WIDE-AREA AUGMENTATION SYSTEM PERFORMANCE ANALYSIS REPORT

Report #4
July 31, 2002

Reporting Period: April 01 to June 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 April 1, 2002 to June 30, 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:

<table>
<tr><th>Parameter</th><th colspan="2">Site/Maximum</th><th colspan="2">Site/Minimum</th></tr>
<tr><td>95% Horizontal Accuracy</td><td colspan="2">Cold Bay
1.575 meters</td><td colspan="2">Chicago
0.884 meters</td></tr>
<tr><td>95% Vertical Accuracy</td><td colspan="2">Cold Bay
2.133 meters</td><td colspan="2">Kansas City
1.238 meters</td></tr>
<tr><td>LNAV/VNAV
Instantaneous Availability –
HPL < 40 meters &
VPL < 50 meters</td><td colspan="2">Kansas City
99.6%</td><td>CONUS
Miami
96.4%</td><td>OCONUS
Cold Bay
45.7%</td></tr>
<tr><td>95% HPL</td><td>CO NUS
Los Angeles
29.0 meters</td><td>OCONUS
Cold Bay
101.8 meters</td><td>CONUS
Kansas City
17.5 meters</td><td>OCONUS
Juneau
38.6 meters</td></tr>
<tr><td>95% VPL</td><td>CO NUS
Miami
45.4 meters</td><td>OCONUS
Cold Bay
133.1 meters</td><td>CONUS
Kansas City
28.2 meters</td><td>OCONUS
Juneau
56.6 meters</td></tr>
</table>

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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 04/01/2002 and 06/30/2002.

Table 1.1 NSTB and WAAS Reference Station Receivers - AORW

NSTB:	Number of Days Evaluated	Number of Samples
• Atlantic City, NJ	88	7,590,096
• Columbus, OH	88	7,580,235
• Denver, CO	81	6,959,246
• Grand Forks, ND	84	7,215,832
• Greenwood, MS	88	7,586,693
• Prescott, AZ	84	7,541,524
WAAS:		
• Atlanta, GA	80	6,926,214
• Billings, MT	80	6,907,503
• Boston, NH	81	6,986,042
• Chicago, IL	80	6,928,851
• Dallas, TX	80	6,912,096
• Kansas City, KS	82	7,054,767
• Miami, FL	80	6,932,212
• Oakland, CA	82	7,048,017
• Salt Lake City, UT	82	7,067,000
• Seattle, WA	82	7,057,698

Table 1.2 WAAS Reference Station Receivers - POR

WAAS:	Number of Days Evaluated	Number of Samples
• Anchorage, AK	82	7,076,203
• Cold Bay, AK	41	3,531,607
• Juneau, AK	80	6,892,413
• Los Angeles, CA	79	6,790,299

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
03/29/02 - 04/12/02	Transition period to the new WAAS message header
04/05/02 – 04/08/02	NSTB receiver failure at Grand Forks
04/17/02 – 04/22/02	NSTB receiver failure at Green Bay
04/20/02 – 04/22/02	No real-time processed data for all WAAS/NSTB sites due to a power outage
04/20/02 – 04/22/02	No database data for all WAAS/NSTB sites due to a power outage
04/17/02 – 04/22/02	Multiple Ionospheric Storms (Kp values between 6 and 7)
05/06/02 - 05/07/02	No WAAS data due to WEI outage
05/07/02 –05/10/02	WAAS receiver failure at Los Angeles (Thread A)
05/08/02	Loss of WAAS SIS due to a faulted GUS switchover. Data was not used in the evaluation.
05/19/02 – 06/30/02	WAAS receiver failure at Cold Bay (Thread A)
06/05/02 –06/06/02	Functional Test Dry Runs. Data was not used in the evaluation.

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 NSTB 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-I (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 spikes occurred on 04/17/02 and 04/19/02 are caused by Ionospheric storms (See Table 1.4 for more details). This event effects both accuracy and availability. Note the gap of data from 04/20/02 to 04/24/02 is due to a power outage.

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 1.81 meters at Cold Bay and 2.133 meters at Cold Bay, respectively. The minimum horizontal and vertical LNAV/VNAV errors are 0.894 meters at Chicago and 1.238 meters at Kansas City, 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	0.927	0.940	1.245	1.134	1.238	99.996
Chicago	0.884	0.894	*	1.329	1.446	99.993
Columbus	0.912	0.919	*	1.393	1.509	99.993
Denver	0.913	0.924	*	1.14	1.258	99.996
Salt Lake City	1.026	1.034	*	1.314	1.515	99.994
Greenwood	1.004	1.016	*	1.303	1.486	99.993
Billings	1.174	1.189	*	1.382	1.555	99.993
Atlanta	1.022	1.040	*	1.175	1.374	99.993
Dallas	0.950	0.966	*	1.153	1.449	99.993
Atlantic City	1.045	1.065	*	1.542	1.910	99.993
Grand Forks	1.235	1.264	*	1.723	2.041	99.993
Prescott	1.238	1.257	*	0.965	1.730	99.974
Boston	1.162	1.198	*	1.631	1.900	99.992
Miami	1.432	1.537	*	1.660	1.813	99.993
Oakland	1.231	1.260	*	1.447	1.843	99.996
Seattle	1.446	1.481	*	1.168	1.460	99.994
Los Angeles	1.186	1.214	*	1.696	1.796	99.994
Anchorage	1.391	1.475	*	1.643	2.004	99.860
Juneau	1.299	1.357	*	1.449	1.795	99.922
Cold Bay	1.575	1.810	*	*	2.133	99.432

* No data available at this operational service level

Figure 2.1 95% Horizontal Accuracy at LNAV/VNAV

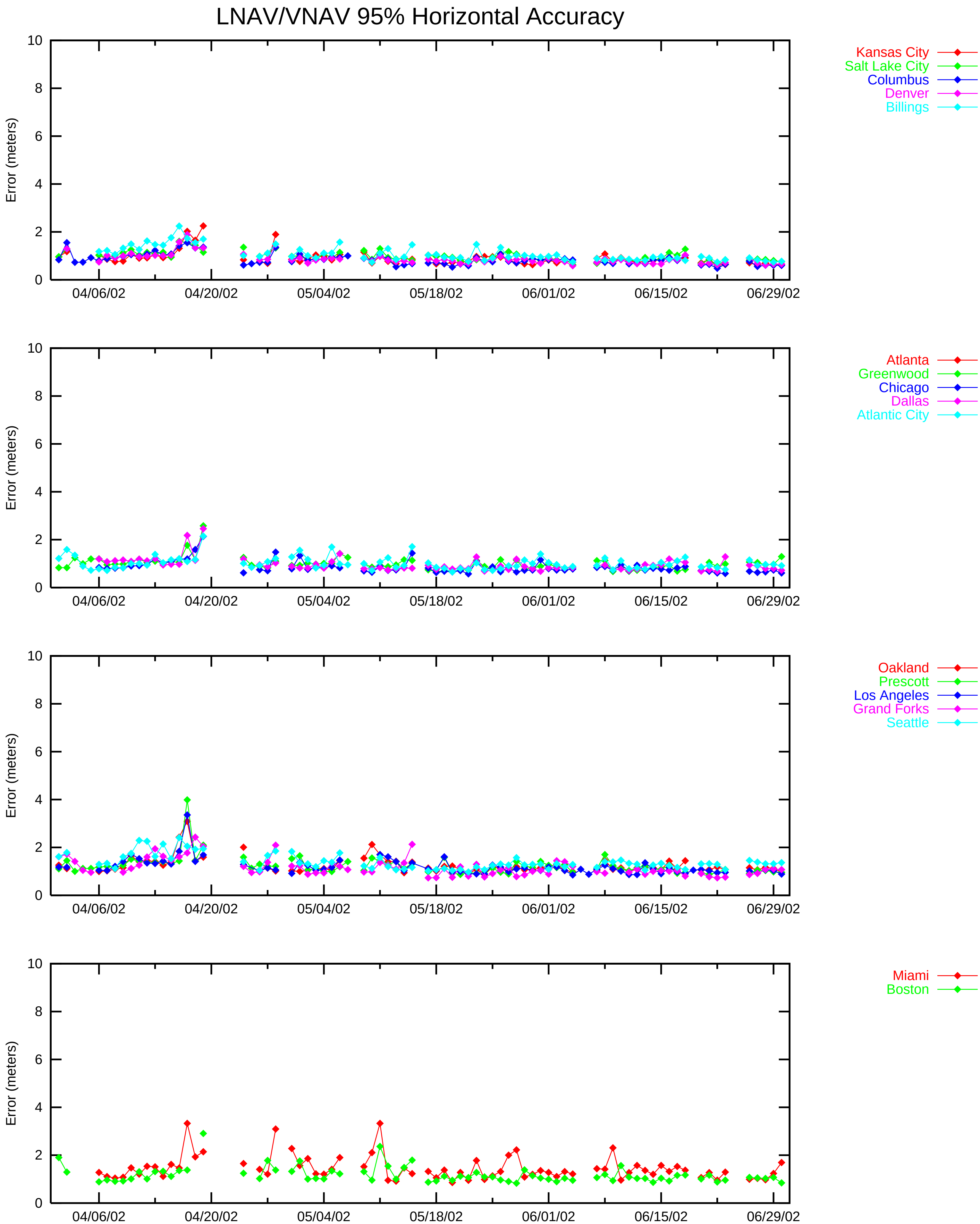


Figure 2.2 95% Vertical Accuracy at LNAV/VNAV

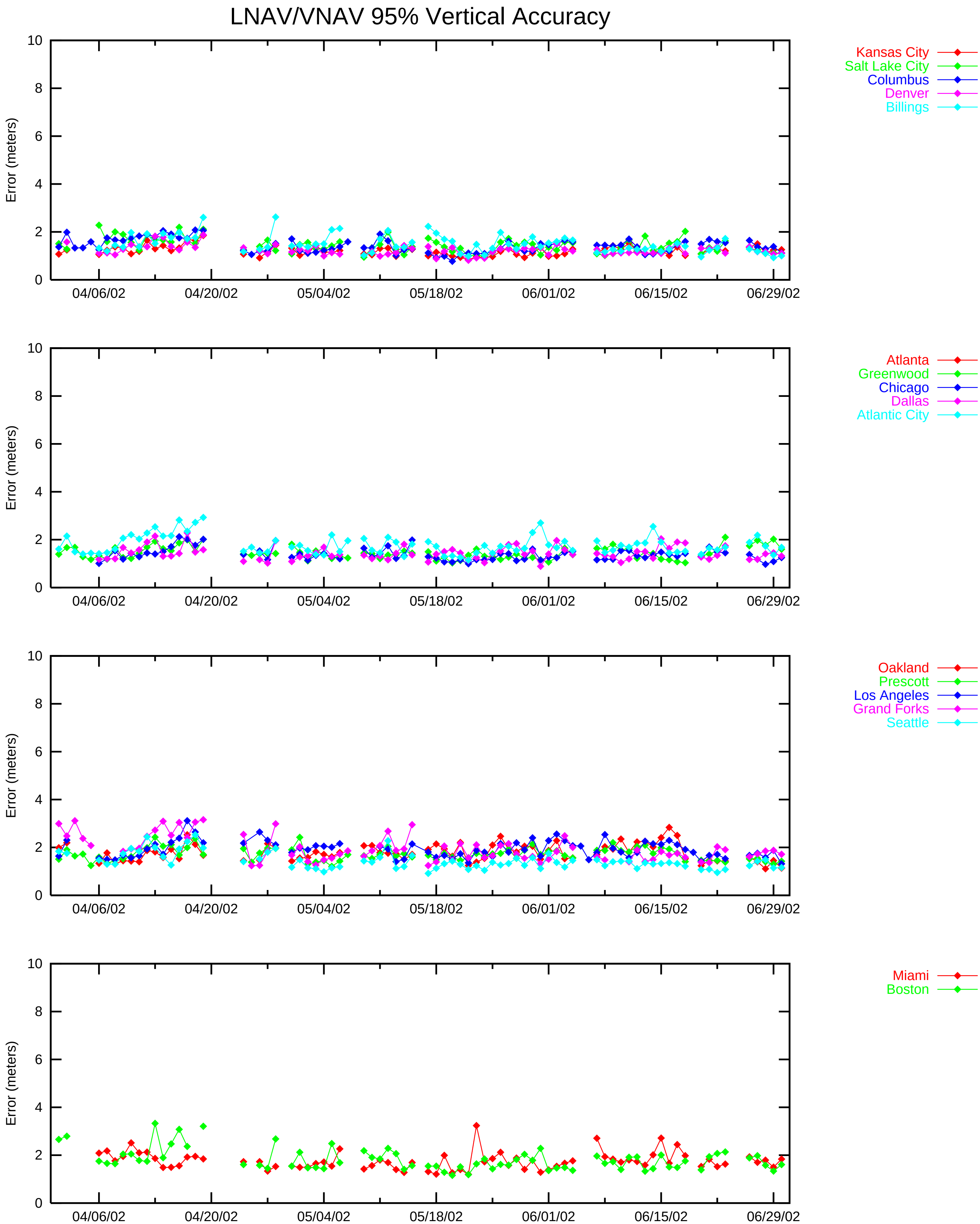


Figure 2.3 Horizontal Triangle Chart for Denver

Site: Denver Date: 04/01/02-06/30/02

PA mode Unavailable(>556m)

