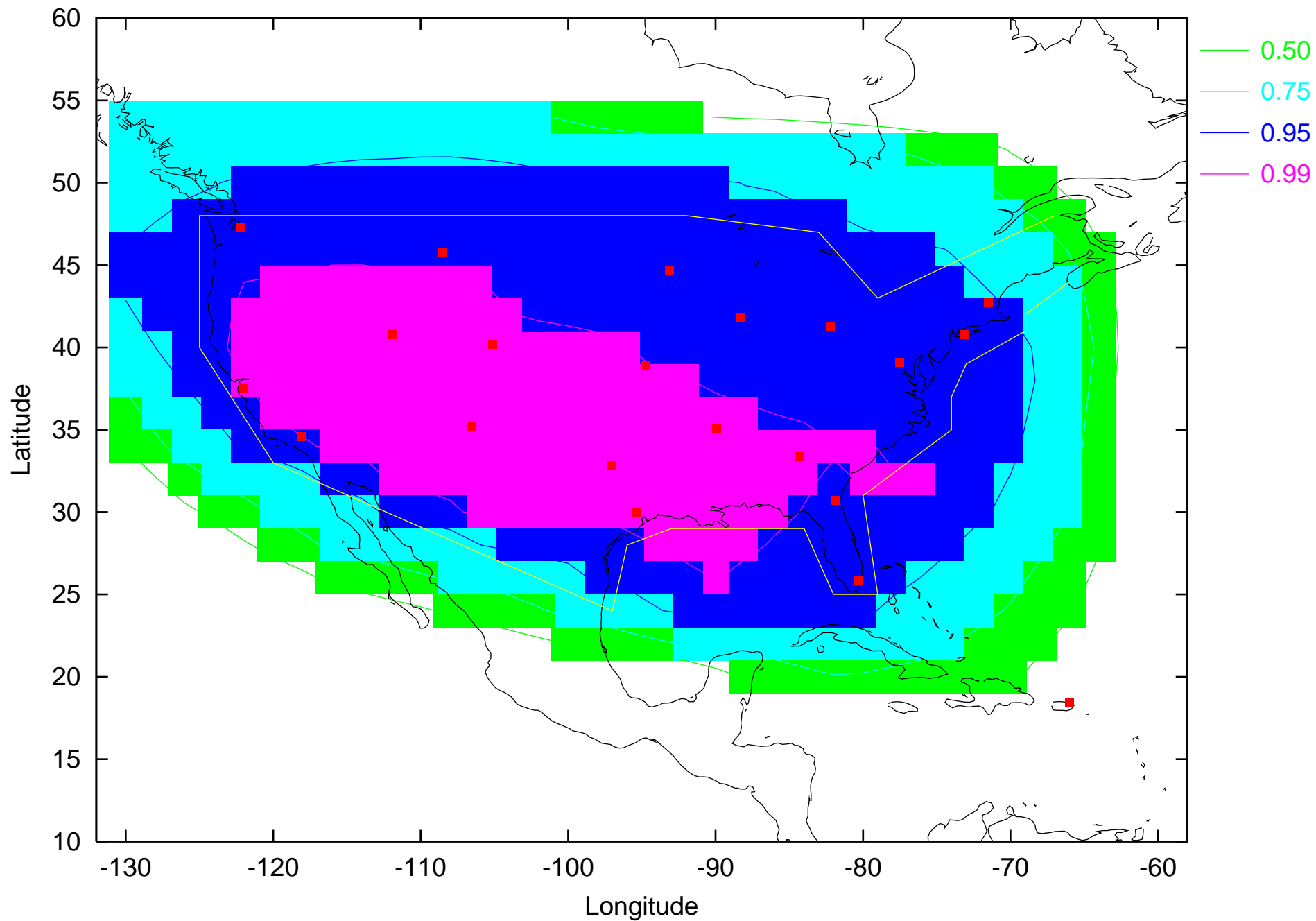


CONUS Coverage = 96 % VAL = 50 m

Figure 4.1 WAAS Coverage - January

WAAS Coverage LNAV/VNAV

February 2002

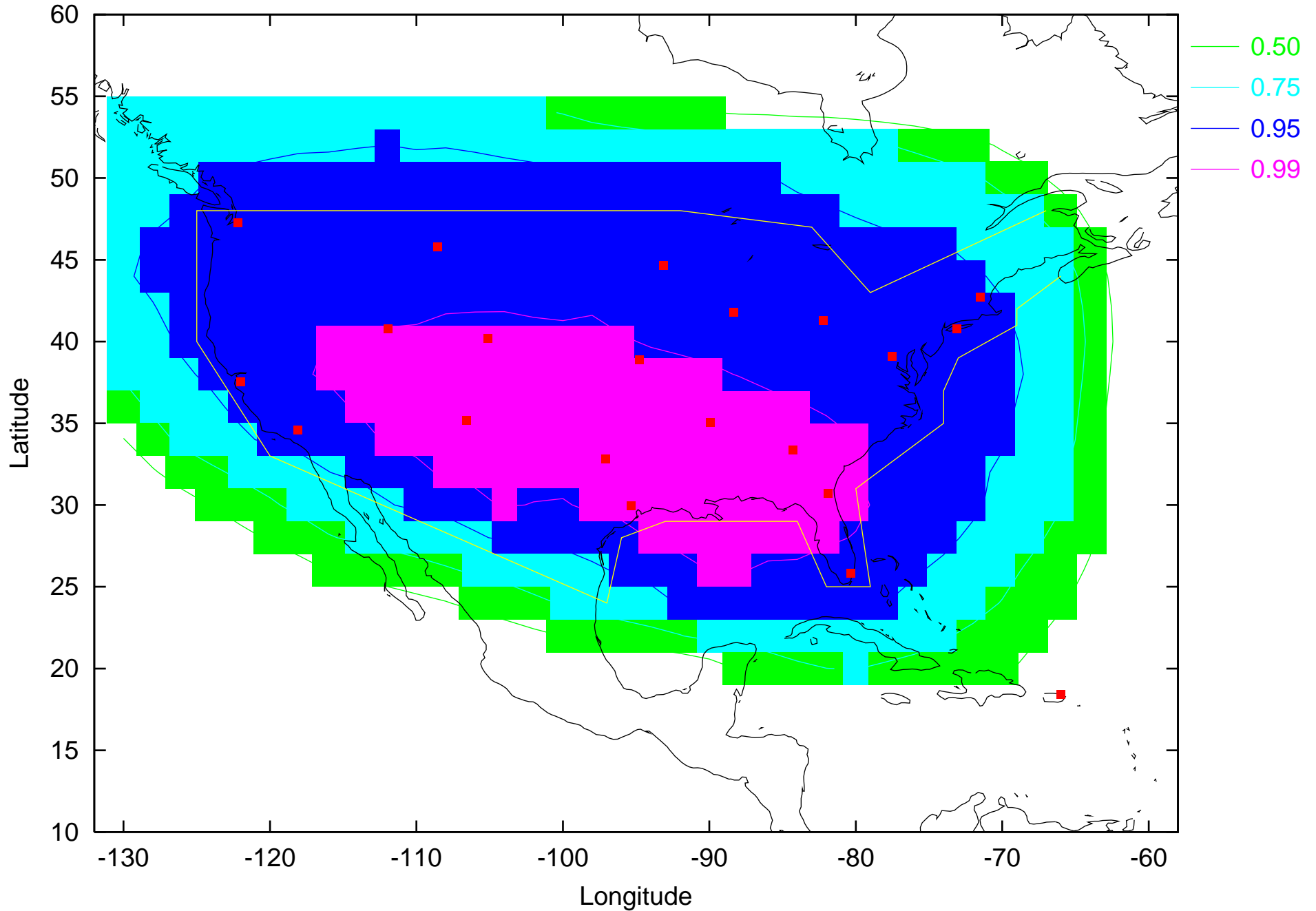


CONUS Coverage = 96 % VAL = 50 m

Figure 4.2 WAAS Coverage - February

WAAS Coverage LNAV/VNAV

March 2002



CONUS Coverage = 95 % VAL = 50 m

Figure 4.3 WAAS Coverage - March

WAAS LNAV/VNAV CONUS Coverage

Kp*10 ◆

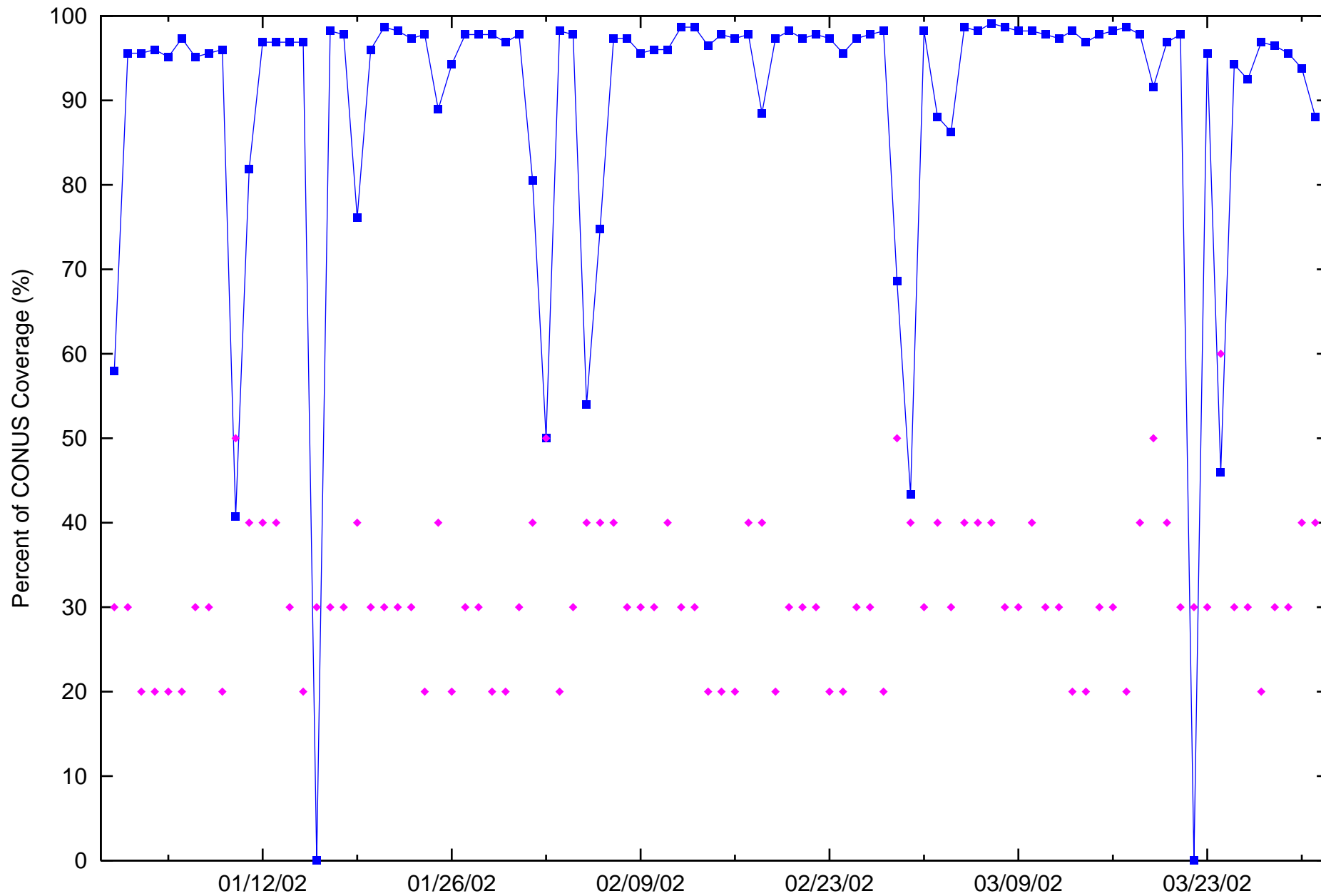


Figure 4.4 Daily WAAS LNAV/VNAV CONUS Coverage

5.0 Continuity

5.1 NPA Continuity of Navigation

NPA continuity of navigation was evaluated by monitoring the accuracy performance throughout each flight hour. Navigation error data for each site was divided into multiple bins consisting of 3600 data samples. The position accuracy data for each bin was analyzed and statistics were generated to evaluate the data. If the horizontal position error is less than 100 meters 95% of the time, then the continuity of navigation flag is set to “1” to indicate the continuity of navigation is met for that particular flight hour. The continuity of navigation percentile statistic was computed for each reference site by summing the continuity of navigation flags of “1” together and dividing by the total number of test hours (bins) accumulated. The NPA Continuity of Navigation column of Table 5.1 shows all evaluated sites for this quarter have the maximum probability of 1.

5.2 NPA Continuity of Fault Detection

