A Summary of the Data Analysis for Halifax GPS Precision Approach Trials

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Outline of the Presentation

- Introduction
- Step 1: Evaluating the Ashtech “ground truth” system.
- Step 2: Software development assessing the Trimble LDGPS solutions based on Ashtech PNAV solutions.
- Step 3: Development of statistics and analysis of results.
- Conclusions
- Recommendations

- **Objective:** to provide evidence that Trimble local differential GPS (LDGPS) can be used for Special CAT I precision runway approaches.

- **Equipment:** a Sikorsky S-76A helicopter equipped with Trimble TNL 3100 DZUS GPS avionics receiver & Ashtech LM-XII GPS geodetic receiver; base station equipped with Trimble TNL-2800G GPS landing system & Ashtech LM-XII GPS geodetic receiver.

- **Data collected:** Trimble real-time differential solution & simultaneous Ashtech raw data at base station and onboard for 73 approaches at Halifax International Airport in Feb/March 1994.

- **Method used to meet objective:** the independent Ashtech solution is used as ‘ground truth’ with which we compared the Trimble LDGPS solution.

Transport Canada Aviation/Cougar Helicopters Inc.
GPS Precision Approach Trials

Sikorsky S-76A helicopter equipped with Trimble TNL 3100 DZUS GPS avionics receiver & Ashtech LM-XII GPS geodetic receiver

Airfield of Halifax International Airport

- **Step 1.** : We used three different solutions to validate the Ashtech solution:
  - C/A-code/carrier phase solution (PNAV),
  - Carrier-phase smoothed C/A-code solution (PNAV),
  - Postprocessed differential smoothed C/A-code solution (PPDIFF).

  Figure 1: Shows an example of the comparison between the three solutions along with the estimated position accuracy of the Ashtech solution.

  Figure 2: Shows an example of the comparison between the three solutions computed from the raw data without cycle slip editing & checking for data quality.

  Figure 3: Gives an indication about how noisy the solution and data are, and how good PNAV thinks the solution is.

- **Conclusion from step 1.**: Estimated position accuracy from Ashtech data is lower than expected. Why? Because pseudorange observations are biased by multipath; carrier-phase ambiguities are not resolved; and observation periods are too short.

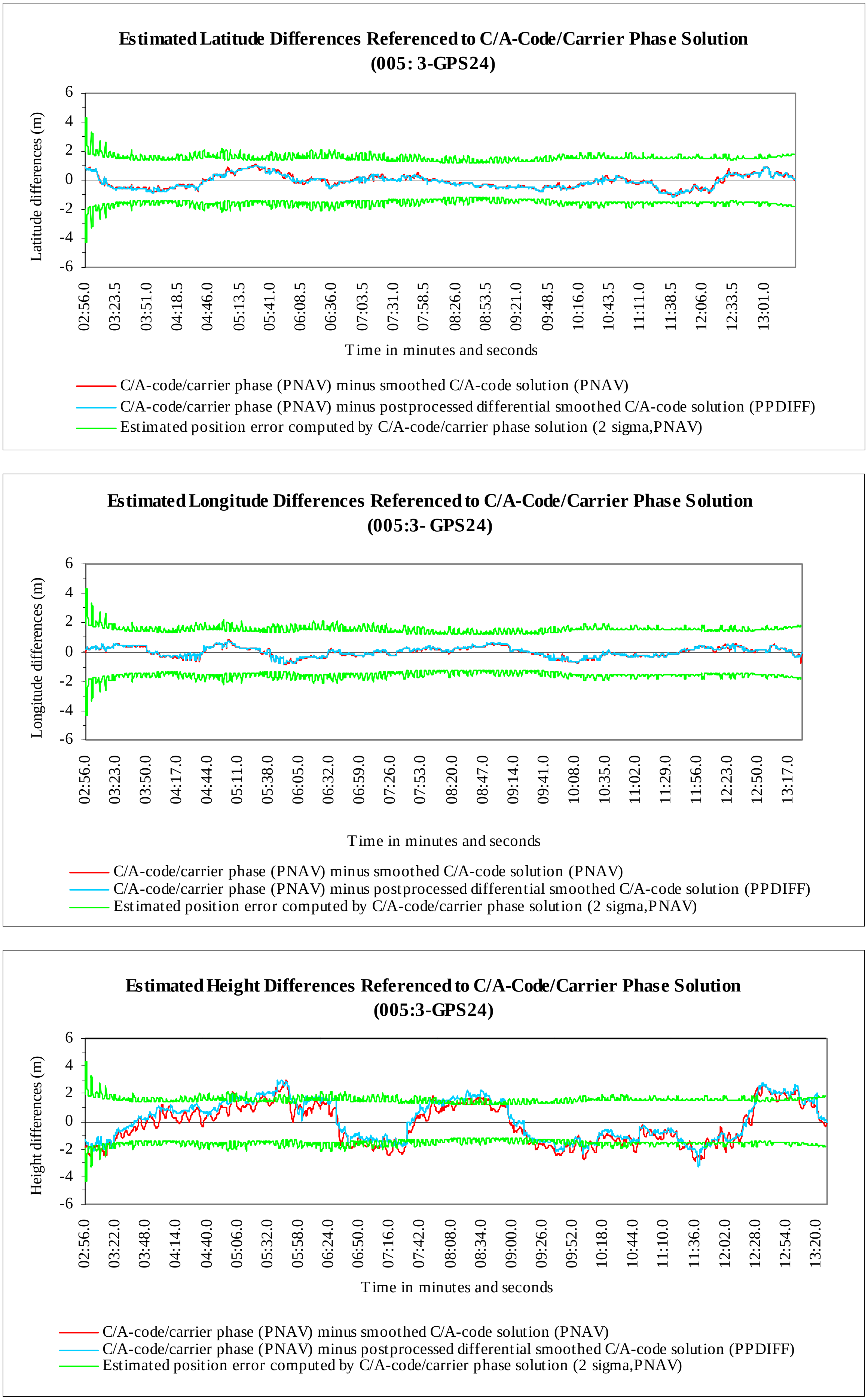

Estimated Latitude Differences Referenced to C/A-Code/Carrier Phase Solution
(005: 3-GPS24)
Latitude differences (m)
Time in minutes and seconds
C/A-code/carrier phase (PNAV) minus smoothed C/A-code solution (PNAV)
C/A-code/carrier phase (PNAV) minus postprocessed differential smoothed C/A-code solution (PPDIFF)
Estimated position error computed by C/A-code/carrier phase solution (2 sigma,PNAV)
Estimated Longitude Differences Referenced to C/A-Code/Carrier Phase Solution
(005:3- GPS24)
Longitude differences (m)
Time in minutes and seconds
C/A-code/carrier phase (PNAV) minus smoothed C/A-code solution (PNAV)
C/A-code/carrier phase (PNAV) minus postprocessed differential smoothed C/A-code solution (PPDIFF)
Estimated position error computed by C/A-code/carrier phase solution (2 sigma,PNAV)
Estimated Height Differences Referenced to C/A-Code/Carrier Phase Solution
(005:3-GPS24)
Height differences (m)
Time in minutes and seconds
C/A-code/carrier phase (PNAV) minus smoothed C/A-code solution (PNAV)
C/A-code/carrier phase (PNAV) minus postprocessed differential smoothed C/A-code solution (PPDIFF)
Estimated position error computed by C/A-code/carrier phase solution (2 sigma,PNAV)