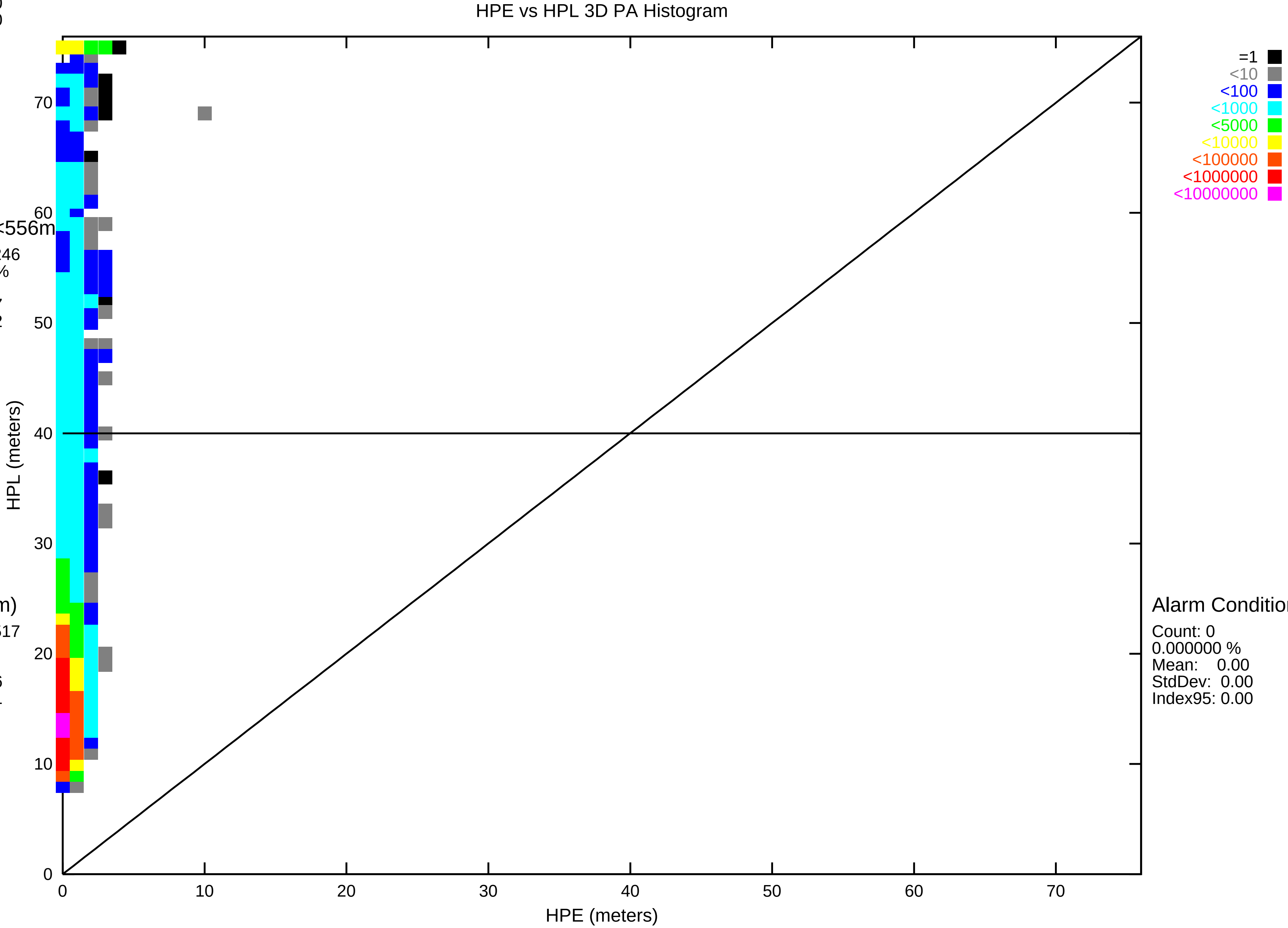
Count: 0
0.000000 %
Mean: 0.00
StdDev: 0.00
Index95: 0.00

All Modes
L/VNAV(=<556m)

Count: 6959246
100.000000 %
Mean: 0.44
StdDev: 0.27
Index95: 0.92

LPV(=<40m)

Count: 6923517
99.486595 %
Mean: 0.44
StdDev: 0.26
Index95: 0.91



Alarm Condition

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

Samples: 6959246

Mean: 0.44
StdDev: 0.27
Index95: 0.92

PA Samples: 6958976

Mean: 0.44
StdDev: 0.27
Index95: 0.92

Not PA Samples: 270

Mean: 3.43
StdDev: 1.82
Index95: 6.43

Figure 2.4 Vertical Triangle Chart for Denver

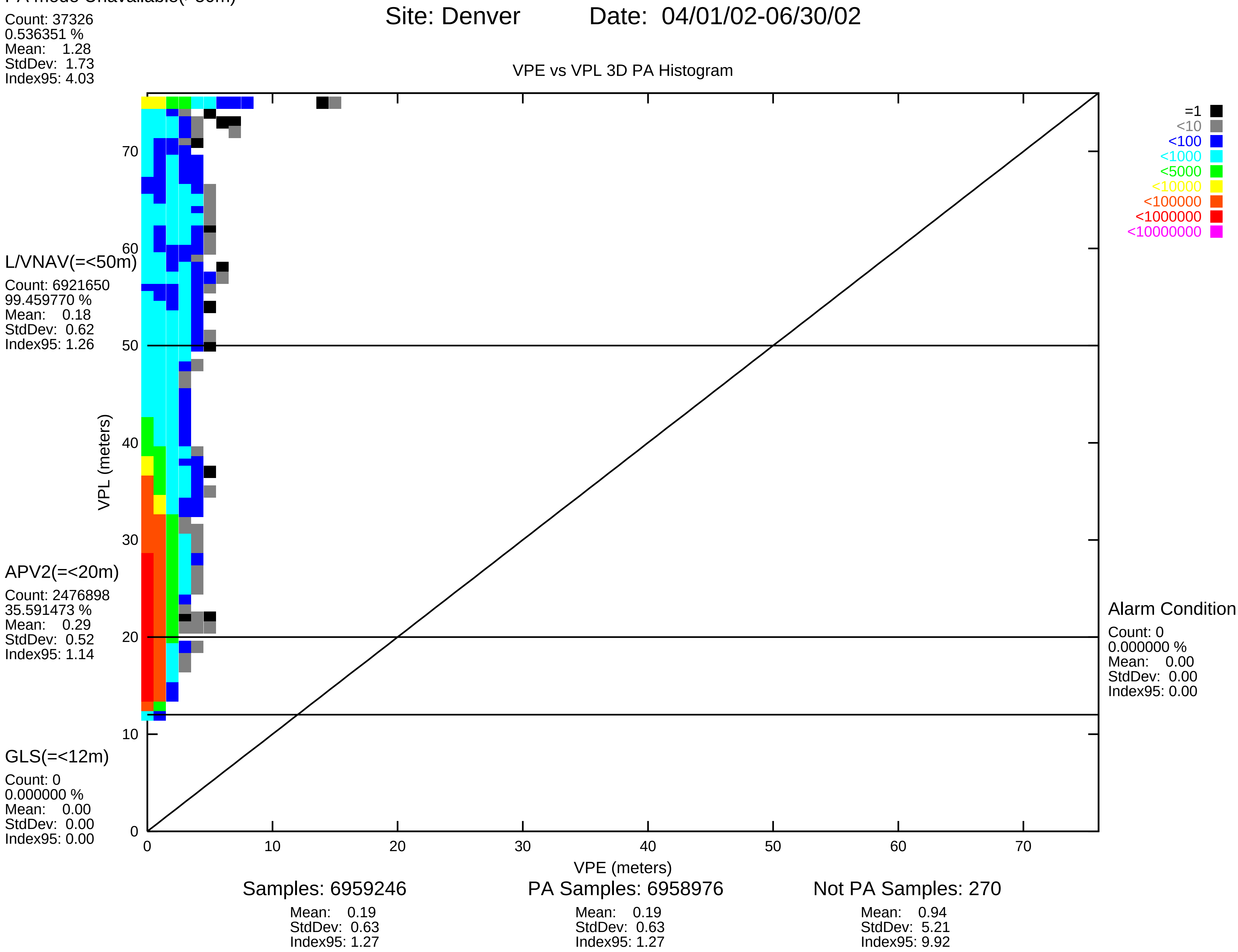


Figure 2.5 2-D Histogram for Denver

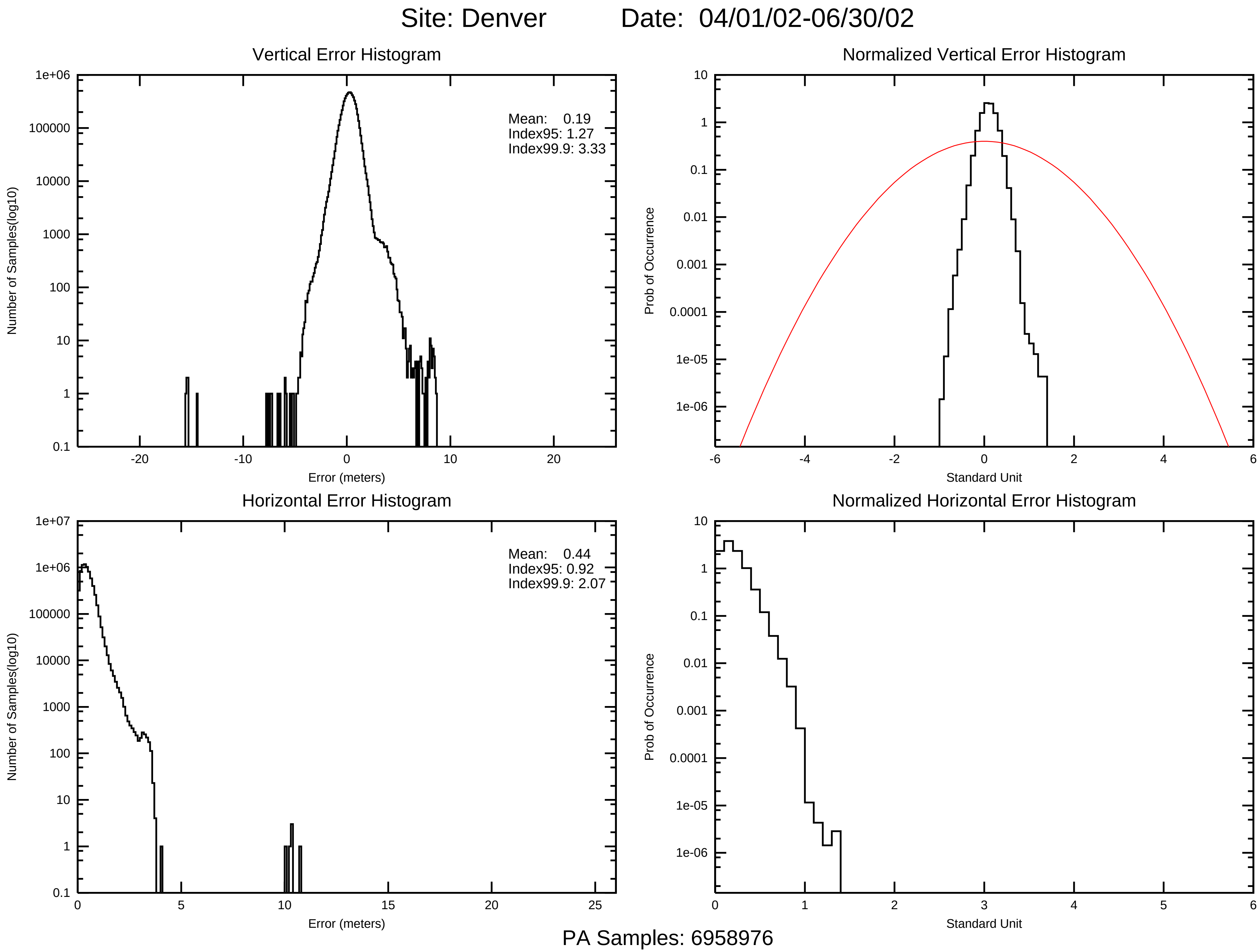


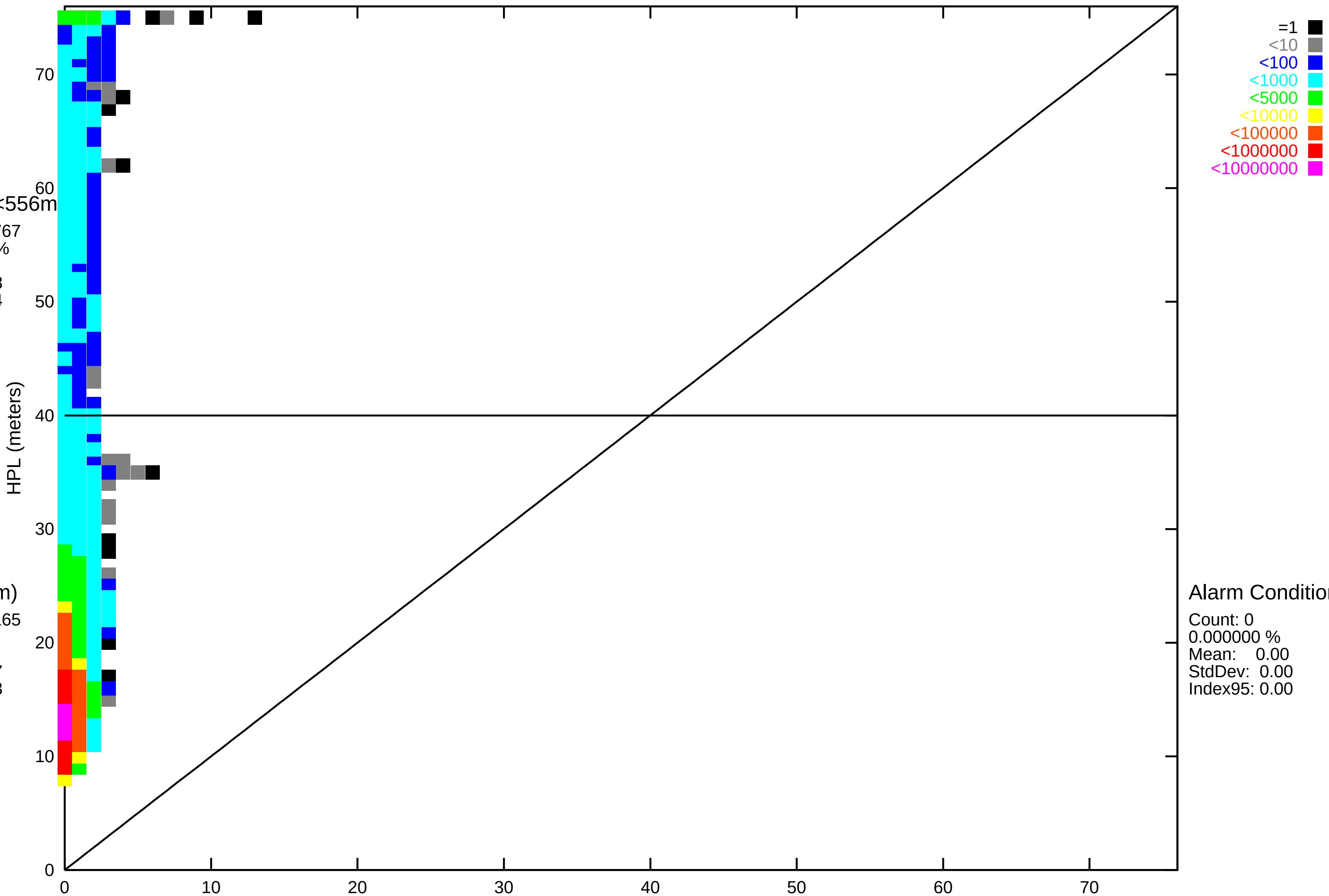
Figure 2.6 Horizontal Triangle Chart for Kansas City