NPA continuity of fault detection was evaluated by monitoring the integrity performance throughout each flight hour. Navigation error data for each reference site was divided into multiple bins consisting of 3600 data samples. The horizontal and vertical position error data for each bin was analyzed and statistics were generated to evaluate the data as follows:

- No HMIs have occurred in the horizontal or vertical dimensions.
- User maintains either PA or NPA navigation mode of operation as defined in section 2.0.

If the above conditions are met, then the continuity of fault detection flag is set to “1” to indicate the continuity of fault detection is met for that particular flight hour. The continuity of fault detection percentile statistic was computed for each reference site by summing the continuity of fault detection flags of “1” together and dividing by the total number of test hours (bins) accumulated. The NPA Continuity of Fault Detection column of Table 5.1 shows the probability ranges from 0.967952 to 0.987052. This probability is much lower than expected for two reasons: first, a number of SV alerts were sent by the WAAS, and second, interruptions of the WAAS SIS that occurred during a GEO switchover. Both of these factors can cause the SV fast corrections to time out reducing the navigation mode to GPS only operation.

5.3 LPV Continuity of Function

LPV continuity of function was evaluated by monitoring the accuracy and integrity performance throughout each flight segment. Navigation error data for each reference site was divided into multiple bins consisting of 150 data samples. The position accuracy and integrity performance data for each bin was analyzed and statistics were generated to evaluate the data as follows:

- The horizontal and vertical position errors are less than 7.6 meter 95% of the time for each bin.
- No HMIs have occurred in the horizontal or vertical dimensions.
- User maintains PA mode of operation as defined in section 2.0.
- VPL is less than or equal to 50m and HPL is less than or equal to 40 m.

If the above conditions are met, then the continuity of function flag is set to “1” to indicate the continuity of function is met for that particular flight segment. The continuity of function percentile statistic was computed for each reference site by summing the continuity of function flags of “1” together and dividing by the total number of test segments (bins) accumulated. LPV Continuity of Function column of Table 5.1 shows the probability for continuity of function ranges from 0.384140(Cold Bay) to 0.997130(Dallas).

5.4 LNAV/VNAV Continuity of Function

LNAV/VNAV continuity of function was evaluated by monitoring the accuracy and integrity performance throughout each flight segment. Navigation error data for each reference site was divided into multiple bins consisting of 150 data samples. The position accuracy and integrity performance data for each bin was analyzed and statistics were generated to evaluate the data as follows:

- The horizontal and vertical position errors are less than 7.6 meter 95% of the time for each bin.
- No HMIs have occurred in the horizontal or vertical dimensions.
- User maintains PA mode of operation as defined in section 2.0.
- VPL is less than or equal to 50m and HPL is less than or equal to 556 m.