Figure 1

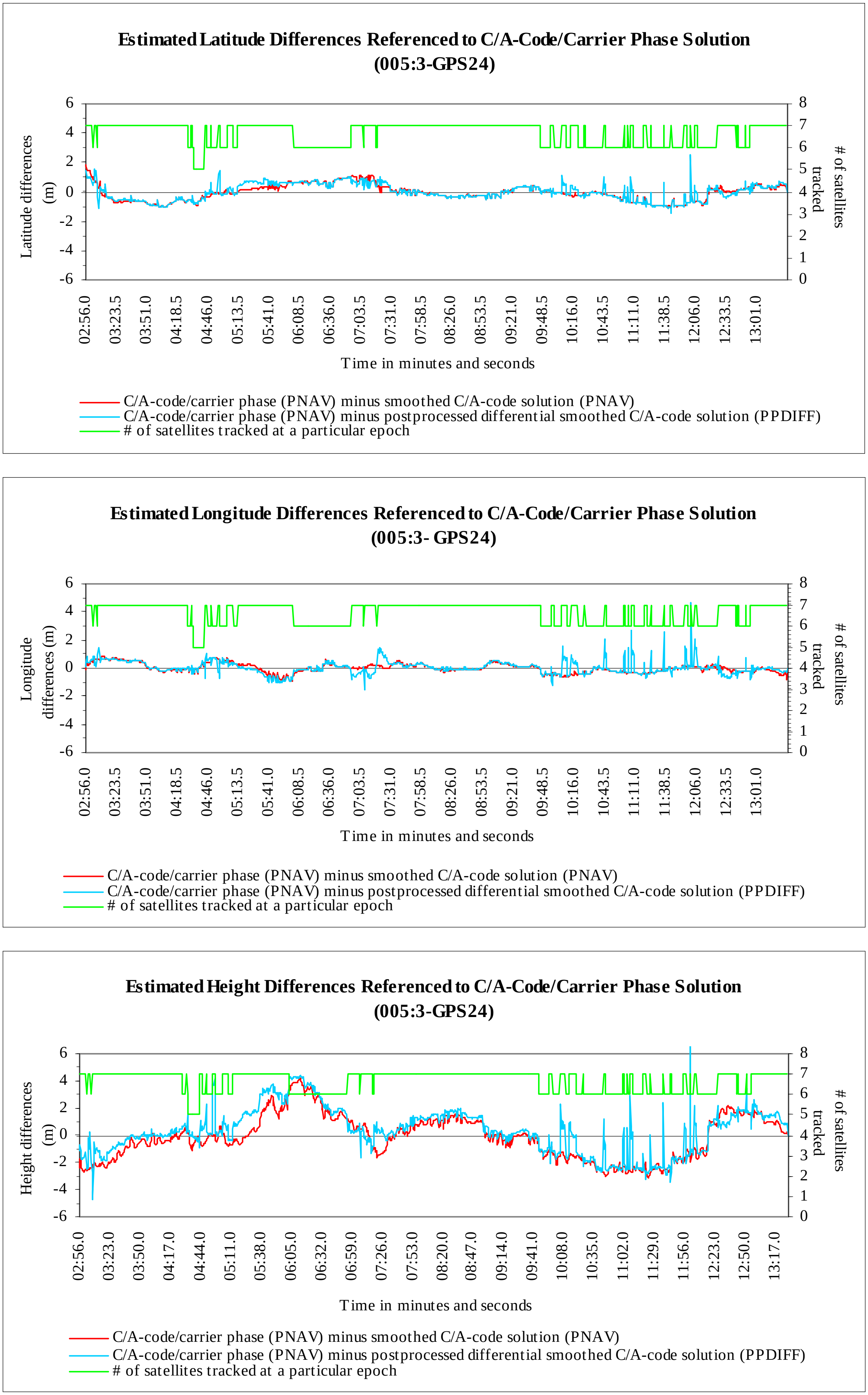
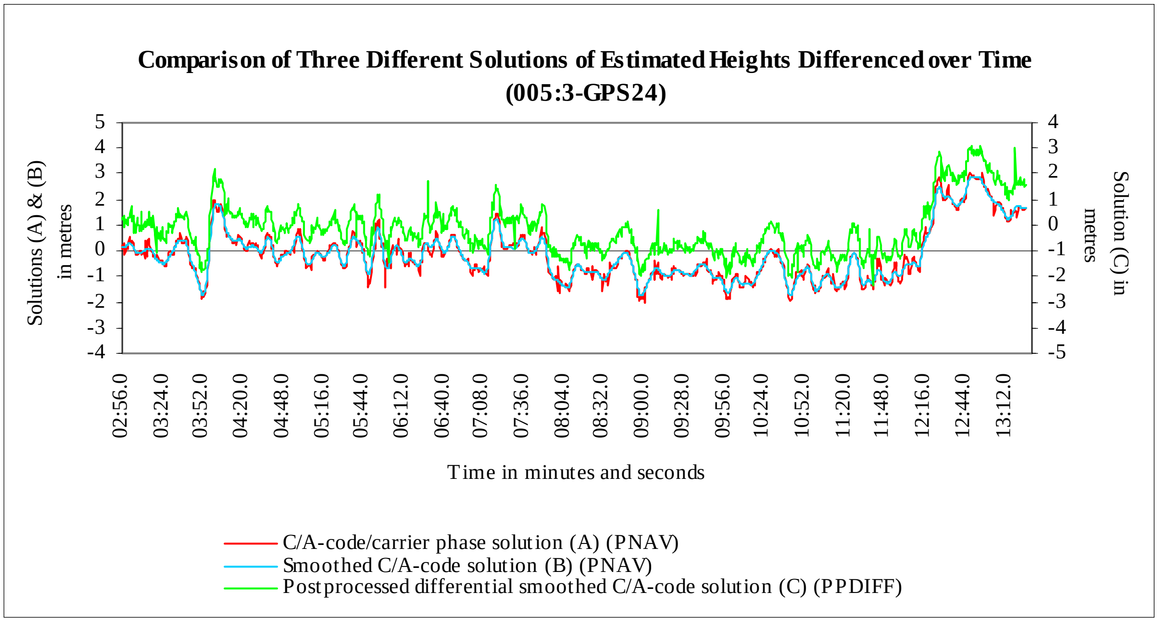
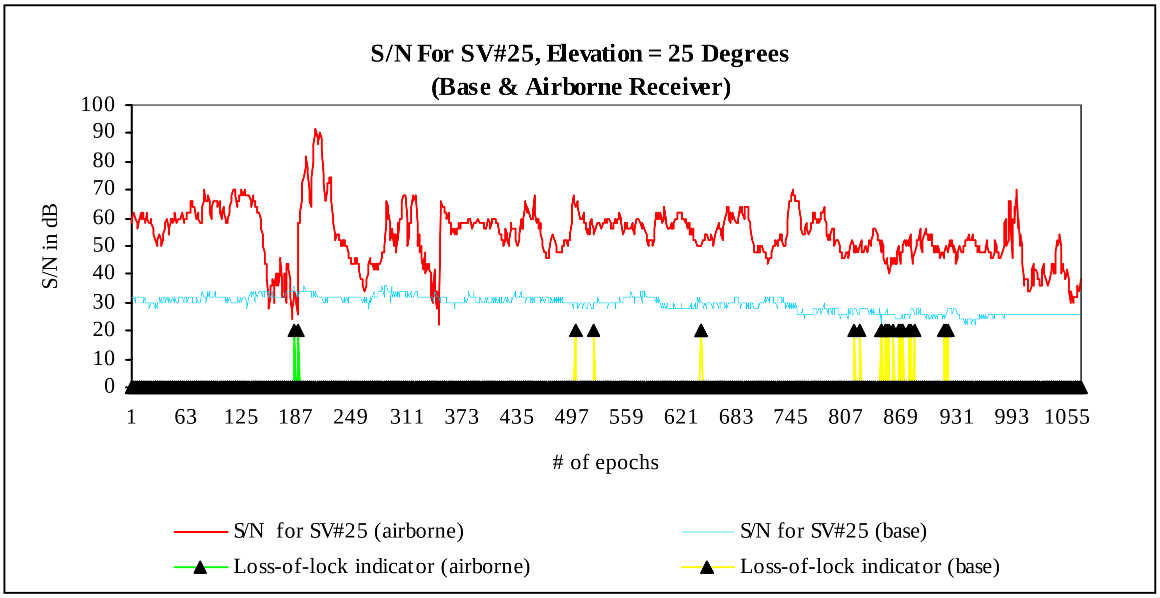