Site: Kansas_City Date: 04/01/02-06/30/02

PA mode Unavailable(>556m)

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

HPE vs HPL 3D PA Histogram



All Modes
L/VNAV(=<556m)

Count: 7054767
100.000000 %
Mean: 0.44
StdDev: 0.28
Index95: 0.94

LPV(=<40m)

Count: 7025165
99.580399 %
Mean: 0.44
StdDev: 0.27
Index95: 0.93

Alarm Condition

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

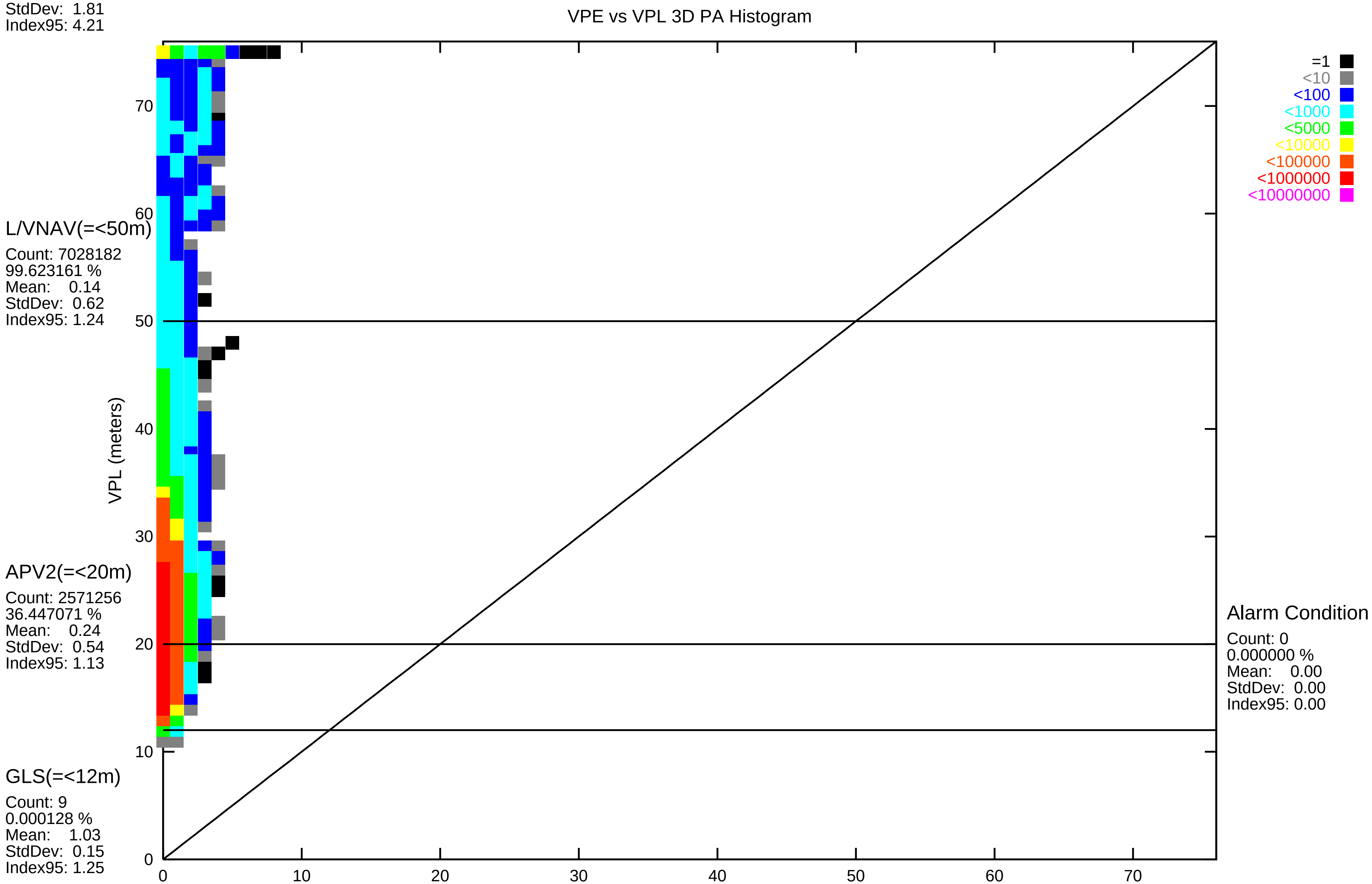
Samples: 7054767
Mean: 0.44
StdDev: 0.28
Index95: 0.94