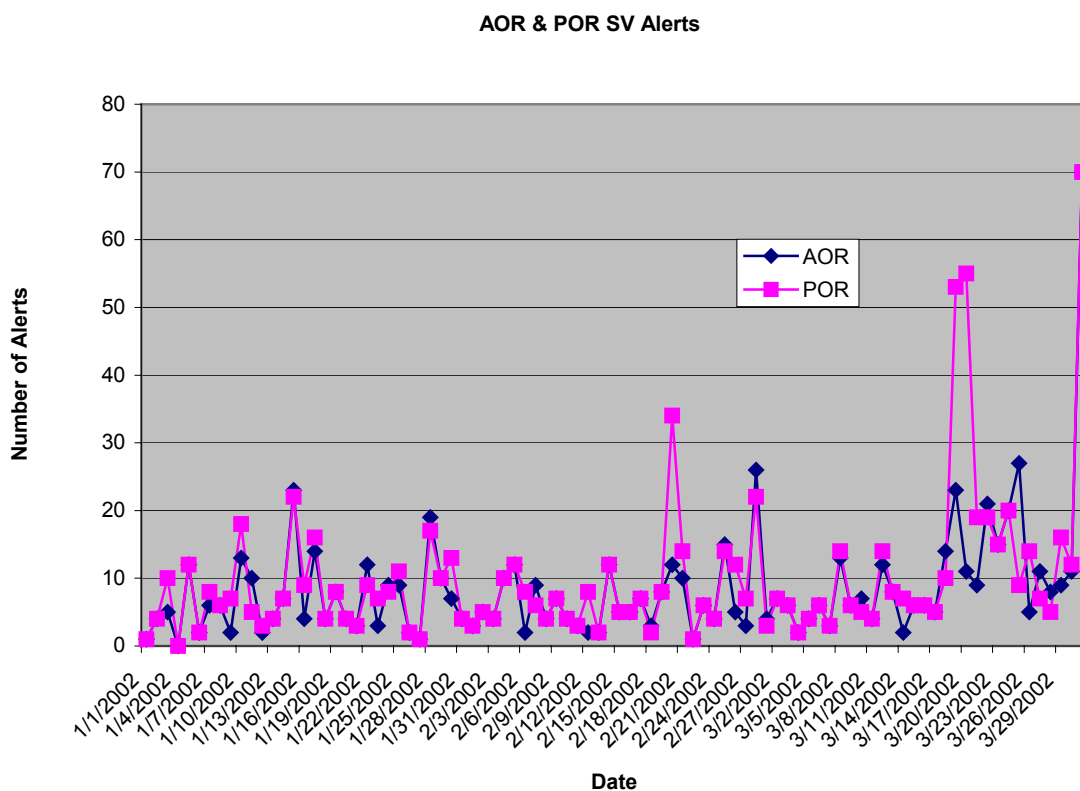
If the above conditions are met, then the continuity of function flag is set to “1” to indicate the continuity of function is met for that particular flight segment. The continuity of function percentile statistic was computed for each reference site by summing the continuity of function flags of “1” together and dividing by the total number of test segments (bins) accumulated. LNAV/VNAV Continuity of Function column of Table 5.1 shows the probability for continuity of function ranges from 0.441637(Cold Bay) to 0.997489(Dallas).

Table 5.1 Continuity

Location	NPA Continuity of Navigation	NPA Continuity of Fault Detection	LPV Continuity of Function	LNAV/VNAV Continuity Of Function
Kansas City	1.000000	0.986044	0.993151	0.993533
Chicago	1.000000	0.985002	0.984878	0.985565
Columbus	1.000000	0.978221	0.988958	0.989635
Denver	1.000000	0.979197	0.991530	0.992115
Salt Lake City	1.000000	0.986811	0.992945	0.993142
Greenwood	1.000000	0.980068	0.996494	0.996879
Billings	1.000000	0.984531	0.984475	0.986265
Atlanta	1.000000	0.984571	0.994971	0.995534
Seattle	1.000000	0.982249	0.967189	0.969990
Dallas	1.000000	0.984946	0.997130	0.997489
Atlantic City	1.000000	0.979138	0.973454	0.975851
Grand Forks	1.000000	0.981387	0.965140	0.967799
Prescott	1.000000	0.967952	0.977766	0.979020
Oakland	1.000000	0.982541	0.980132	0.982066
Boston	1.000000	0.984017	0.955732	0.956688
Miami	1.000000	0.987052	0.974135	0.978436
Los Angeles	1.000000	0.976074	0.979534	0.981939
Juneau	1.000000	0.979827	0.780414	0.786706
Anchorage	1.000000	0.979720	0.665840	0.673078
Cold Bay	1.000000	0.978735	0.384140	0.441637

The WAAS produces alert messages to protect the users from satellite degradation or severe ionospheric activity, both of which can cause unsafe conditions for a user. Space Vehicle (SV) alerts increase the User Differential Range Error (UDRE) of satellites, which can reduce the weighting of the satellite in the navigation solution, or completely exclude it from the navigation solution. Ionospheric Grid Point (IGP) alerts increase the Grid Ionospheric Vertical Error (GIVE) of IGP's, which can affect the usage of satellites whose pierce points are in the vicinity of the IGP. An increase in either UDRE's or GIVE's after an alert effectively increases the user protection levels (HPL and VPL), which affect the availability. Additionally, if an alert message sequence lasts for more than 12 seconds, WAAS fast corrections can time out, causing continuity of fault detection to not be met for that flight segment. Figure 5.1 shows the number of SV alerts that occurred daily during the reporting period. Note there are no IGP alerts since the installation of the new GIVE Monitor in November 2001.

Figure 5.1 SV Quarterly Alert Trends



6.0 Integrity

Analysis of integrity includes the identification and evaluation of HMIs (hazardously misleading information), as well as the generation of a safety index to illustrate the margin of safety that WAAS protection levels are maintaining. The safety margin index (shown in Table 6.1) is a metric that shows how well the protection levels are bounding the maximum observed error. The process for determining this index involves normalizing the largest error observed at a site. This is accomplished by dividing this maximum observed error by the WAAS estimated standard deviation of the error. The safety margin requirement, 5.33 standard units for vertical and 6 standard units for horizontal, is then divided by this maximum normalized error.