Estimated Latitude Differences Referenced to C/A-Code/Carrier Phase Solution
(005:3-GPS24)
Latitude differences (m)
# of satellites tracked
6
4
2
0
-2
-4
-6
8
7
6
5
4
3
2
1
0
02:56.0
03:23.5
03:51.0
04:18.5
04:46.0
05:13.5
05:41.0
06:08.5
06:36.0
07:03.5
07:31.0
07:58.5
08:26.0
08:53.5
09:21.0
09:48.5
10:16.0
10:43.5
11:11.0
11:38.5
12:06.0
12:33.5
13:01.0
Time in minutes and seconds
C/A-code/carrier phase (PNAV) minus smoothed C/A-code solution (PNAV)
C/A-code/carrier phase (PNAV) minus postprocessed differential smoothed C/A-code solution (PPDIFF)
# of satellites tracked at a particular epoch
Estimated Longitude Differences Referenced to C/A-Code/Carrier Phase Solution
(005:3- GPS24)
Longitude differences (m)
# of satellites tracked
6
4
2
0
-2
-4
-6
8
7
6
5
4
3
2
1
0
02:56.0
03:23.5
03:51.0
04:18.5
04:46.0
05:13.5
05:41.0
06:08.5
06:36.0
07:03.5
07:31.0
07:58.5
08:26.0
08:53.5
09:21.0
09:48.5
10:16.0
10:43.5
11:11.0
11:38.5
12:06.0
12:33.5
13:01.0
Time in minutes and seconds
C/A-code/carrier phase (PNAV) minus smoothed C/A-code solution (PNAV)
C/A-code/carrier phase (PNAV) minus postprocessed differential smoothed C/A-code solution (PPDIFF)
# of satellites tracked at a particular epoch
Estimated Height Differences Referenced to C/A-Code/Carrier Phase Solution
(005:3-GPS24)
Height differences (m)
# of satellites tracked
6
4
2
0
-2
-4
-6
8
7
6
5
4
3
2
1
0
02:56.0
03:23.0
03:50.0
04:17.0
04:44.0
05:11.0
05:38.0
06:05.0
06:32.0
06:59.0
07:26.0
07:53.0
08:20.0
08:47.0
09:14.0
09:41.0
10:08.0
10:35.0
11:02.0
11:29.0
11:56.0
12:23.0
12:50.0
13:17.0
Time in minutes and seconds
C/A-code/carrier phase (PNAV) minus smoothed C/A-code solution (PNAV)
C/A-code/carrier phase (PNAV) minus postprocessed differential smoothed C/A-code solution (PPDIFF)
# of satellites tracked at a particular epoch