PA Samples: 7054478
Mean: 0.44
StdDev: 0.28
Index95: 0.94

Not PA Samples: 289
Mean: 3.39
StdDev: 2.08
Index95: 7.49

Figure 2.7 Vertical Triangle Chart for Kansas City

Site: Kansas_City Date: 04/01/02-06/30/02



Samples: 7054767
Mean: 0.14
StdDev: 0.63
Index95: 1.25

PA Samples: 7054478
Mean: 0.14
StdDev: 0.62
Index95: 1.25

Not PA Samples: 289
Mean: 1.39
StdDev: 5.75
Index95: 9.79

Figure 2.8   2-D Histogram fro Kansas City

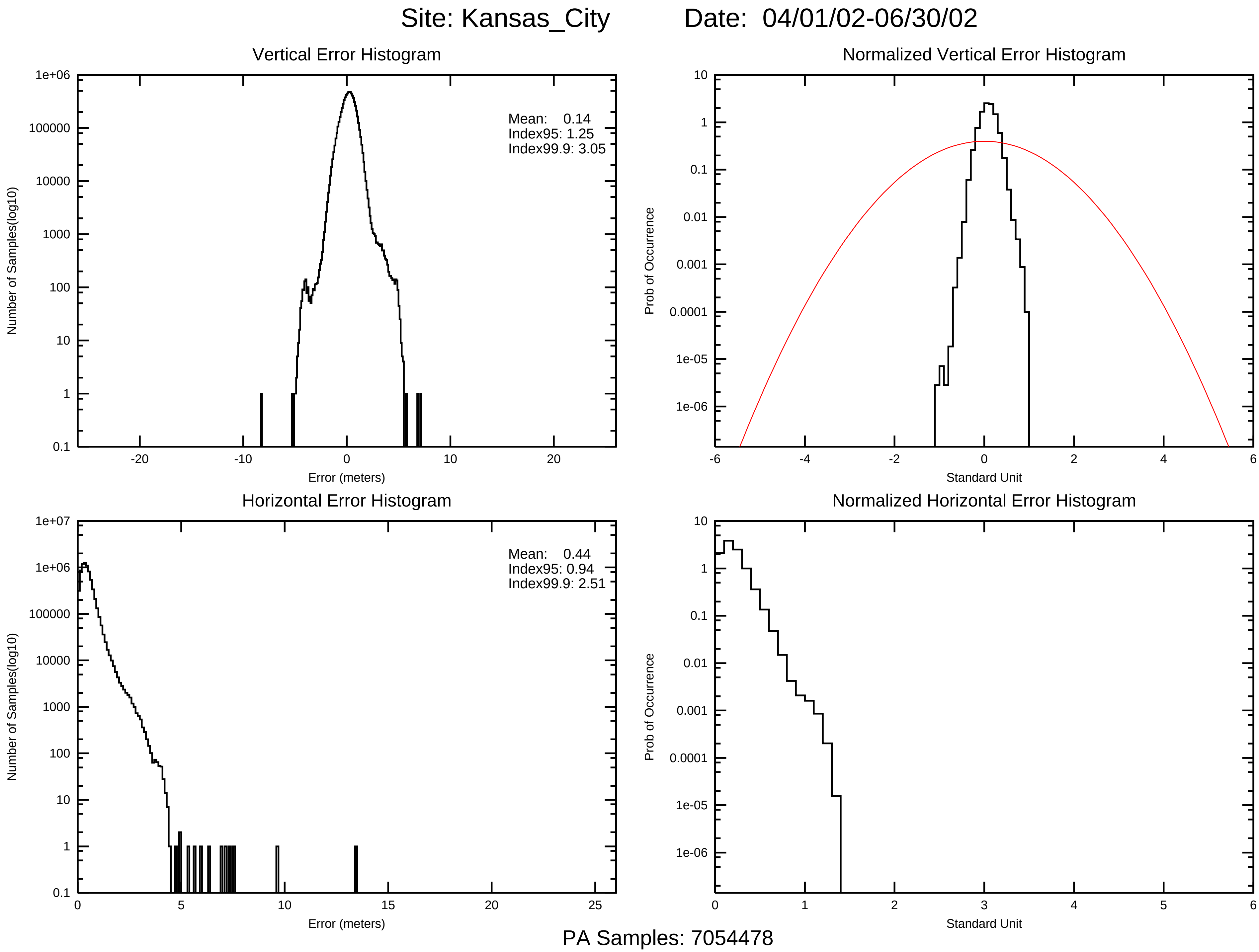


Figure 2.9 Horizontal Triangle Chart for Juneau

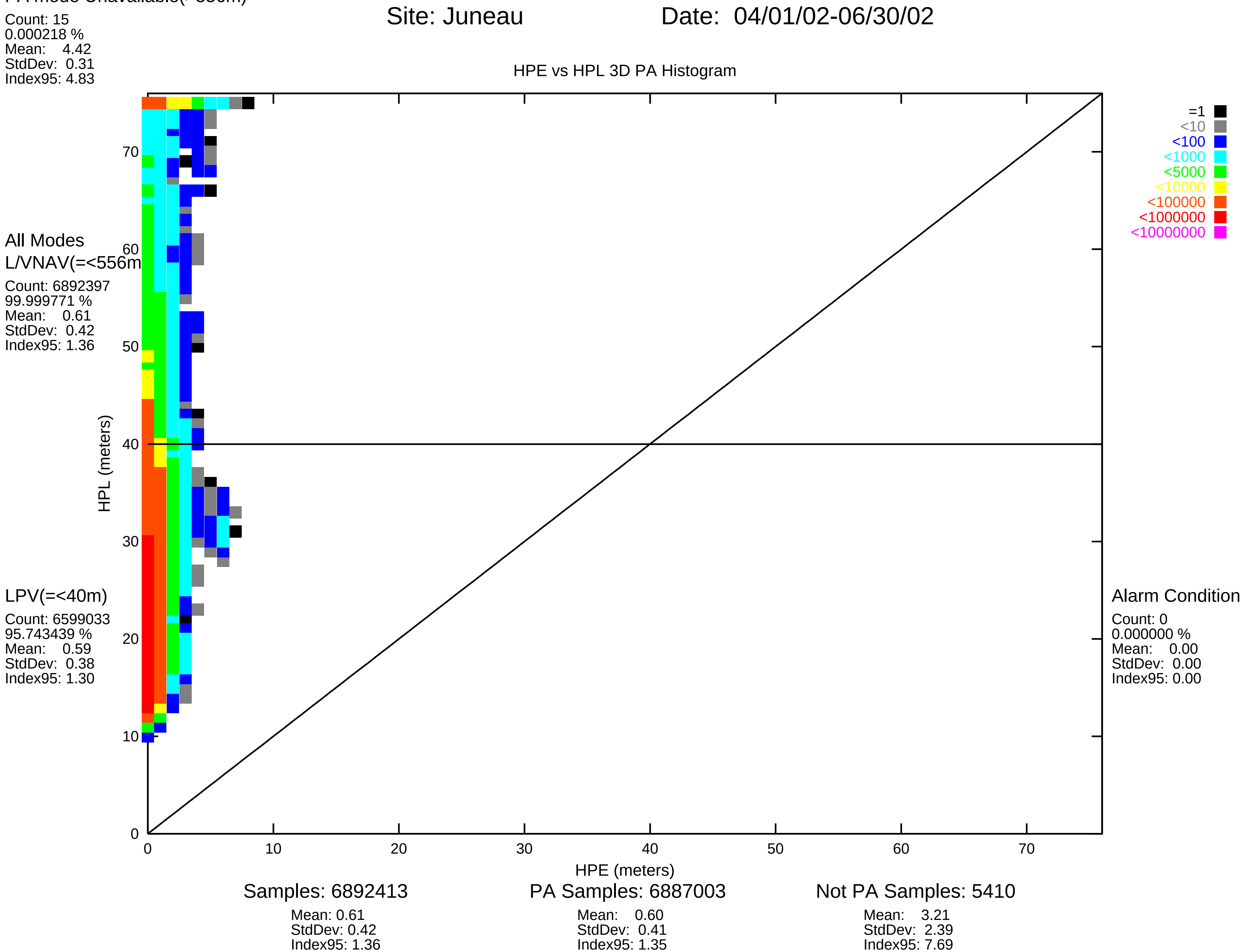


Figure 2.10 Vertical Triangle Chart for Juneau

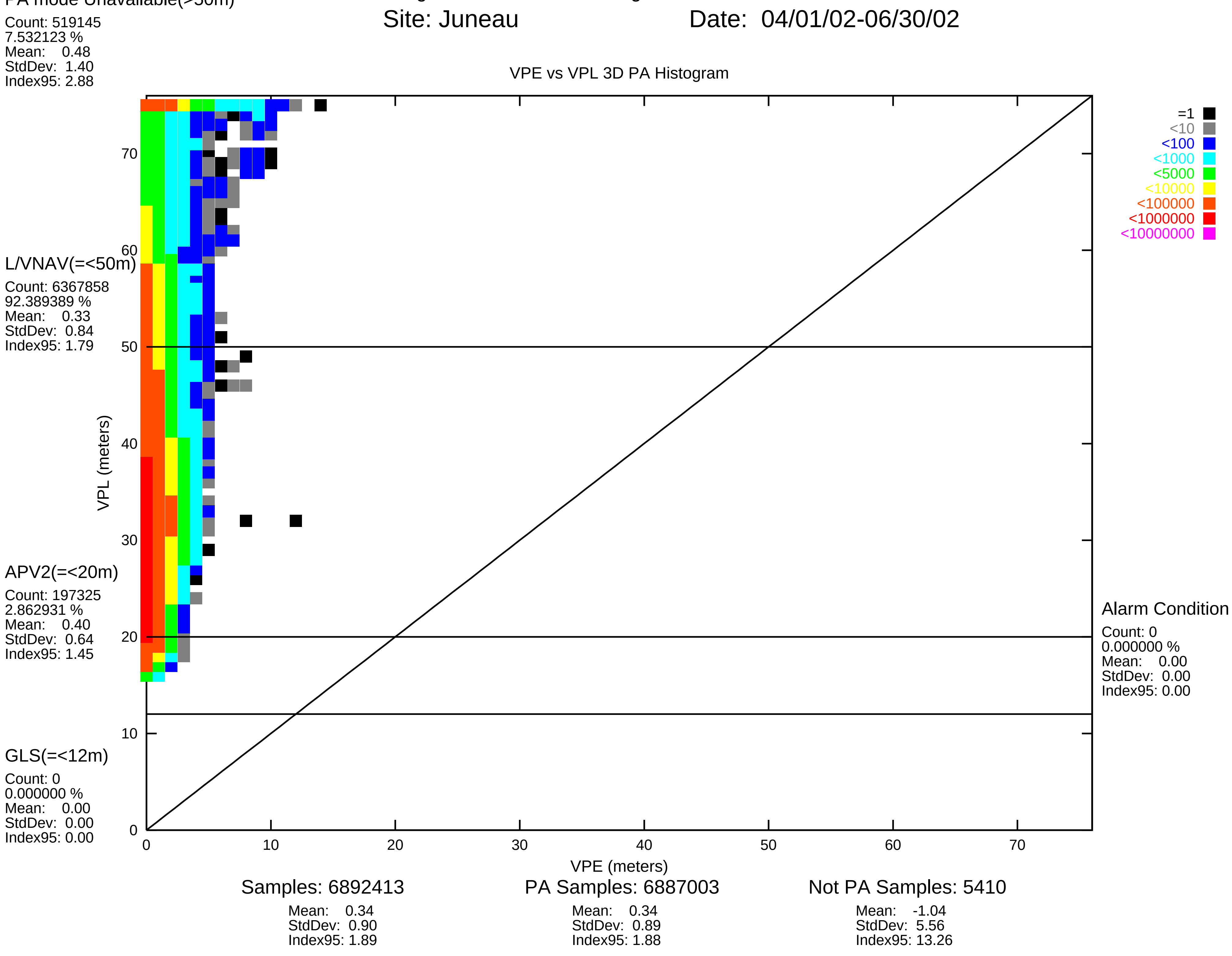
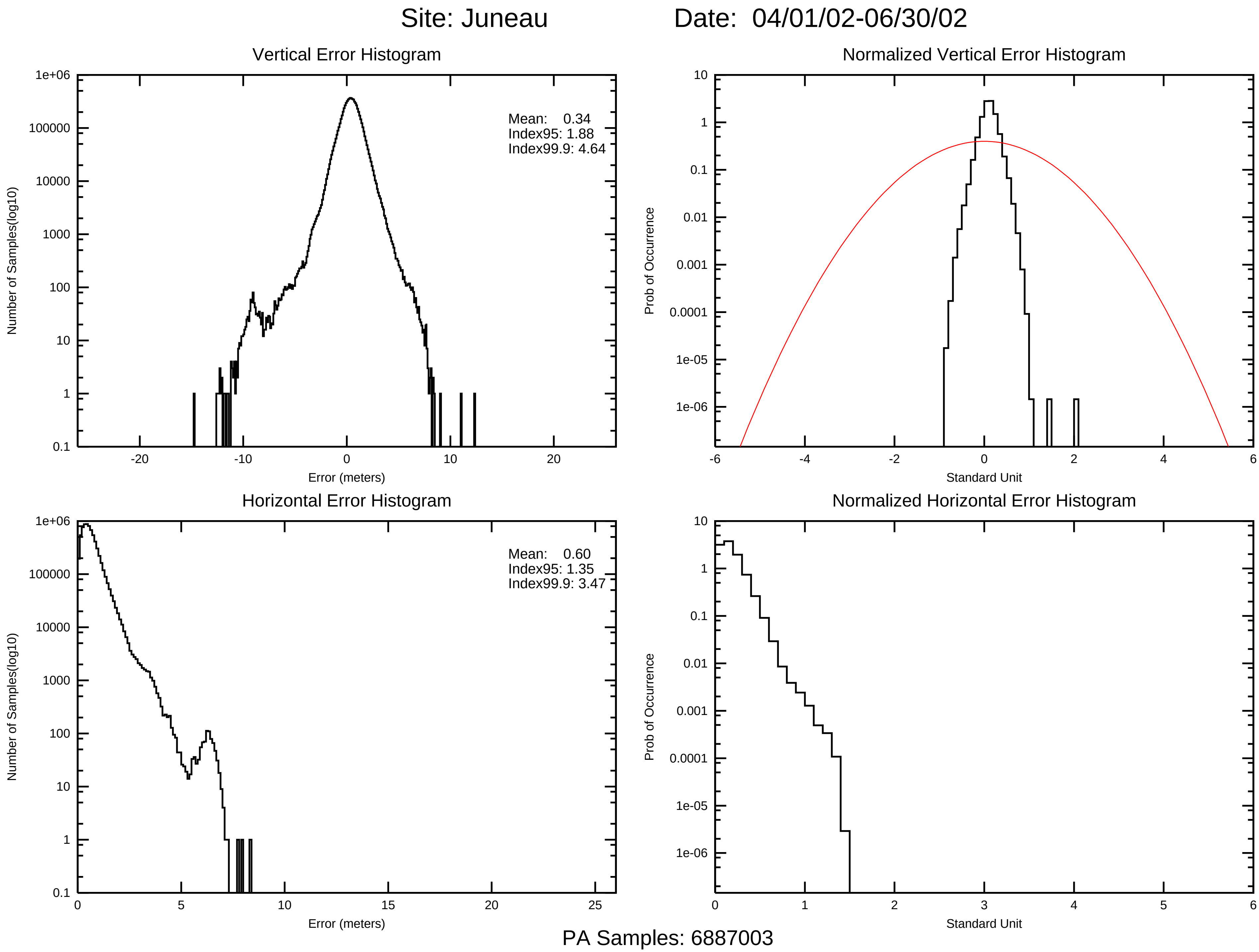


Figure 2.11   2-D Histogram for Juneau



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. Figure 3.1and 3.2 show the daily instantaneous availability of LPV and LNAV/VNAV service levels for the evaluated period.

The geographic location of each receiver evaluated is depicted in Figure 3.3, 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	17.456	28.159	99.996
Chicago	18.106	29.403	99.993
Columbus	18.325	29.495	99.993
Denver	18.918	30.469	99.996
Salt Lake City	19.736	31.013	99.994
Greenwood	18.522	31.154	99.993
Billings	20.487	32.253	99.993
Atlanta	19.173	33.031	99.993
Dallas	19.031	32.29	99.993
Atlantic City	22.666	35.308	99.994
Grand Forks	26.233	36.827	99.993
Prescott	27.647	43.699	99.974
Boston	26.298	41.871	99.993
Miami	27.933	45.396	99.993
Oakland	28.558	45.301	99.996
Seattle	24.803	35.777	99.994
Los Angeles	29.045	44.384	99.994
Anchorage	48.954	79.209	99.860
Juneau	38.552	56.613	99.922
Cold Bay	101.813	133.140	99.437

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	0.00000128	0.36447072	0.99500549	0.99623162
Chicago	*	0.36307144	0.99480575	0.99522704
Columbus	*	0.31942835	0.99381948	0.99452734
Denver	*	0.35591471	0.99417740	0.99459767
Salt Lake City	*	0.34193179	0.99377573	0.99404502
Greenwood	*	0.25146160	0.99345553	0.99438256
Billings	*	0.36716047	0.99163115	0.99275571
Atlanta	*	0.28887758	0.99105138	0.99258268
Dallas	*	0.21195105	0.99226516	0.99261206
Atlantic City	*	0.16197544	0.99126142	0.99312496
Grand Forks	*	0.13918202	0.98314804	0.98468089
Prescott	*	0.07520045	0.97353292	0.97459215
Boston	*	0.04239348	0.97479767	0.97679830
Miami	*	0.04861926	0.95982277	0.96366584
Oakland	*	0.09213571	0.97038031	0.97157258
Seattle	*	0.30493823	0.98411393	0.98591280
Los Angeles	*	0.06651799	0.97524101	0.97925287
Anchorage	*	0.00512252	0.77217287	0.79548144
Juneau	*	0.02862931	0.90991473	0.92389387
Cold Bay	*	*	0.37314719	0.45731822

* No data is available at this operational service level.

During the evaluated period, the maximum 95% HPL and VPL for CONUS sites are 29.045 meters at Los Angeles and 45.396 meters at Miami, respectively. The minimum 95% HPL and VPL for CONUS sites are 17.456 meters and 28.159 meters at Kansas City. For CONUS sites, LNAV/VNAV instantaneous availability ranges between 96.37% and 99.62%. For the Alaska sites, LNAV/VNAV instantaneous availability ranges between 45.73% and 92.39%.