Table 6.1 Safety Margin Index and HMI Statistics

Location	Safety Margin Index		Number of HMIs
	Horizontal	Vertical	
Kansas City	2.50	2.54	0
Chicago	3.53	3.55	0
Columbus	5.00	4.10	0
Denver	2.40	1.78	0
Salt Lake City	2.14	3.55	0
Greenwood	4.00	2.81	0
Billings	3.75	3.14	0
Atlanta	4.62	4.10	0
Seattle	4.00	4.10	0
Dallas	4.29	2.42	0
Atlantic City	4.29	2.96	0
Grand Forks	2.50	2.22	0
Prescott	5.45	4.85	0
Oakland	6.00	4.85	0
Boston	4.00	3.81	0
Miami	4.62	4.10	0
Los Angeles	5.45	4.44	0
Juneau	4.29	3.55	0
Anchorage	3.75	3.33	0
Cold Bay	5.45	3.55	0

An observed safety margin index of greater than one indicates safe bounding of the greatest observed error, less than one indicates that the maximum error was not bounded, and a result equal to one means that the error was equal to the protection level. As evidenced by the statistics in the above table, the safety margin index never drops below 1.78 at any site. Also, Table 6.1 shows the number of HMIs that occurred during the quarter, of which there were none. An HMI occurs if the position error exceeds the protection level in the vertical or horizontal dimensions at any time and 6.2 or more seconds pass before this event is corrected by WAAS.

7.0 SV Range Accuracy

Range accuracy evaluation computes the probability that the WAAS User Differential Range Error (UDRE) and Grid Ionospheric Vertical Error (GIVE) statistically bound 99.9% of the range residuals for each satellite tracked by the receiver. A UDRE is broadcast by the WAAS for each satellite that is monitored by the system and is required to bound 99.9% of the residual error on a pseudorange after application of fast and long-term corrections. The pseudorange residual error is determined by taking the difference between the raw pseudorange and a calculated reference range. The reference range is equal to the true range between the corrected satellite position and surveyed user antenna plus all corrections (WAAS Fast Clock, WAAS Long-Term Clock, WAAS Ionospheric delay, Tropospheric delay, Receiver Clock Bias, and Multipath).

Since the true ionospheric delay and multipath error are not precisely known, the estimated variance in these error sources are added to the UDRE before the comparing it to the residual error.

GPS satellite range residual errors were calculated for the WAAS receivers in Atlanta (AORW) and Salt Lake City (POR) during the quarter. Table 7.1 and 7.2 show the range error 95% index and 3.29σ bounding statistics for each SV at Atlanta and Salt Lake City, respectively. During the evaluated period at Atlanta (as shown in Table 7.1), all GPS satellite residual errors were less than 2.14 meters 95% of the time, and all satellites range errors were bounded 100% of the time by the UDRE. At Salt Lake City (as shown in Table 7.2), all GPS satellite residual errors were less than 1.70 meters 95% of the time, and all satellites range errors were bounded 100% of the time by the UDRE.

A GIVE is broadcast by the WAAS for each IGP that is monitored by the system and is required to bound 99.9% of the ionospheric error. The WAAS broadcast the ionospheric model using IGP's at predefined geographic locations. Each IGP contains the vertical ionospheric delay and the error in that delay in the form of the GIVE. The ionospheric error is determined by taking the difference between the WAAS ionospheric delay interpolated from the IGP's and GPS dual frequency measurement at that GPS satellite.

GPS satellite ionospheric errors were calculated for the WAAS receivers in Atlanta and Salt Lake City during the quarter. Table 7.1 and 7.2 show the ionospheric error 95% index and 3.29σ bounding statistics for each SV at Atlanta and Salt Lake City, respectively. At Atlanta (as shown in Table 7.1), all GPS satellite ionospheric errors were less than 2.9 meters 95% of the time and all satellites were bounded at least 99.9% of the time except PRN 3, which bounded 99.86%. At Salt Lake City (as shown in Table 7.2), all GPS satellite ionospheric errors were less than 2.70 meters 95% of the time and all GPS satellites ionospheric errors were bounded at least 99.9%.

Table 7.1 Range and Ionospheric Error 95% index and 3.29 Sigma Bounding - Atlanta

SV	95% Range Error	Range Error Bounding	95% Ionospheric Error	Ionospheric Error Bounding
1	1.060	100.00	1.060	100.00
2	1.390	100.00	1.260	100.00
3	1.200	100.00	2.140	99.861
4	1.800	100.00	2.180	99.994
5	1.350	100.00	1.720	100.00
6	1.800	100.00	2.490	100.00
7	1.440	100.00	1.260	100.00
8	1.950	100.00	1.220	99.999
9	1.320	100.00	2.450	100.00
10	2.050	100.00	1.500	100.00
11	1.460	100.00	1.630	100.00
13	1.310	100.00	2.290	100.00
14	1.310	100.00	0.980	100.00
15	1.480	100.00	1.220	99.999
17	1.610	100.00	1.550	100.00
18	1.310	100.00	0.900	99.999
20	1.460	100.00	1.510	100.00
21	1.260	100.00	1.490	99.998
22	1.200	100.00	1.360	100.00
23	1.930	100.00	1.400	99.998
24	1.590	100.00	1.760	100.00
25	1.110	100.00	1.630	100.00
26	2.130	100.00	2.890	99.993
27	1.460	100.00	1.390	99.994
28	1.530	100.00	0.990	99.999
29	1.200	100.00	1.710	100.00
30	1.340	100.00	2.200	100.00
31	1.300	100.00	1.280	100.00