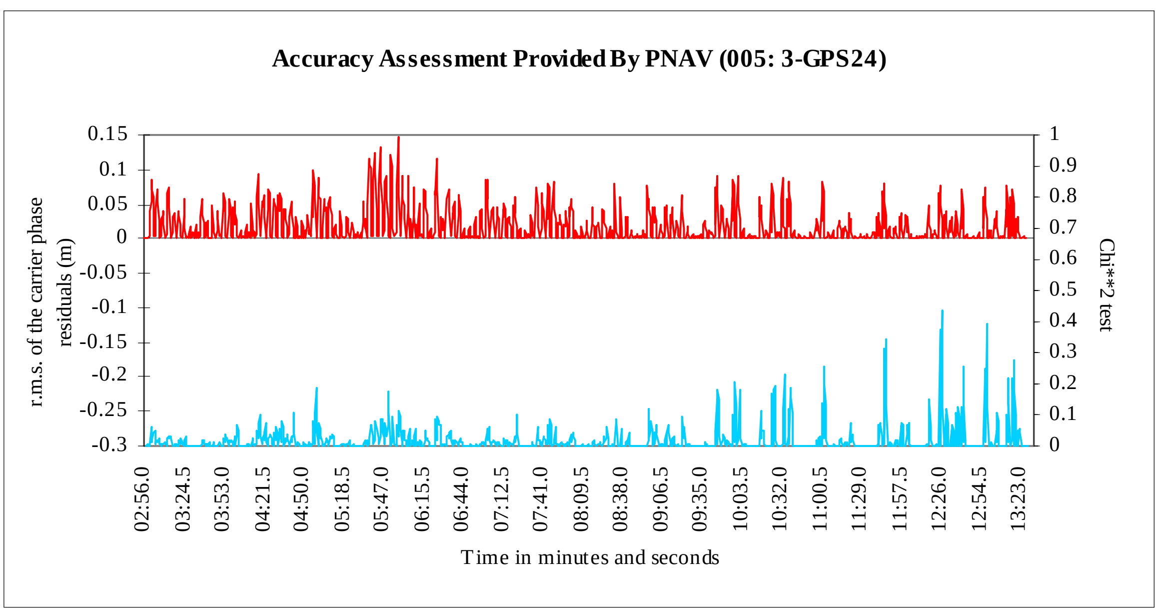
Figure 2



Comparison of Three Different Solutions of Estimated Heights Differenced over Time
(005:3-GPS24)
Solutions (A) & (B) in metres
Solution (C) in metres
Time in minutes and seconds
C/A-code/carrier phase solution (A) (PNAV)
Smoothed C/A-code solution (B) (PNAV)
Postprocessed differential smoothed C/A-code solution (C) (PPDIFF)



S/N For SV#25, Elevation = 25 Degrees
(Base & Airborne Receiver)
S/N in dB
# of epochs
S/N for SV#25 (airborne)
S/N for SV#25 (base)
Loss-of-lock indicator (airborne)
Loss-of-lock indicator (base)



Accuracy Assessment Provided By PNAV (005: 3-GPS24)
r.m.s. of the carrier phase residuals (m)
Chi**2 test
Time in minutes and seconds

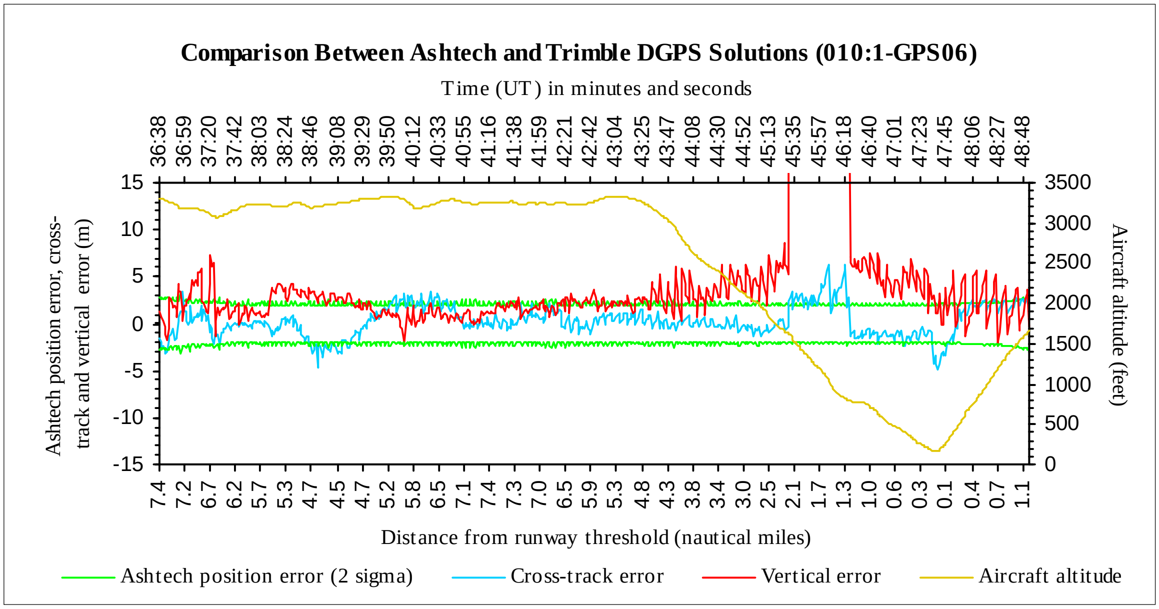
Figure 3

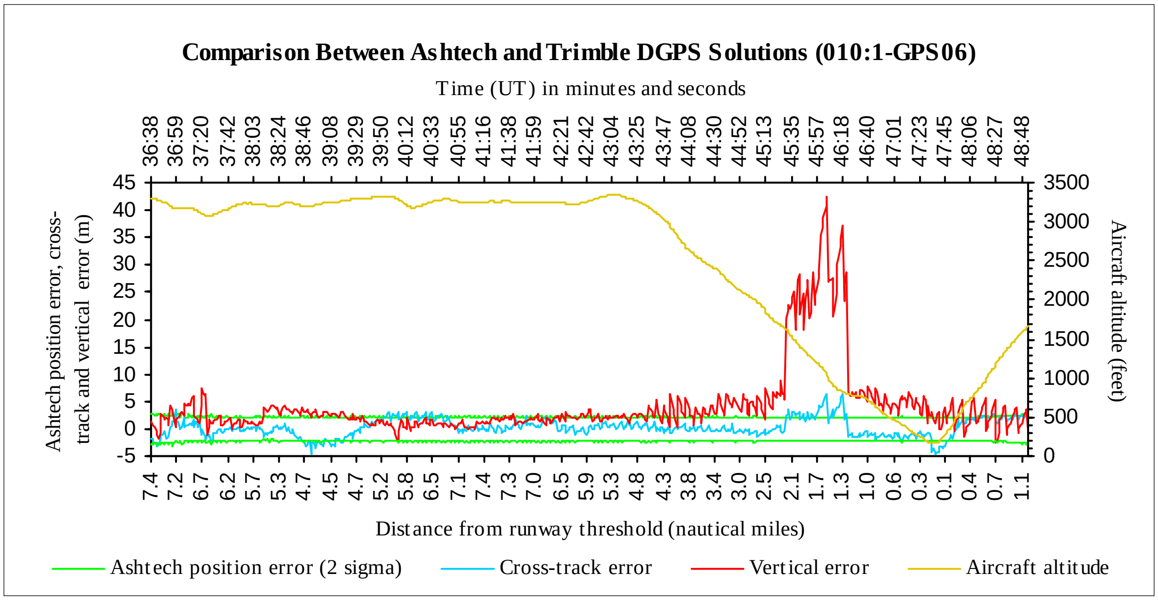
- **Step 2.**: - We used the Ashtech solution as a benchmark against the Trimble DGPS solution.
  - Software development that performs the analysis:
    - use aircraft velocity to interpolate aircraft position between epochs,
    - use of geoidal model that accounts for geoidal undulation,
    - use aircraft velocities to compute cross-track error and vertical error.