Figure 3.1 LNAV/VNAV Instantaneous Availability

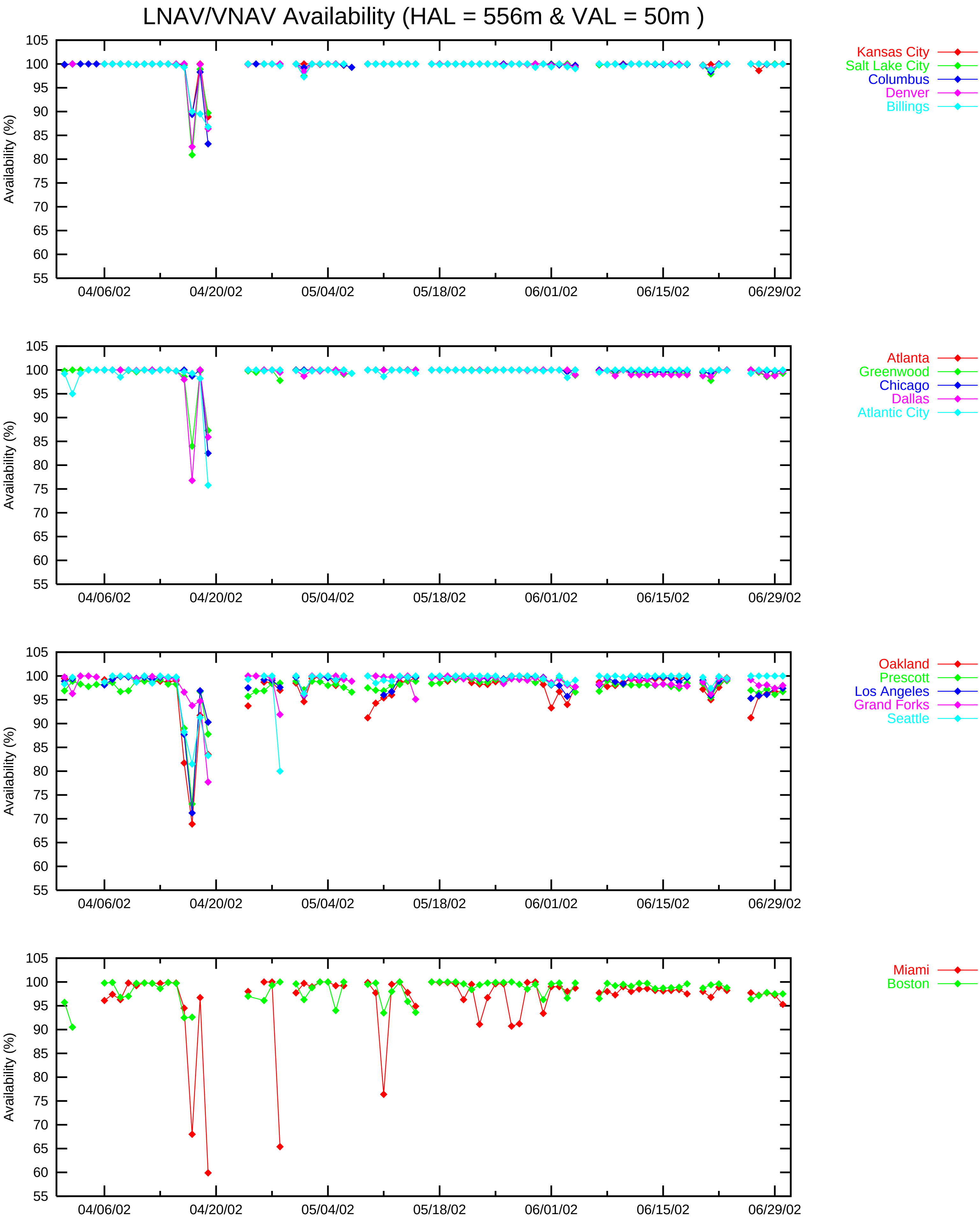


Figure 3.2 LPV Instantaneous Availability

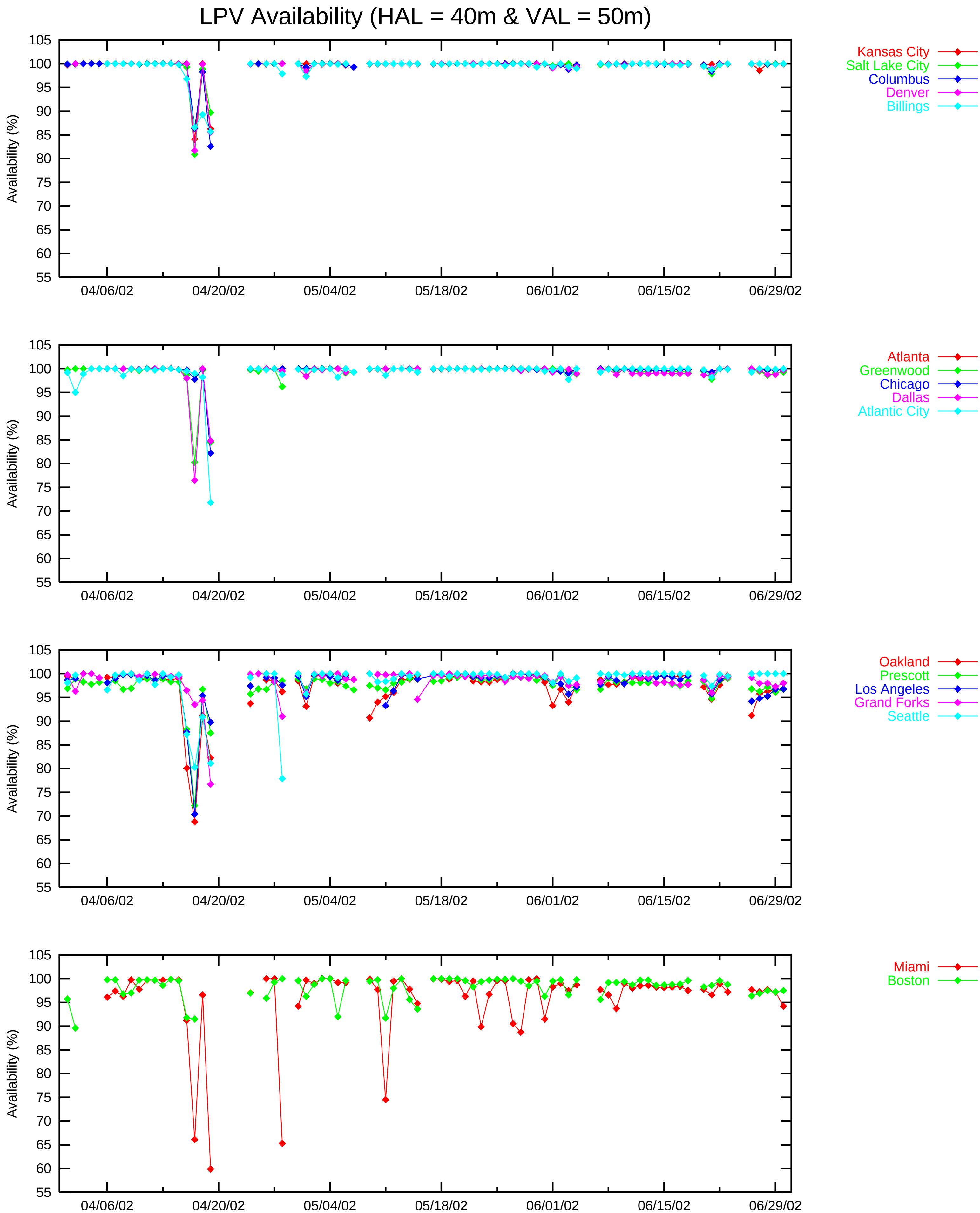
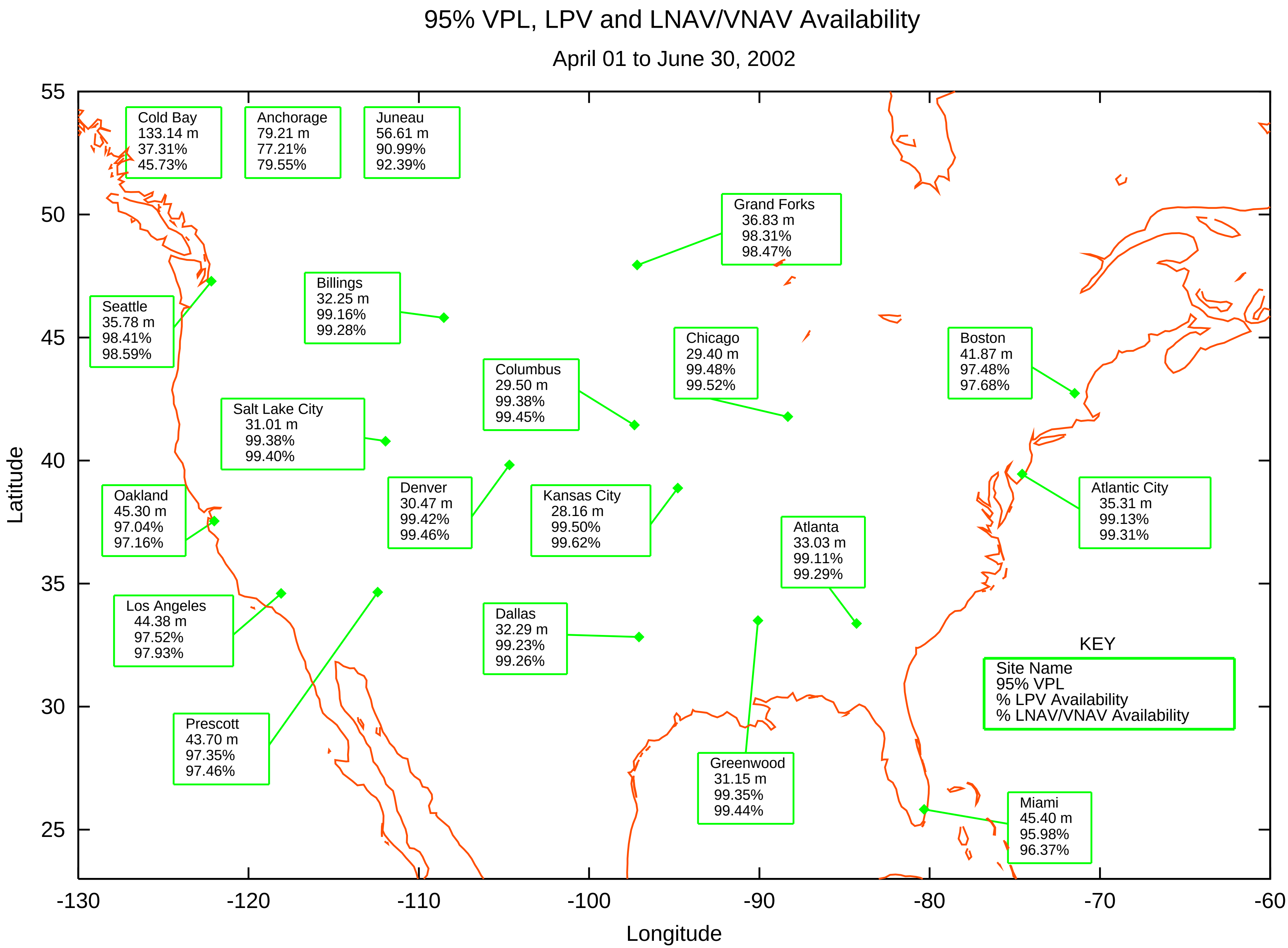


Figure 3.3 95% VPL, LPV, and LNAV/VNAV Availability



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 drop between 04/16/02 and 04/21/02 is caused Ionospheric storms.

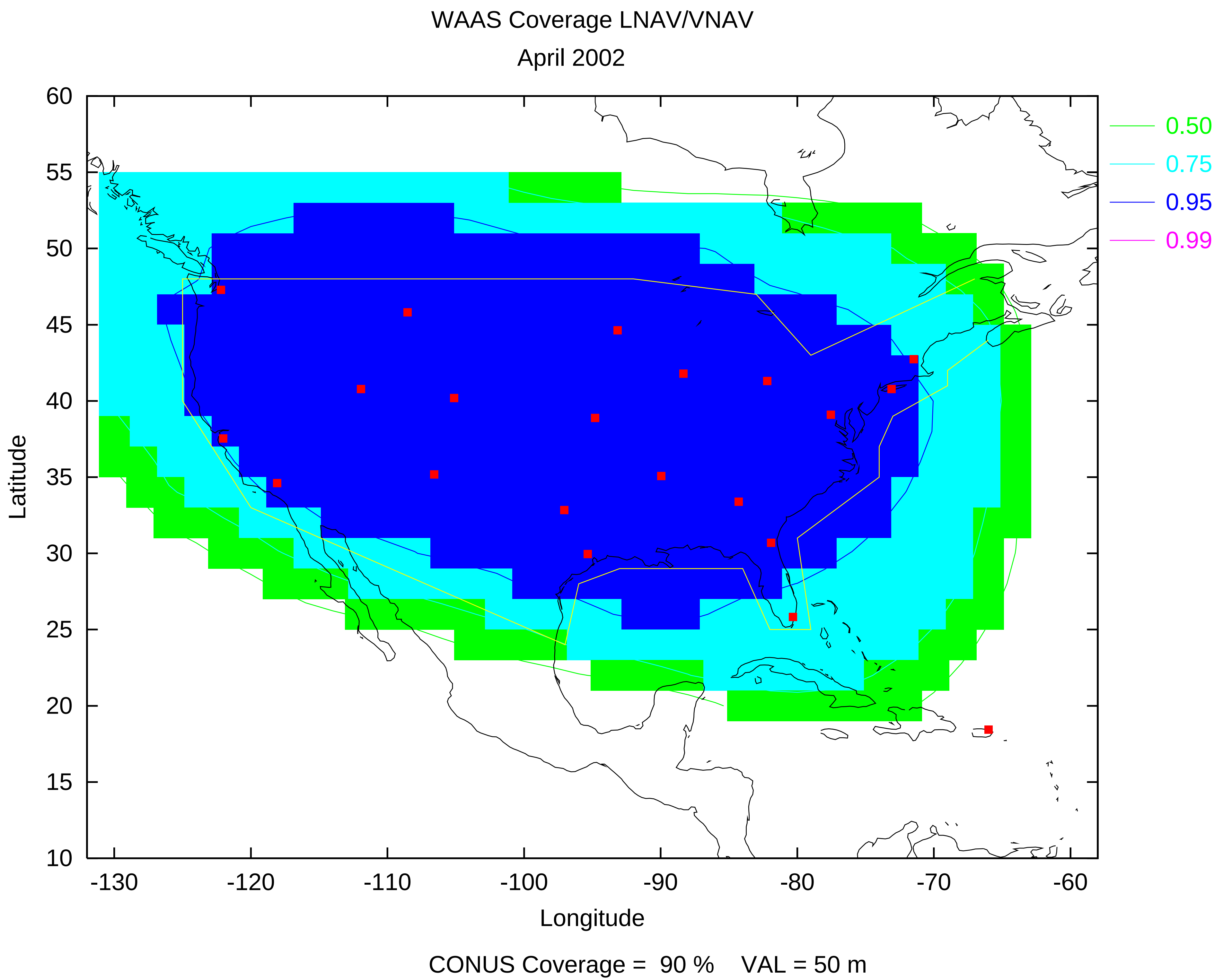
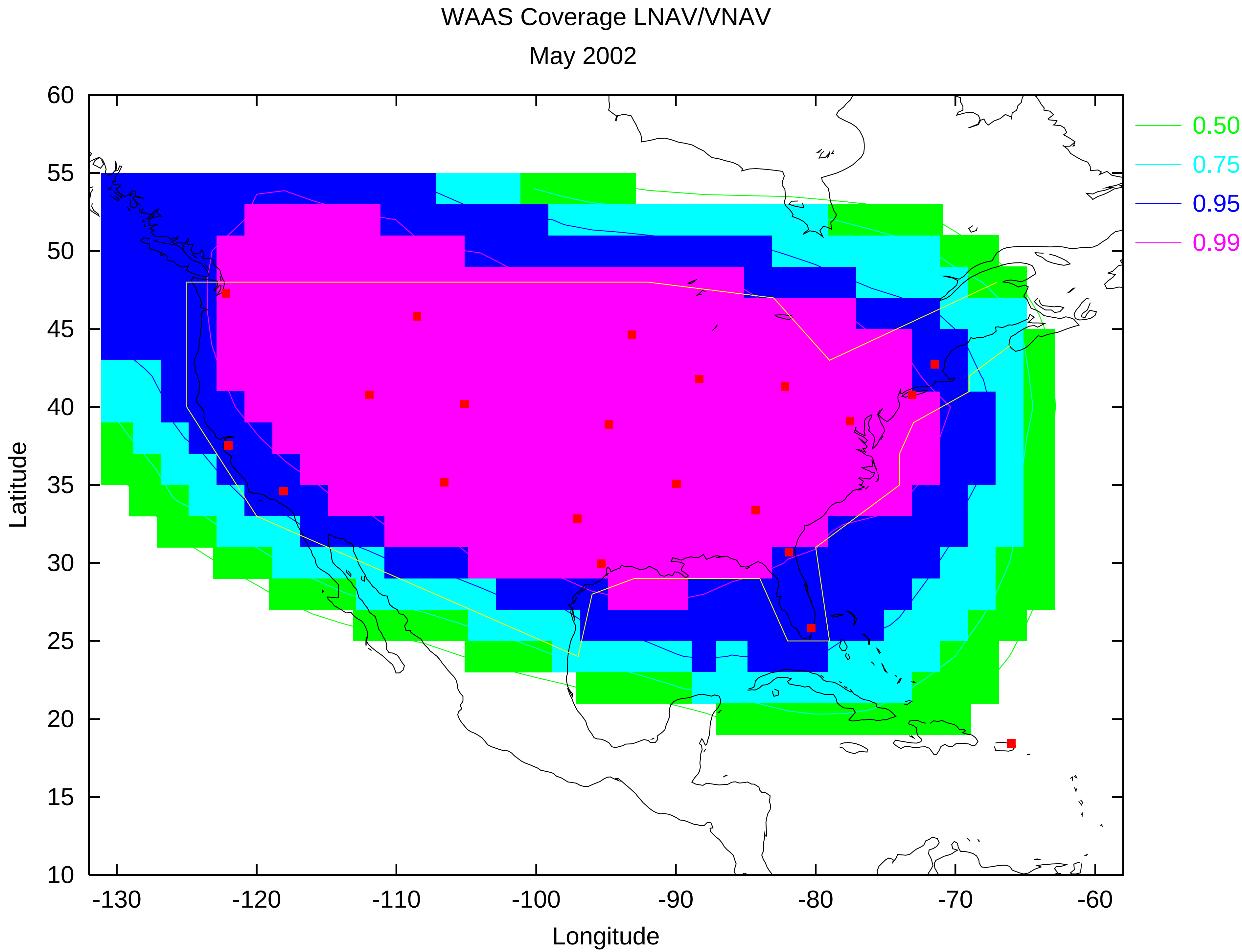