Figure 7.1 95% Range Error (SV 1 - SV 16) - Atlanta

95% Index Range Error

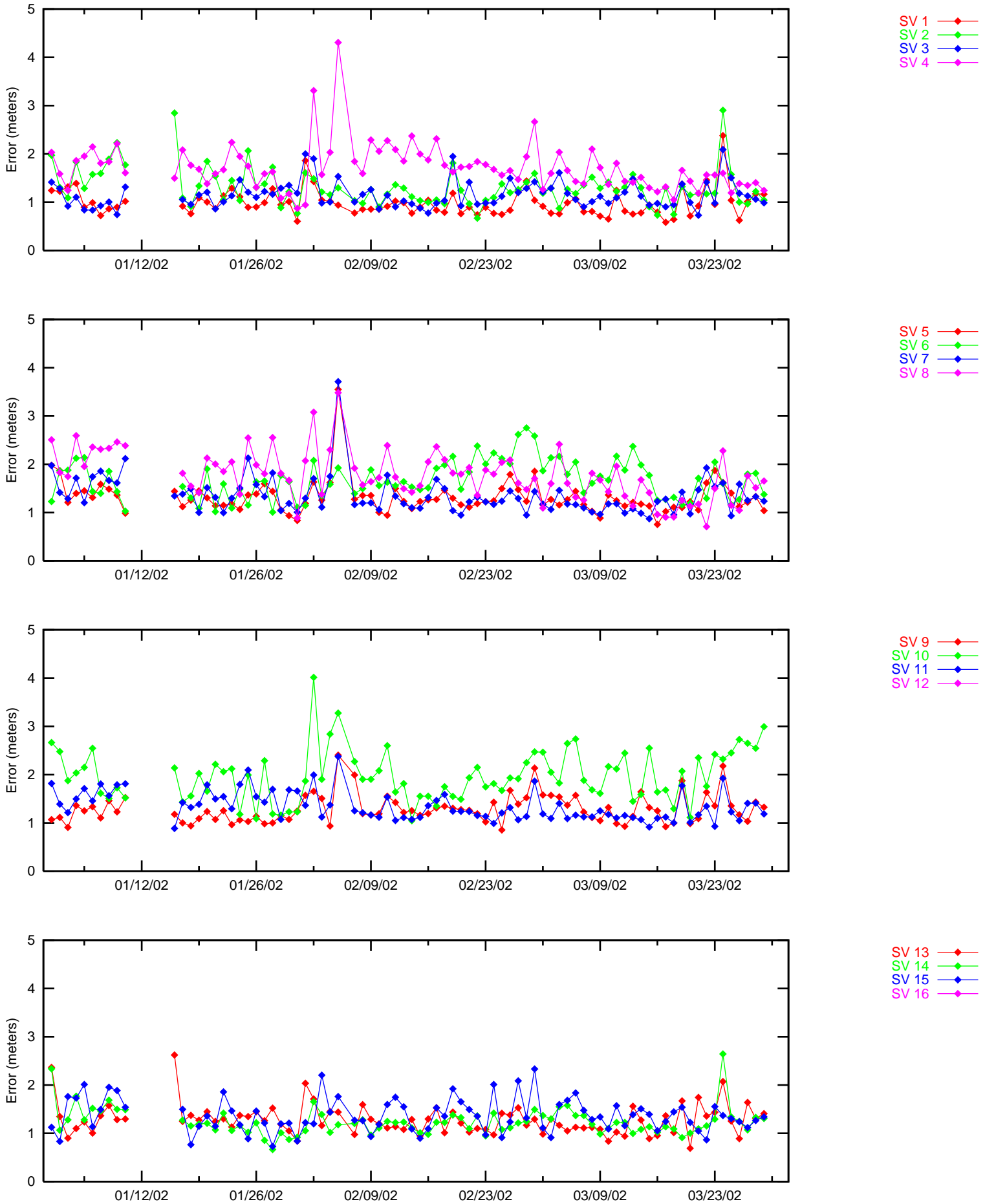


Figure 7.2 95% Range Error (SV 17- SV 31) - Atlanta

95% Index Range Error

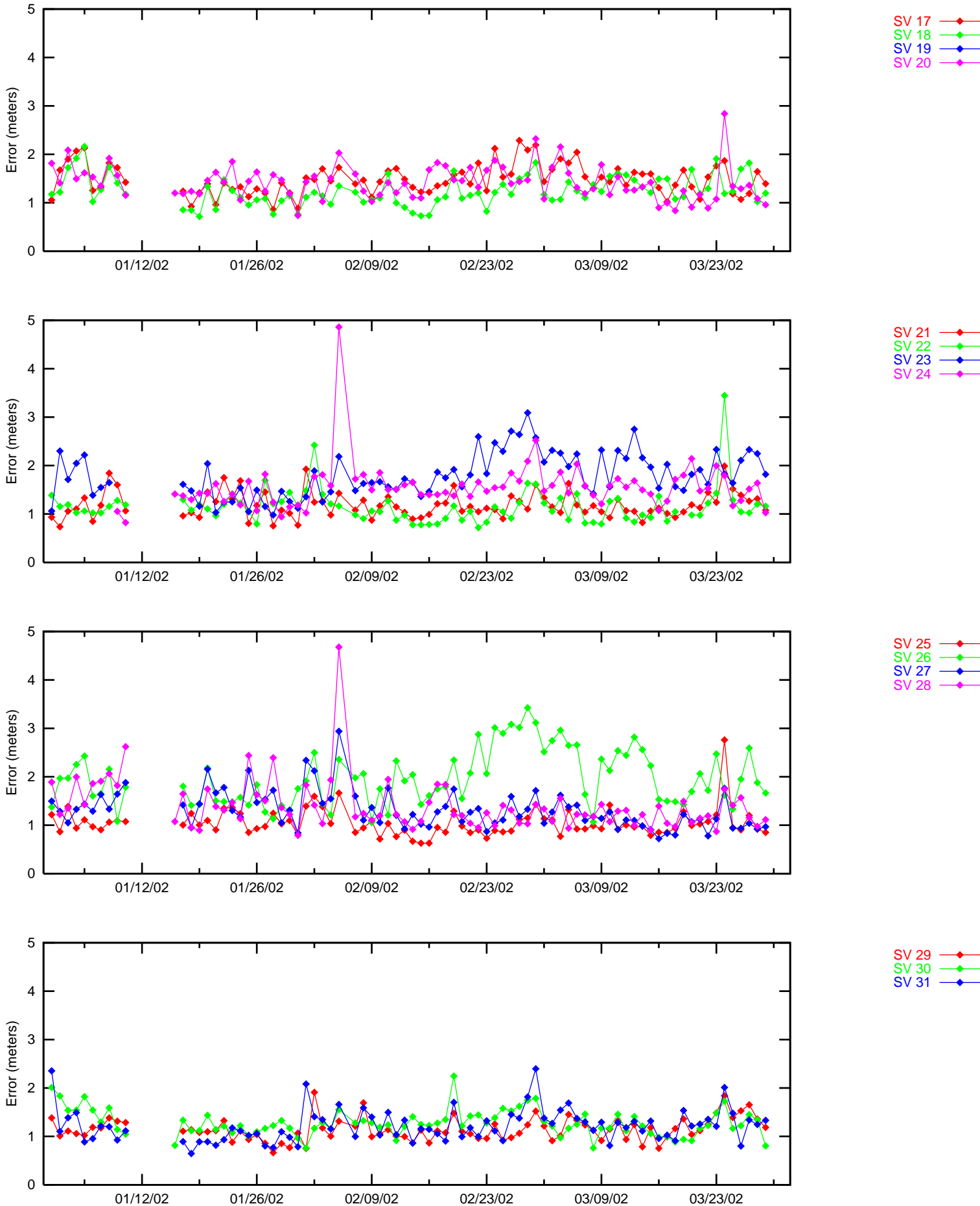


Table 7.2 Range and Ionospheric Error 95% index and 3.29 Sigma Bounding – Salt Lake City

SV	95% Range Error	Range Error Bounding	95% Ionospheric Error	Ionospheric Error Bounding
1	1.12	100.00	1.29	100.00
2	1.46	100.00	1.49	100.00
3	1.17	100.00	1.30	100.00
4	1.32	100.00	1.50	100.00
5	1.78	100.00	1.84	100.00
6	1.38	100.00	1.28	100.00
7	1.54	100.00	1.45	100.00
8	1.37	100.00	1.26	100.00
9	1.53	100.00	1.35	100.00
10	1.46	100.00	2.68	100.00
11	1.30	100.00	2.03	100.00
13	1.16	100.00	1.38	100.00
14	1.22	100.00	1.84	99.99
15	1.34	100.00	1.23	100.00
17	1.41	100.00	1.23	99.99
18	1.41	100.00	1.73	100.00
20	1.27	100.00	1.95	99.99
21	1.24	100.00	1.19	99.97
22	1.27	100.00	2.05	100.00
23	1.63	100.00	1.30	99.99
24	1.57	100.00	1.69	100.00
25	1.24	100.00	1.01	100.00
26	1.49	100.00	1.73	100.00
27	1.29	100.00	1.24	99.98
28	1.37	100.00	1.54	99.99
29	1.38	100.00	1.38	100.00
30	1.47	100.00	1.68	100.00
31	1.38	100.00	2.18	99.99
134	6.63	99.99	-	-

8.0 WAAS Problem Summary

During the ongoing WAAS evaluation process any problems or anomalies discovered will be documented in this section. Many WAAS performance parameters are evaluated at each reference receiver on a daily basis. If WAAS performance fails to meet requirements then a problem description and detailed analysis will be included in this section.

1. Description: WAAS availability was reduced during software uploads on January 16, 2002