  Figures 4 & 5 : Show examples of the comparisons between the two sensors.

- **Conclusions from step 2.**:
  - All 73 approaches were able to be processed.
  - Trimble solutions show distinct jumps both in cross-track and vertical sense which could be due to:
    - sudden change in the # of satellites tracked,
    - delay in airborne receiver solution updates.

Runway Threshold Approach **010:1-GPS06**





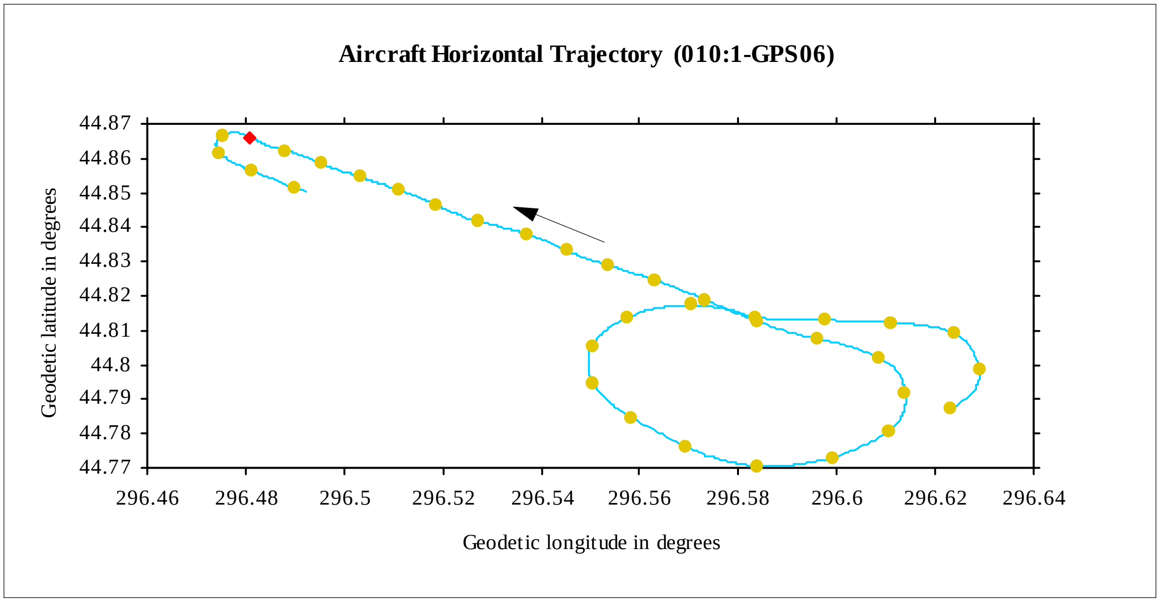
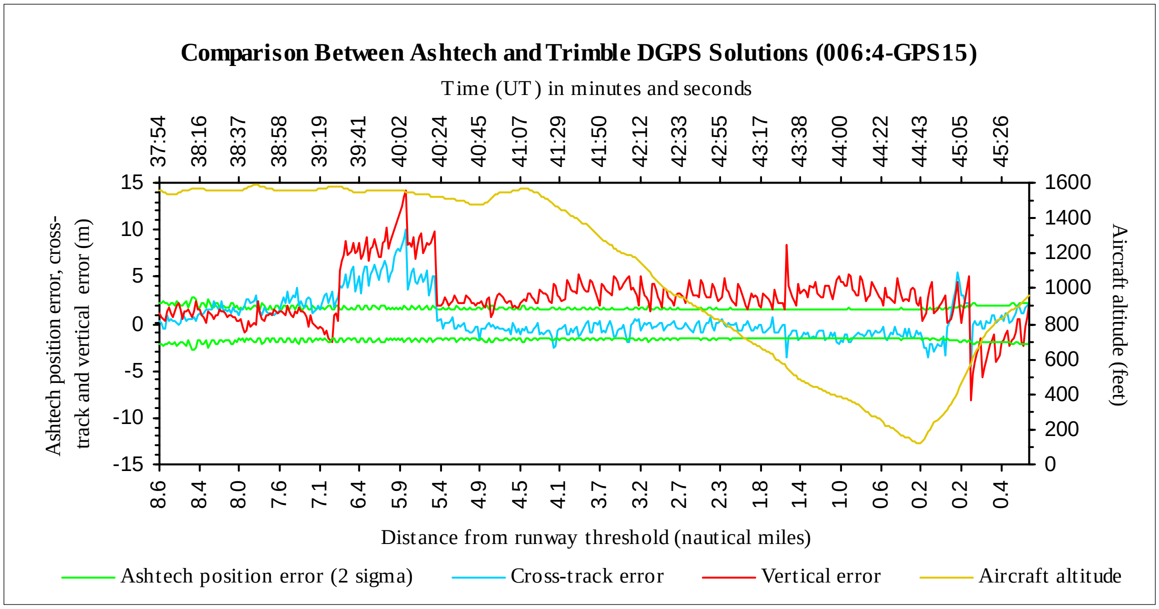
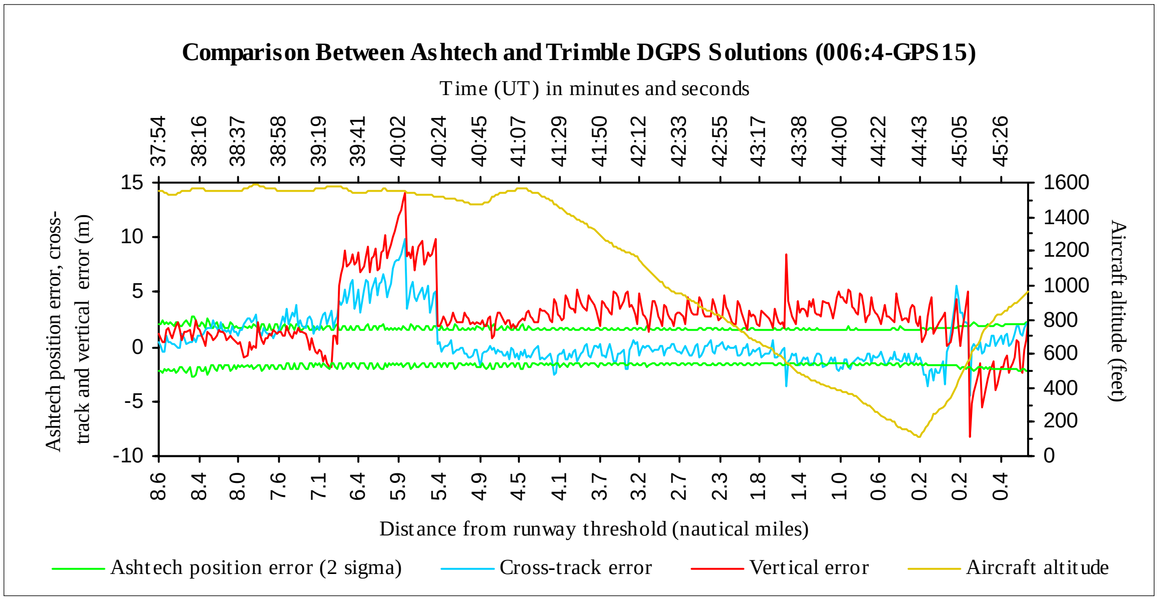