Figure 4.1 WAAS Coverage - April



CONUS Coverage = 96 % VAL = 50 m

Figure 4.2 WAAS Coverage - May

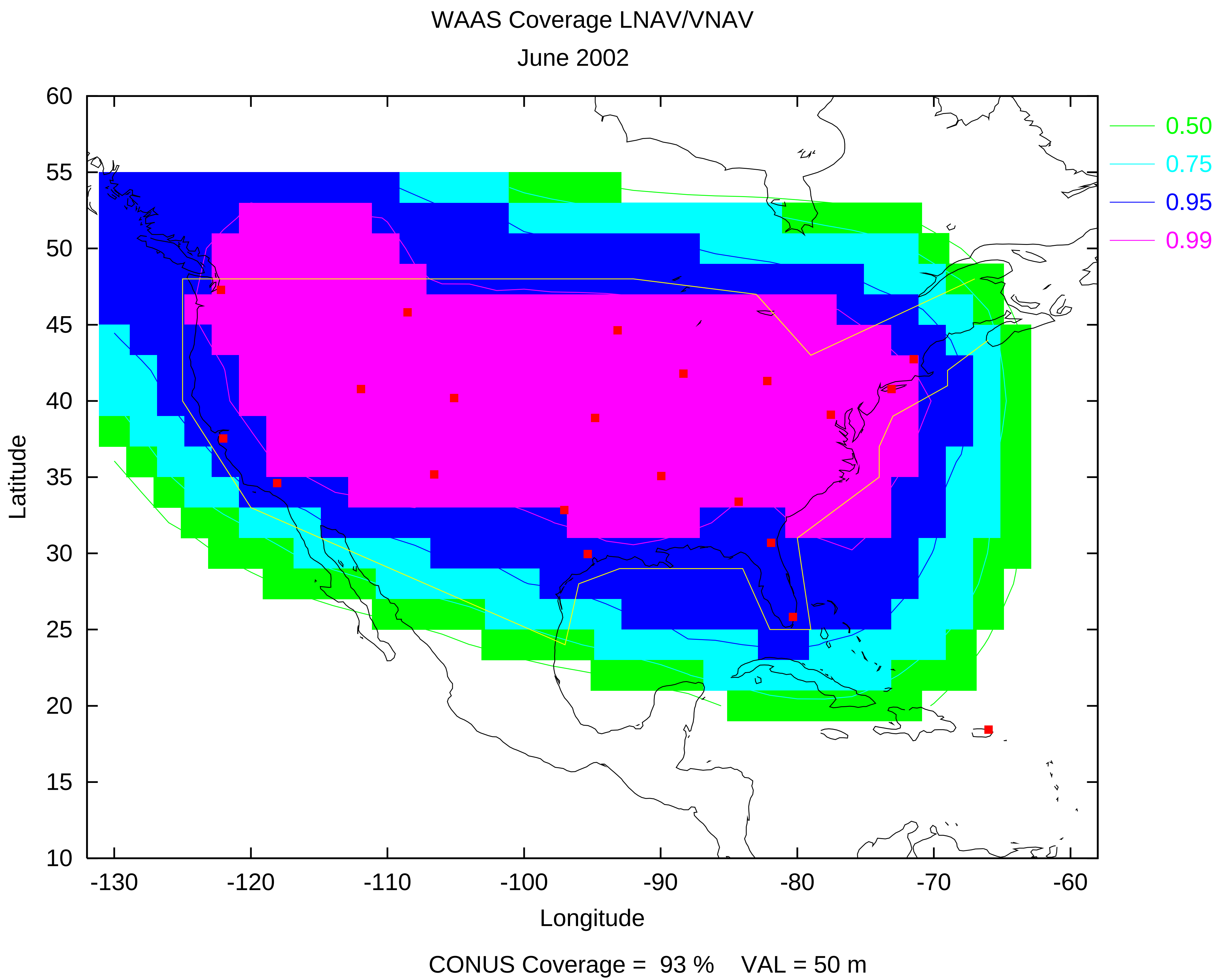
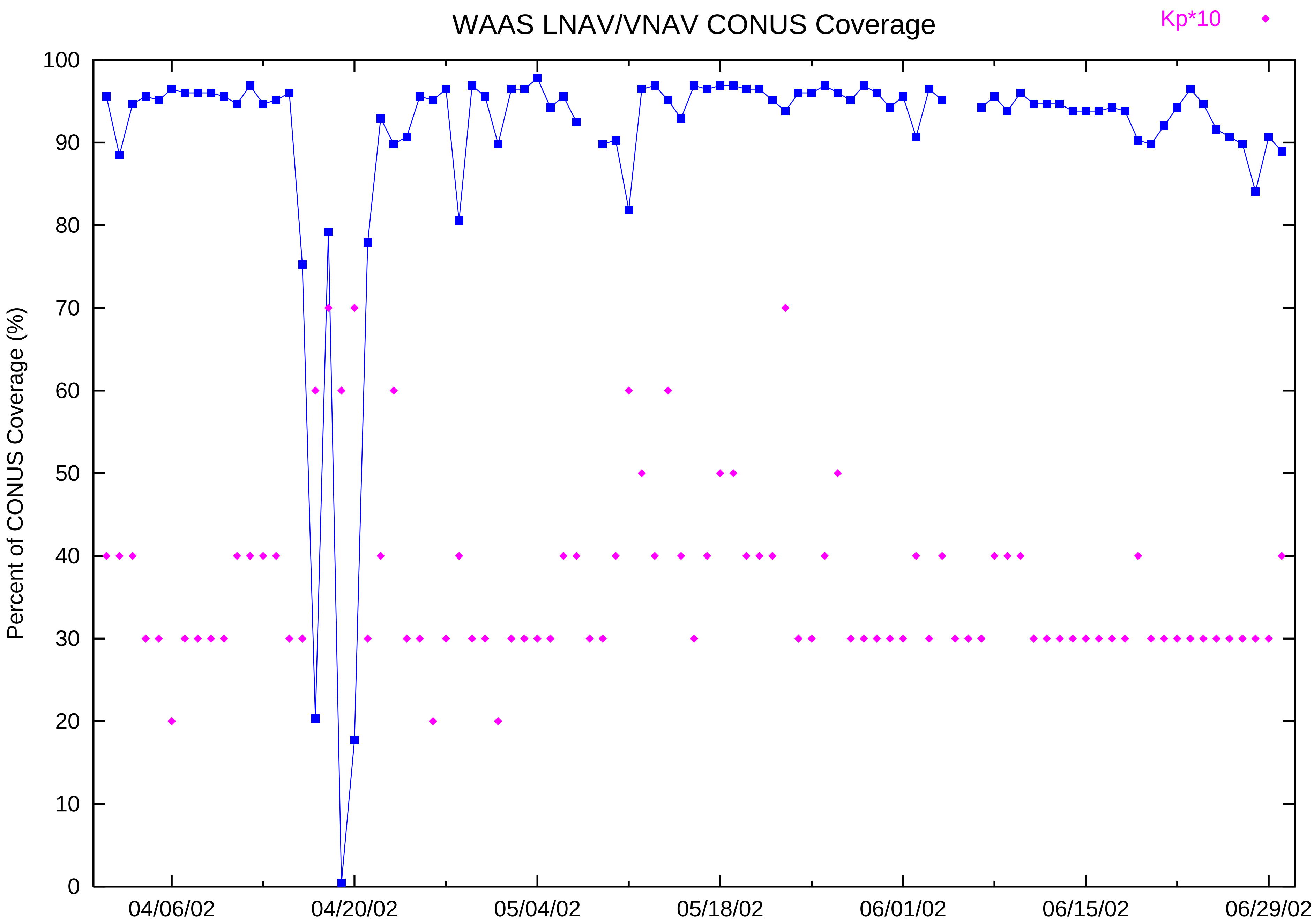


Figure 4.3 WAAS Coverage - June

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 0.981853 to 0.990311. 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 0.292475(Cold Bay) to 0.993663(Kansas City).

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.

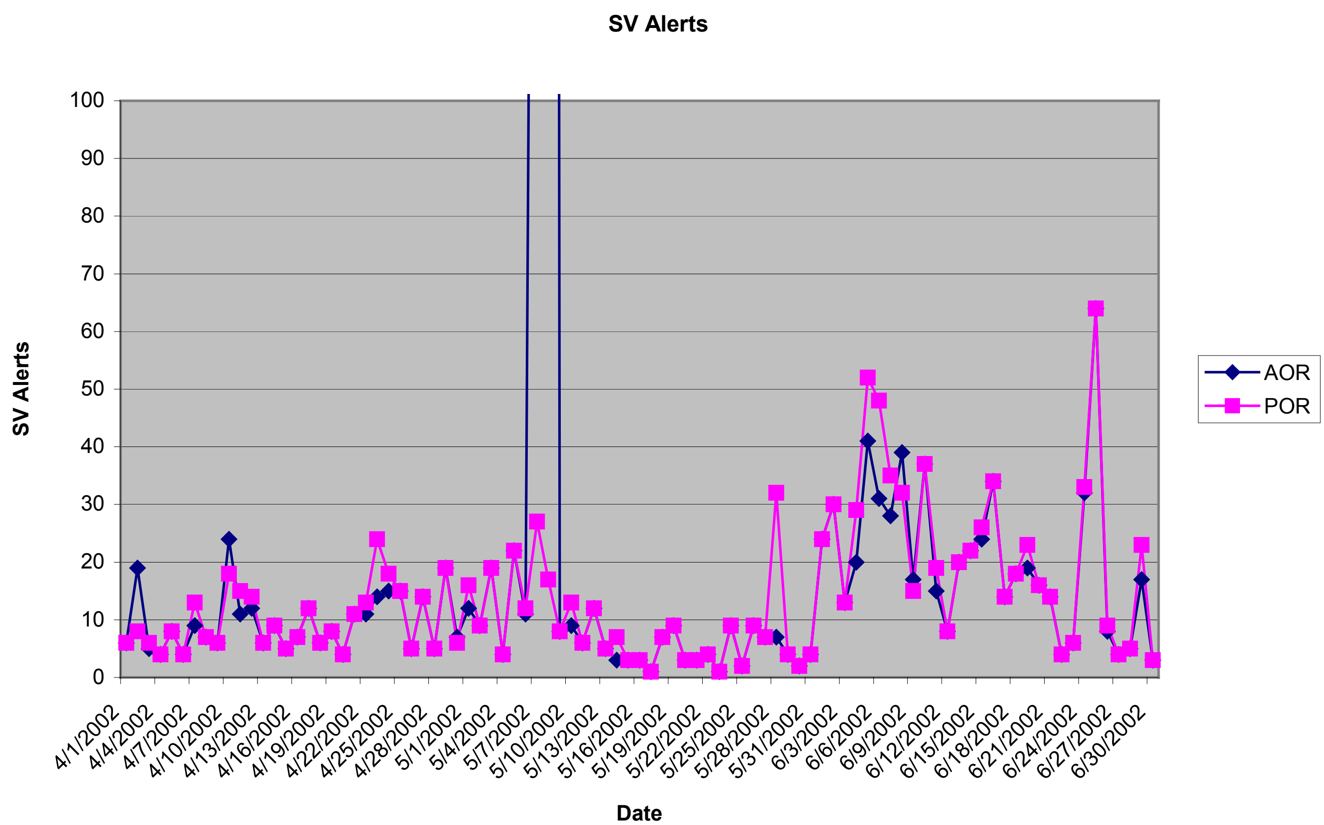
If the above conditions are met, then the continuity of function flag is set to "1" to indicate the continuity of function is met for that particular flight segment. The continuity of function percentile statistic was computed for each reference site by summing the continuity of function flags of "1" 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 0.382592(Cold Bay) to 0.995024(Kansas City).