Analysis: GPS satellite corrections and UDREI's broadcast by WAAS were all set to not monitored for a period of approximately 2.5 hours. After WAAS maintenance was completed LNAV/VNAV availability was restored.

2. Description: WAAS AORW and POR GEO stopped broadcasting the WAAS navigation messages for approximately 2 hours on March 22, 2002.

Analysis: NSTB and WAAS reference receivers lost track of AORW and POR GEOs. AORW – 2738 seconds and POR – 3113 seconds.

3.

Appendix A: Glossary

General Terms and Definitions

Alert. An alert is an indication provided by the GPS/WAAS equipment to inform the user when the positioning performance achieved by the equipment does not meet the integrity requirements.

APV-ILNAV/VNAV. APV-I is a WAAS operational service level with an HAL equal to 556 meters and a VAL equal to 50 meters.

Availability. The availability of a navigation system is the ability of the system to provide the required function and performance at the initiation of the intended operation. Availability is an indication of the ability of the system to provide usable service within the specified coverage area.

AVP-II. APV-II is a WAAS operational service level with an HAL equal to 40 meters and a VAL equal to 20 meters.

CONUS. Continental United States.

Continuity. The continuity of a system is the ability of the total system (comprising all elements necessary to maintain aircraft position within the defined airspace) to perform its function without interruption during the intended operation. More specifically, continuity is the probability that the specified system performance will be maintained for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation.