Figure 4


Comparison Between Ashtech and Trimble DGPS Solutions (006:4-GPS15)
Time (UT) in minutes and seconds
37:54 38:16 38:37 38:58 39:19 39:41 40:02 40:24 40:45 41:07 41:29 41:50 42:12 42:33 42:55 43:17 43:38 44:00 44:22 44:43 45:05 45:26
15 10 5 0 -5 -10 -15
Ashtech position error, cross-track and vertical error (m)
1600 1400 1200 1000 800 600 400 200 0
Aircraft altitude (feet)
8.6 8.4 8.0 7.6 7.1 6.4 5.9 5.4 4.9 4.5 4.1 3.7 3.2 2.7 2.3 1.8 1.4 1.0 0.6 0.2 0.2 0.4
Distance from runway threshold (nautical miles)
Ashtech position error (2 sigma)
Cross-track error
Vertical error
Aircraft altitude


Comparison Between Ashtech and Trimble DGPS Solutions (006:4-GPS15)
Time (UT) in minutes and seconds
37:54 38:16 38:37 38:58 39:19 39:41 40:02 40:24 40:45 41:07 41:29 41:50 42:12 42:33 42:55 43:17 43:38 44:00 44:22 44:43 45:05 45:26
15 10 5 0 -5 -10
Ashtech position error, cross-track and vertical error (m)
1600 1400 1200 1000 800 600 400 200 0
Aircraft altitude (feet)
8.6 8.4 8.0 7.6 7.1 6.4 5.9 5.4 4.9 4.5 4.1 3.7 3.2 2.7 2.3 1.8 1.4 1.0 0.6 0.2 0.2 0.4
Distance from runway threshold (nautical miles)
Ashtech position error (2 sigma)
Cross-track error
Vertical error
Aircraft altitude

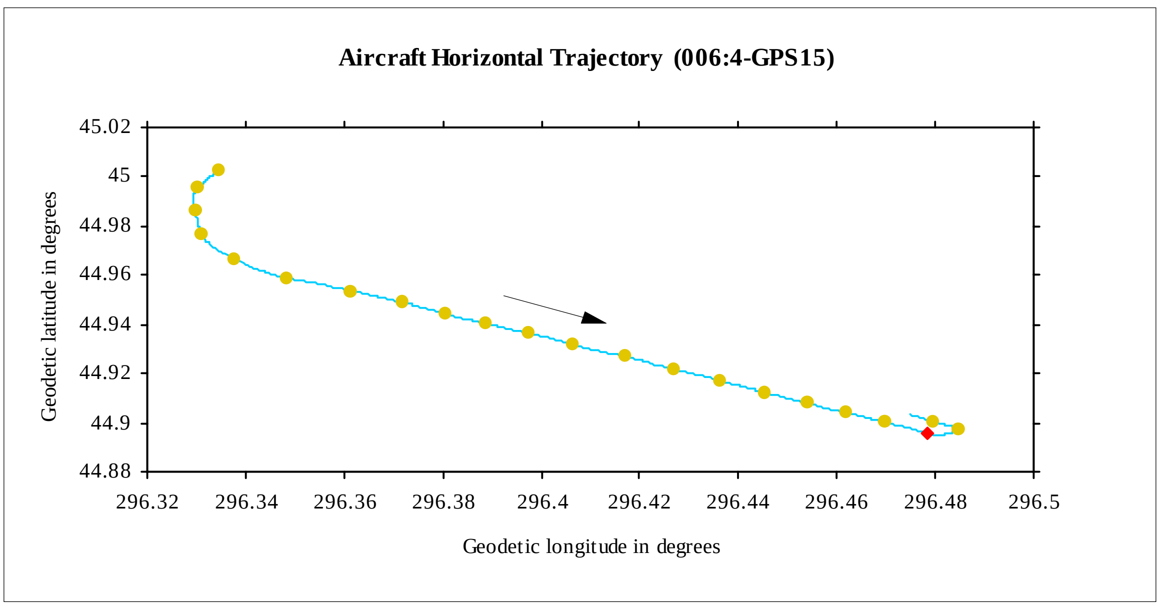

Aircraft Horizontal Trajectory (006:4-GPS15)
45.02 45 44.98 44.96 44.94 44.92 44.9 44.88
Geodetic latitude in degrees
296.32 296.34 296.36 296.38 296.4 296.42 296.44 296.46 296.48 296.5
Geodetic longitude in degrees

Figure 5

- **Step 3.**: - A.) Analysis of the whole data set.

  - We computed the means & standard deviations of cross-track & vertical errors for all data (**Fig. 6&7**).