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	0.989286	0.993663	0.995024
Chicago	1	0.988571	0.991708	0.992401
Columbus	1	0.986230	0.991115	0.991986
Denver	1	0.989659	0.992132	0.992628
Salt Lake City	1	0.989308	0.991722	0.992168
Greenwood	1	0.985294	0.989066	0.989936
Billings	1	0.987494	0.988794	0.990032
Atlanta	1	0.989085	0.987417	0.988933
Dallas	1	0.988548	0.989192	0.989757
Atlantic City	1	0.985775	0.985454	0.988102
Grand Forks	1	0.985536	0.973598	0.976218
Prescott	1	0.981853	0.947337	0.948889
Boston	1	0.988150	0.963069	0.965731
Miami	1	0.989097	0.946550	0.951375
Oakland	1	0.988764	0.952282	0.954112
Seattle	1	0.990311	0.979339	0.981571
Los Angeles	1	0.985162	0.955642	0.962689
Anchorage	1	0.982706	0.717564	0.747347
Juneau	1	0.982245	0.879250	0.901335
Cold Bay	1	0.987780	0.292475	0.382592

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	4.62	4.85	0
Chicago	5.00	5.33	0
Columbus	3.75	3.55	0
Denver	4.62	4.10	0
Salt Lake City	4.62	4.10	0
Greenwood	4.00	4.10	0
Billings	2.86	4.44	0
Atlanta	4.62	4.85	0
Dallas	4.62	4.44	0
Atlantic City	2.31	4.10	0
Grand Forks	5.00	3.33	0
Prescott	4.29	4.44	0
Boston	2.00	1.84	0
Miami	4.00	4.10	0
Oakland	5.00	3.55	0
Seattle	3.53	2.66	0
Los Angeles	4.29	4.85	0
Anchorage	4.62	2.96	0
Juneau	4.29	2.66	0
Cold Bay	8.57	5.92	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 1.84 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 7.1and 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 1.83 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 1.64 meters 95% of the time, and all satellites range errors were bounded at least 99.9% 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 predefine 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.

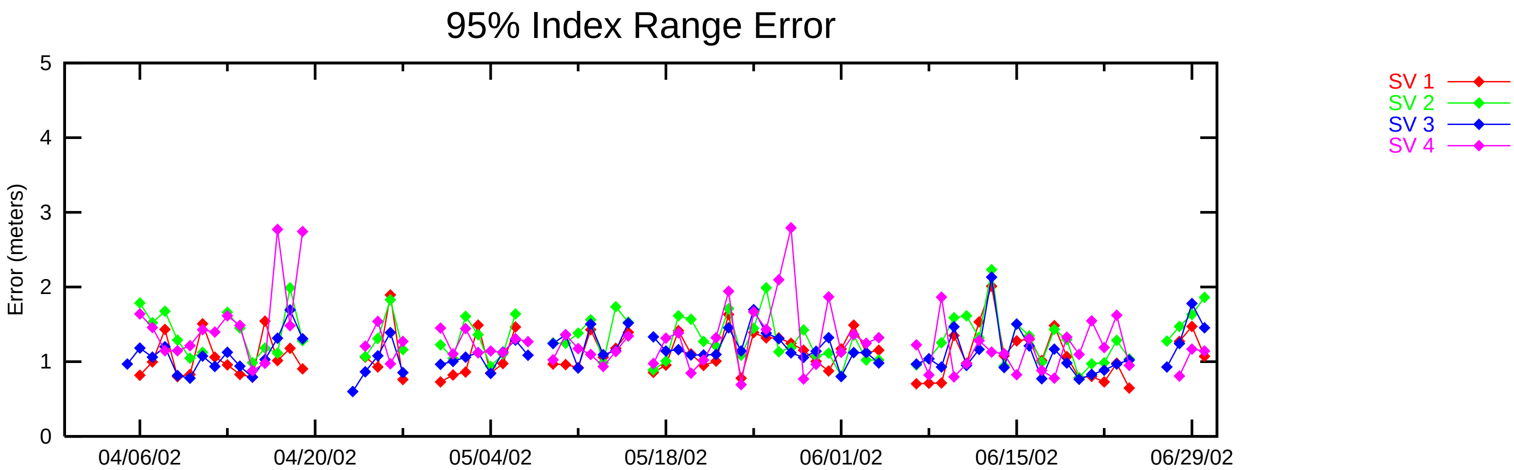
GPS satellite ionospheric errors were calculated for the WAAS receivers in Atlanta and Salt Lake City during the quarter. Table 7.1and 7.2 show the ionospheric error 95% index and 3.29σ bounding statistics for each SV at Atlanta and Salt Lake City, respectively. At Atlanta (as shown in Table 7.1), all GPS satellite ionospheric errors were less than 3.12 meters 95% of the time and all satellites were bounded at least 99.9% of the time. At Salt Lake City (as shown in Table 7.2), all GPS satellite ionospheric errors were less than 2.97 meters 95% of the time and all GPS satellites ionospheric errors were bounded at least 99.9%.

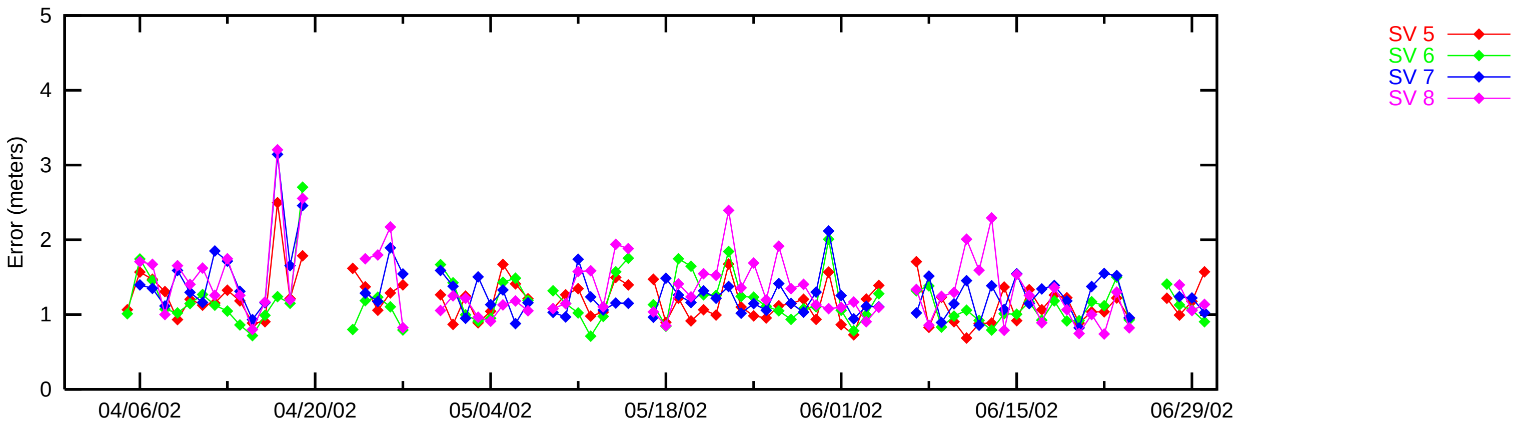
Figure 7.1 to 7.4 show the daily trend of the 95% Range and Ionospheric Errors for Atlanta. For this quarter, the daily trend data for Salt Lake City is not available.

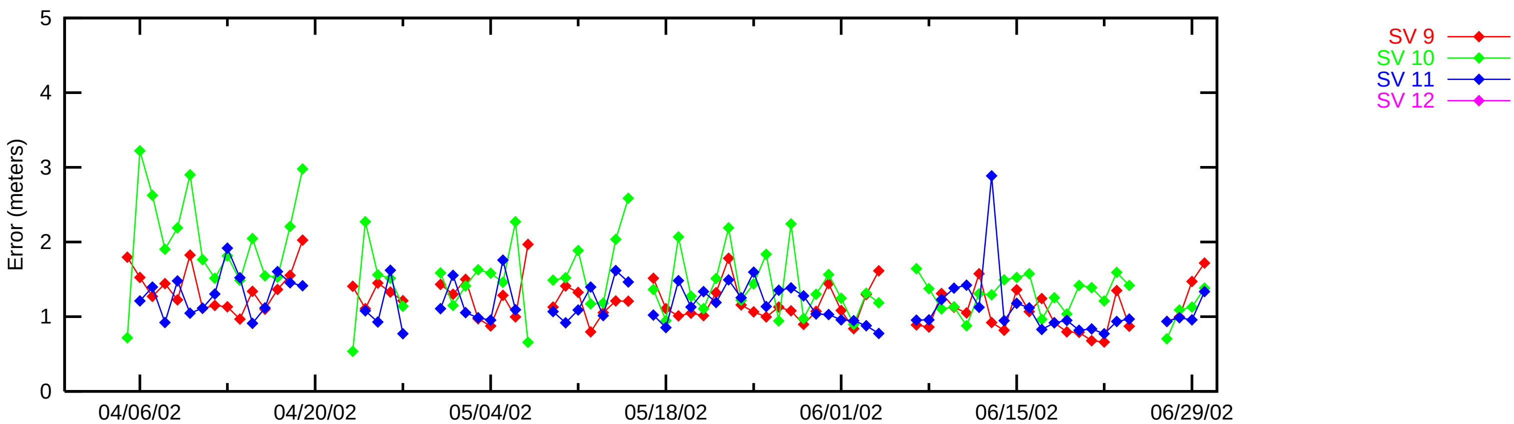
Table 7.1 Range and Ionopheric Error 95% index and 3.29 Sigma Bounding - Atlanta

SV	95% Range Error	Range Error Bounding	95% Ionospheric Error	Ionospheric Error Bounding
1	1.20	100.000	1.61	100.000
2	1.40	100.000	1.82	99.998
3	1.17	100.000	2.56	100.000
4	1.40	100.000	2.32	99.981
5	1.23	100.000	2.48	100.000
6	1.23	100.000	2.73	100.000
7	1.37	100.000	2.08	100.000
8	1.51	100.000	1.48	100.000
9	1.23	100.000	3.05	100.000
10	1.83	100.000	1.36	100.000
11	1.25	100.000	1.63	99.997
13	1.37	100.000	2.46	99.998
14	1.42	100.000	1.45	100.000
15	1.27	100.000	1.50	99.983
17	1.37	100.000	1.82	100.000
18	1.29	100.000	1.41	99.993
20	1.25	100.000	2.01	99.996
21	1.37	100.000	1.99	100.000
22	1.28	100.000	1.59	100.000
23	1.47	100.000	1.68	100.000
24	1.39	100.000	2.29	100.000
25	1.21	100.000	2.32	100.000
26	1.62	100.000	3.12	100.000
27	1.35	100.000	1.68	100.000
28	1.32	100.000	1.39	100.000
29	1.56	100.000	2.78	99.999
30	1.24	100.000	2.90	100.000
31	1.30	100.000	1.76	100.000
122	3.66	100.000	-	-