Coverage. The coverage provided by a radio navigation system is that surface area or space volume in which the signals are adequate to permit the user to determine position to a specified level of accuracy. Coverage is influenced by system geometry, signal power levels, receiver sensitivity, atmospheric noise conditions, and other factors that affect signal availability.

Dilution of Precision (DOP). The magnifying effect on GPS position error induced by mapping GPS ranging errors into position through the position solution. The DOP may be represented in any user local coordinate desired. Examples are HDOP for local horizontal, VDOP for local vertical, PDOP for all three coordinates, and TDOP for time.

Fault Detection and Exclusion (FDE). Fault detection and exclusion is a receiver processing scheme that autonomously provides integrity monitoring for the position solution, using redundant range measurements. The FDE consists of two distinct parts: fault detection and fault exclusion. The fault detection part detects the presence of an unacceptably large position error for a given mode of flight. Upon the detection, fault exclusion follows and excludes the source of the unacceptably large position error, thereby allowing navigation to return to normal performance without an interruption in service.

GEO. Geostationary Satellite.

Global Positioning System (GPS). A space-based positioning, velocity, and time system composed of space, control, and user segments. The space segment, when fully operational, will be composed of 24 satellites in six orbital planes. The control segment consists of five monitor stations, three ground antennas, and a master control station. The user segment consists of antennas and receiver-processors that provide positioning, velocity, and precise timing to the user.

GLS. GLS is a WAAS operational service level with HAL equal to 40 meters and VAL equal to 12 meters.

Grid Ionospheric Vertical Error (GIVE). GIVEs indicate the accuracy of ionospheric vertical delay correction at a geographically defined ionospheric grid point (IGP). WAAS transmits one GIVE for each IGP in the mask.

Hazardous Misleading Information (HMI). Hazardous misleading information is any position data, that is output, that has an error larger than the current protection level (HPL/VPL), without any indication of the error (e.g., alert message sequence).

Horizontal Alert Limit (HAL). The Horizontal Alert Limit (HAL) is the radius of a circle in the horizontal plane (the local plane tangent to the WGS-84 ellipsoid), with its center being at the true position, which describes the region that is required to contain the indicated horizontal position with a probability of $1-10^{-7}$ per flight hour, for a particular navigation mode, assuming the probability of a GPS satellite integrity failure being included in the position solution is less than or equal to 10^{-4} per hour.

Horizontal Protection Level (HPL). The Horizontal Protection Level is the radius of a circle in the horizontal plane (the plane tangent to the WGS-84 ellipsoid), with its center being at the true position, which describes the region that is assured to contain the indicated horizontal position. It is based upon the error estimates provided by WAAS.

Ionospheric Grid Point (IGP). IGP is a geographically defined point for which the WAAS provides the vertical ionospheric delay.

LNAV. Lateral Navigation.

MOPS. Minimum Operational Performance Standards.

Navigation Message. Message structure designed to carry navigation data.

Non-Precision Approach (NPA) Navigation Mode. The Non-Precision Approach navigation mode refers to the navigation solution operating with a minimum of four satellites with fast and long term WAAS corrections (no WAAS ionospheric corrections) available.

Position Solution. The use of ranging signal measurements and navigation data from at least four satellites to solve for three position coordinates and a time offset.

Precision Approach (PA) Navigation Mode. The Precision Approach navigation mode refers to the navigation solution operating with a minimum of four satellites with all WAAS corrections (fast, long term, and ionospheric) available.

Selective Availability. Protection technique employed by the DOD to deny full system accuracy to unauthorized users.

Standard Positioning Service (SPS). Three-dimensional position and time determination capability provided to a user equipped with a minimum capability GPS SPS receiver in accordance with GPS national policy and the performance specifications.

SV. Satellite Vehicle.

User Differential Range Error (UDRE). UDRE's indicate the accuracy of combined fast and slow error corrections. WAAS transmits one UDRE for each satellite in the mask.

Vertical Alert Limit (VAL). The Vertical Alert Limit is half the length of a segment on the vertical axis (perpendicular to the horizontal plane of WGS-84 ellipsoid), with its center being at the true position, which describes the region that is required to contain the indicated vertical position with a probability of $1-10^{-7}$ per flight hour, for a particular navigation mode, assuming the probability of a GPS satellite integrity failure being included in the position solution is less than or equal to 10^{-4} per hour.

Vertical Protection Level (VPL). The Vertical Protection Level is half the length of a segment on the vertical axis (perpendicular to the horizontal plane of WGS-84 ellipsoid), with its center being at the true position, which describes the region that is assured to contain the indicated vertical position. It is based upon the error estimates provided by WAAS.

VNAV. Vertical Navigation.

Wide Area Augmentation System (WAAS). The WAAS is made up of an integrity reference monitoring network, processing facilities, geostationary satellites, and control facilities. Wide area reference stations and integrity monitors are widely dispersed data collection sites that contain GPS/WAAS ranging receivers that monitor all signals from the GPS, as well as the WAAS geostationary satellites. The reference stations collect measurements from the GPS and WAAS satellites so that differential corrections, ionospheric delay information, GPS/WAAS accuracy, WAAS network time, GPS time, and UTC can be determined. The wide area reference station and integrity monitor data are forwarded to the central data processing sites. These sites process the data in order to determine differential corrections, ionospheric delay information, and GPS/WAAS accuracy, as well as verify residual error bounds for each monitored satellite. The central data processing sites also generate navigation messages for the geostationary satellites and WAAS messages. This information is modulated on the GPS-like signal and broadcast to the users from geostationary satellites.