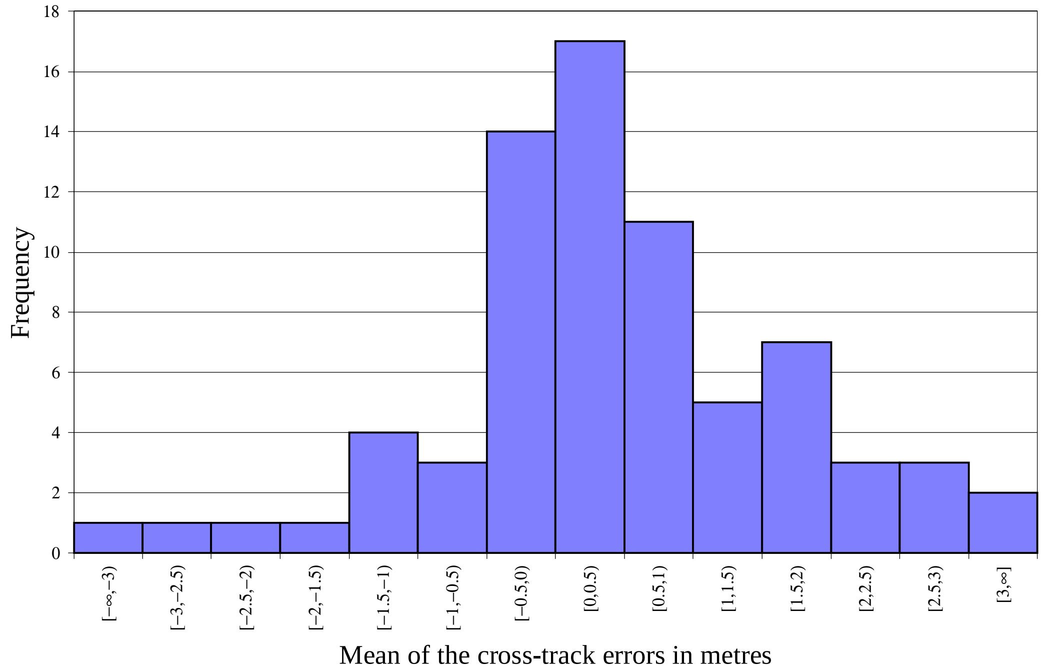
  - B.) Setting up categories to develop further statistics.

  - We also investigated several categories of approaches:
    - 3 & 6 degree glidepath approaches,
    - 200 & 100 ft decision height approaches,
    - missed approaches (landing, left-right, straight),
    - 50&70 knot approaches.
  - We looked at the data before & after the Trimble airborne receiver firmware modifications.
  - We treated: **1**. all the data collected, **2**. all data except 3 approaches which needed to be eliminated due to bad quality of Ashtech “ground truth” solution.

Figure 8: as an example shows cross-track error statistics for 3 & 6 degree glidepath approaches.

Figure 9: shows vertical error statistics for 3 & 6 degree glidepath approaches.

Mean of the Cross-track Errors for All 73 Approaches



Standard Deviation of the Cross-track Errors for All 73 Approaches

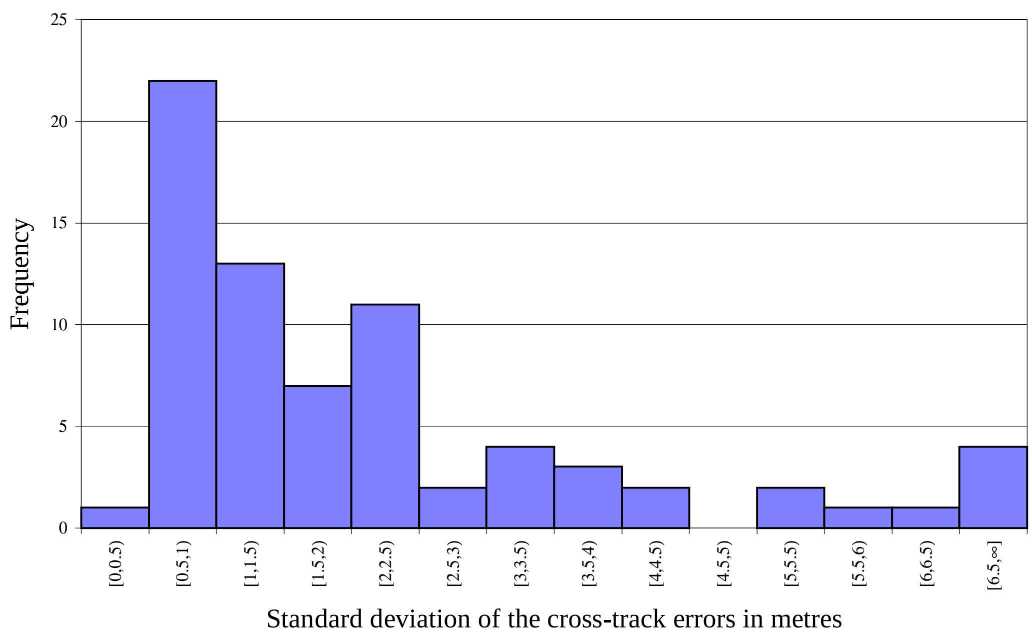
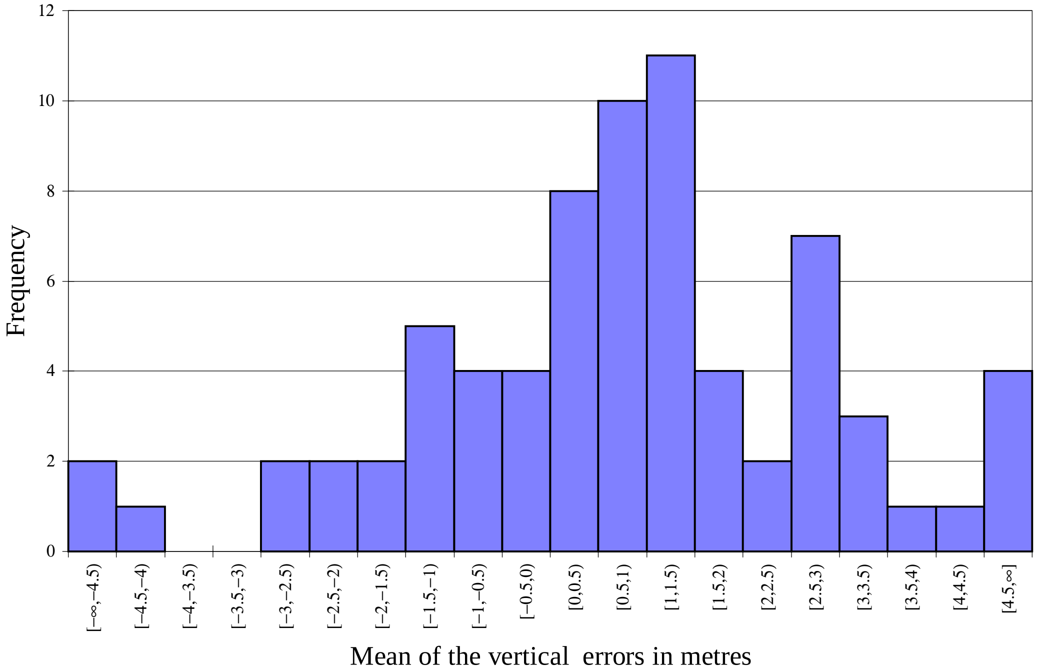