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







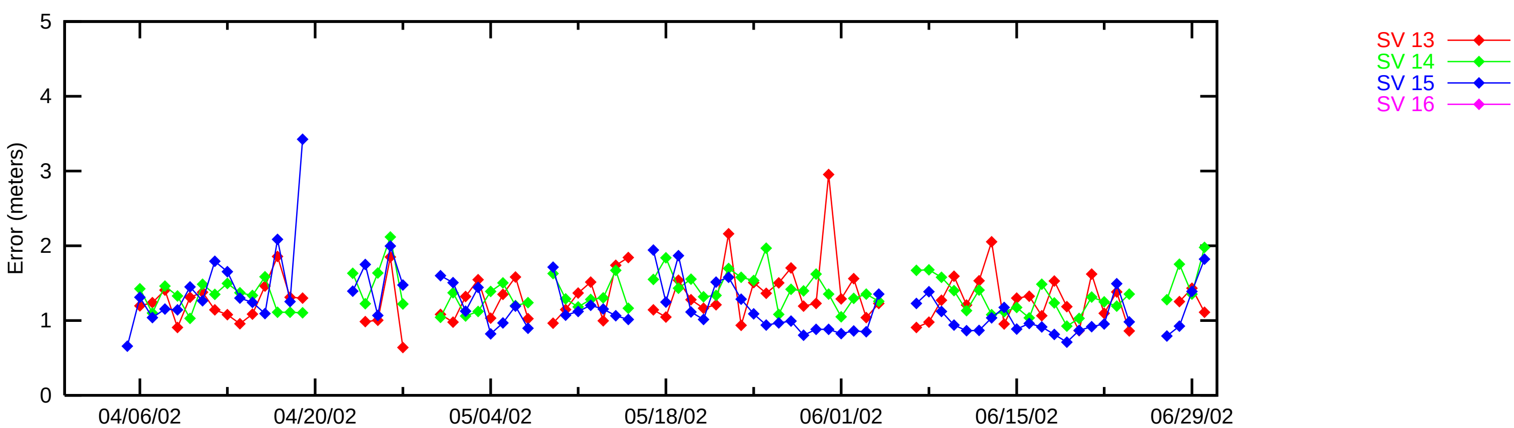


Figure 7.2 95% Range Error (SV 17- SV 31) - Atlanta

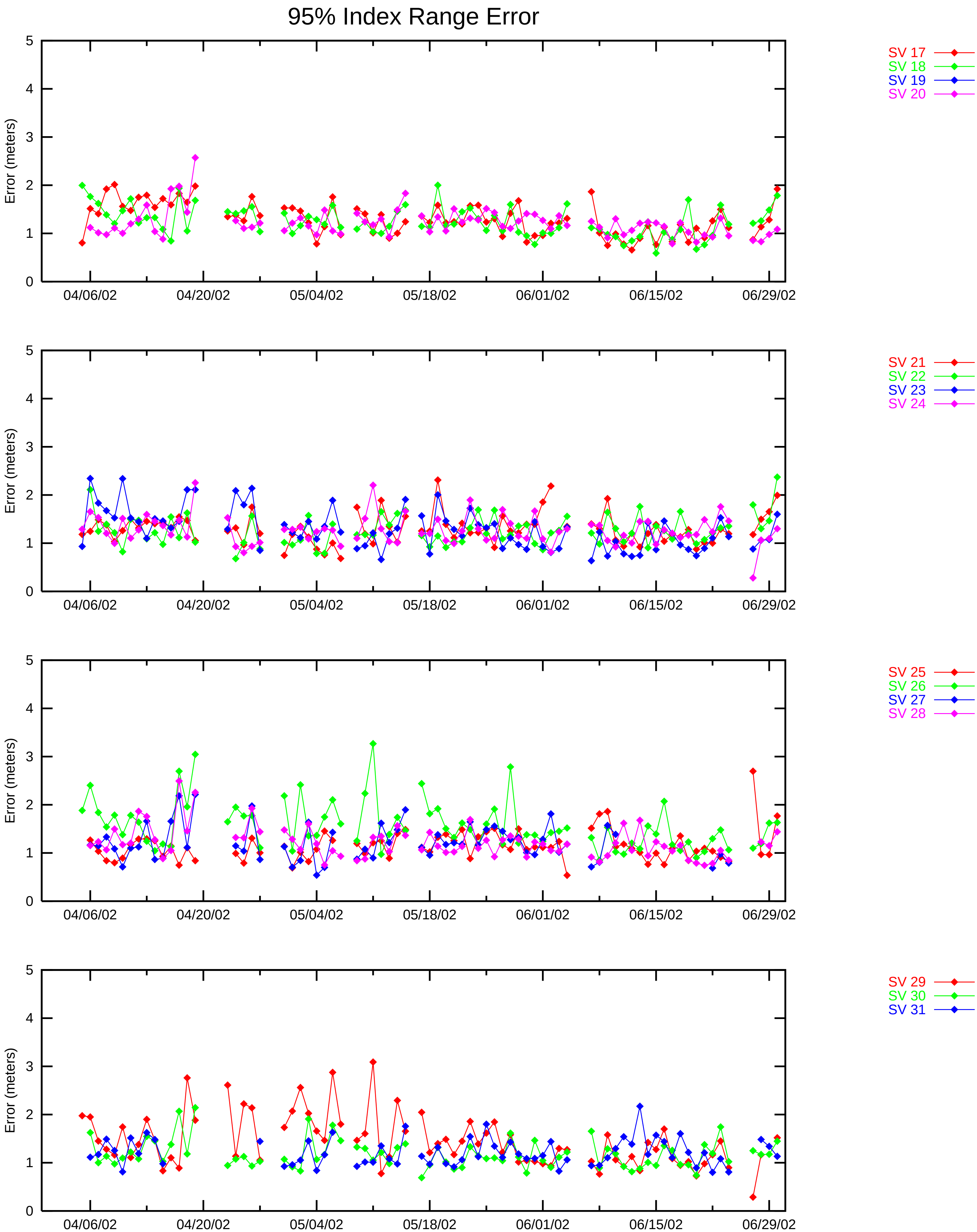


Figure 7.3 95% Ionospheric Error (SV 1- SV 16) - Atlanta

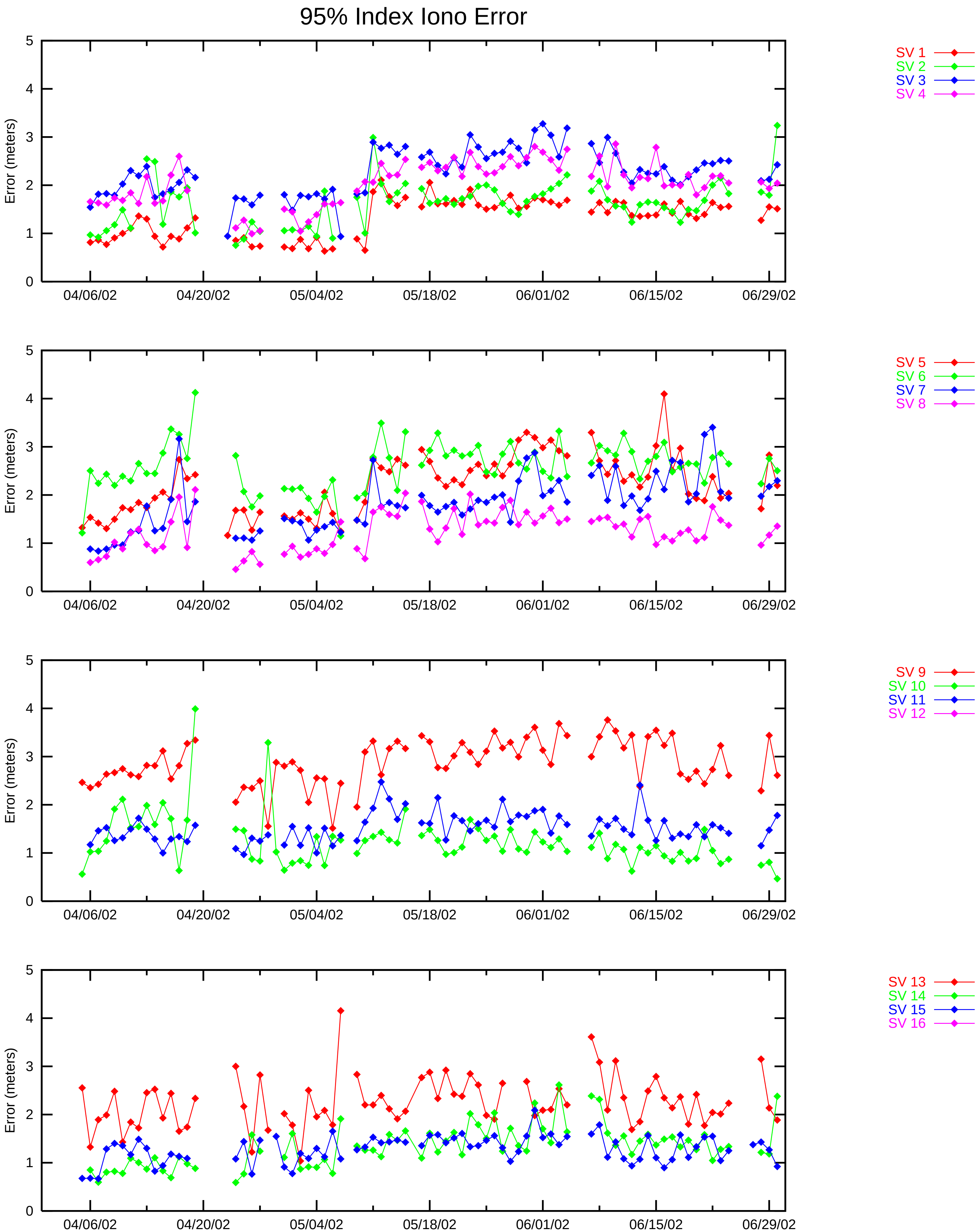


Figure 7.4 95% Ionospheric Error (SV 17 - SV 31) - Atlanta

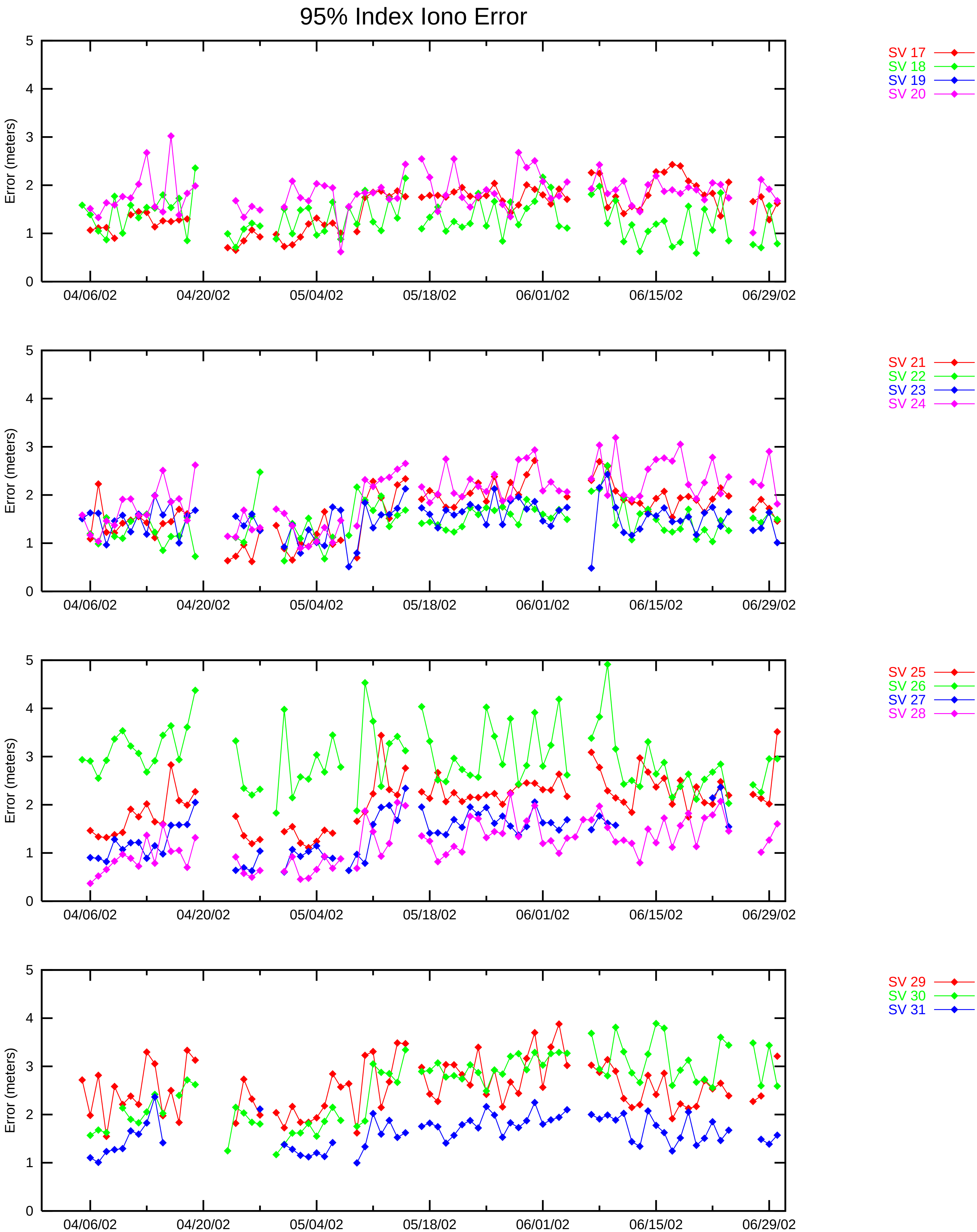


Table 7.2 Range and Ionospheric Error 95% index and 3.29 Sigma Bounding – Salt Lake City

SV	95% Range Error	Range Error Bounding	95% Ionospheric Error	Ionospheric Error Bounding
1	0.97	100.000	1.40	99.996
2	1.31	100.000	1.90	99.999
3	1.05	100.000	1.33	100.000
4	1.17	100.000	1.71	99.999
5	1.50	100.000	2.03	99.991
6	1.39	100.000	1.09	100.000
7	1.23	100.000	1.39	100.000
8	1.06	100.000	1.60	100.000
9	1.10	100.000	1.42	100.000
10	1.38	100.000	2.97	99.995
11	1.18	100.000	2.13	100.000
13	1.04	100.000	1.50	100.000
14	1.14	100.000	1.73	100.000
15	1.20	100.000	1.84	100.000
17	1.35	100.000	1.37	100.000
18	1.20	100.000	2.13	100.000
20	1.21	100.000	2.20	99.991
21	1.20	100.000	1.39	99.992
22	1.21	100.000	2.45	100.000
23	1.43	99.999	2.09	100.000
24	1.43	100.000	1.00	100.000
25	1.64	100.000	1.66	100.000
26	1.19	100.000	1.69	100.000
27	1.09	100.000	1.35	99.994
28	1.15	100.000	1.76	100.000
29	1.12	100.000	1.60	99.998
30	1.26	100.000	1.52	99.998
31	1.16	100.000	2.37	99.935
134	6.91	99.957	-	-

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.

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 $1\text{-}10^{-7}$ 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 $1\text{-}10^{-7}$ 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.