Figure 6

Mean of the Vertical Errors for All 73 Approaches



Standard Deviation of the Vertical Errors for All 73 Approaches

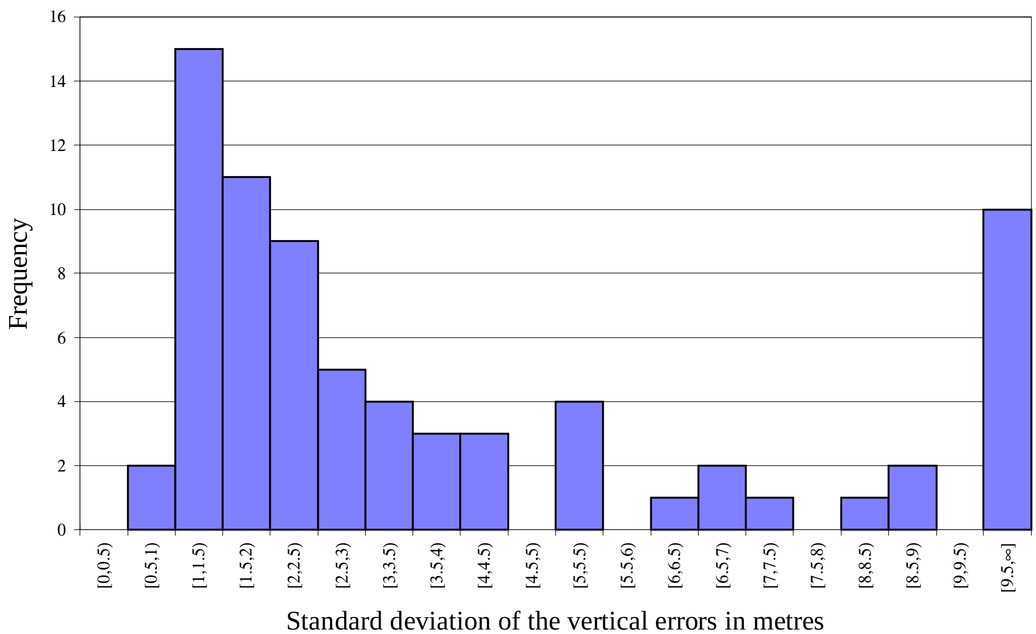
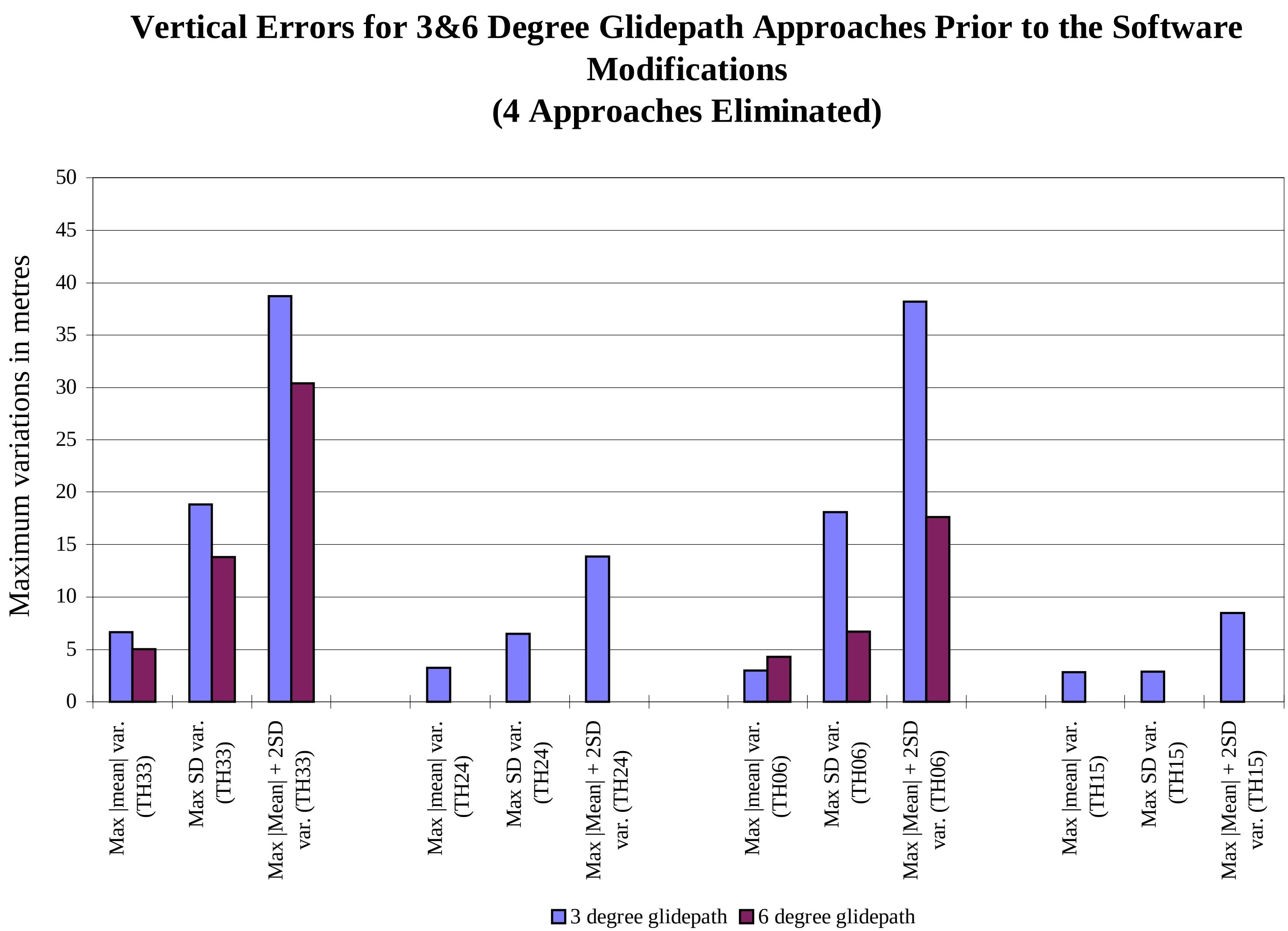


Figure 7



Vertical Errors for 3&6 Degree Glidepath Approaches Prior to the Software Modifications
(4 Approaches Eliminated)
Maximum variations in metres
50
45
40
35
30
25
20
15
10
5
0
Max |mean| var. (TH33)
Max SD var. (TH33)
Max |Mean| + 2SD var. (TH33)
Max |mean| var. (TH24)
Max SD var. (TH24)
Max |Mean| + 2SD var. (TH24)
Max |mean| var. (TH06)
Max SD var. (TH06)
Max |Mean| + 2SD var. (TH06)
Max |mean| var. (TH15)
Max SD var. (TH15)
Max |Mean| + 2SD var. (TH15)
3 degree glidepath
6 degree glidepath

Figure 8

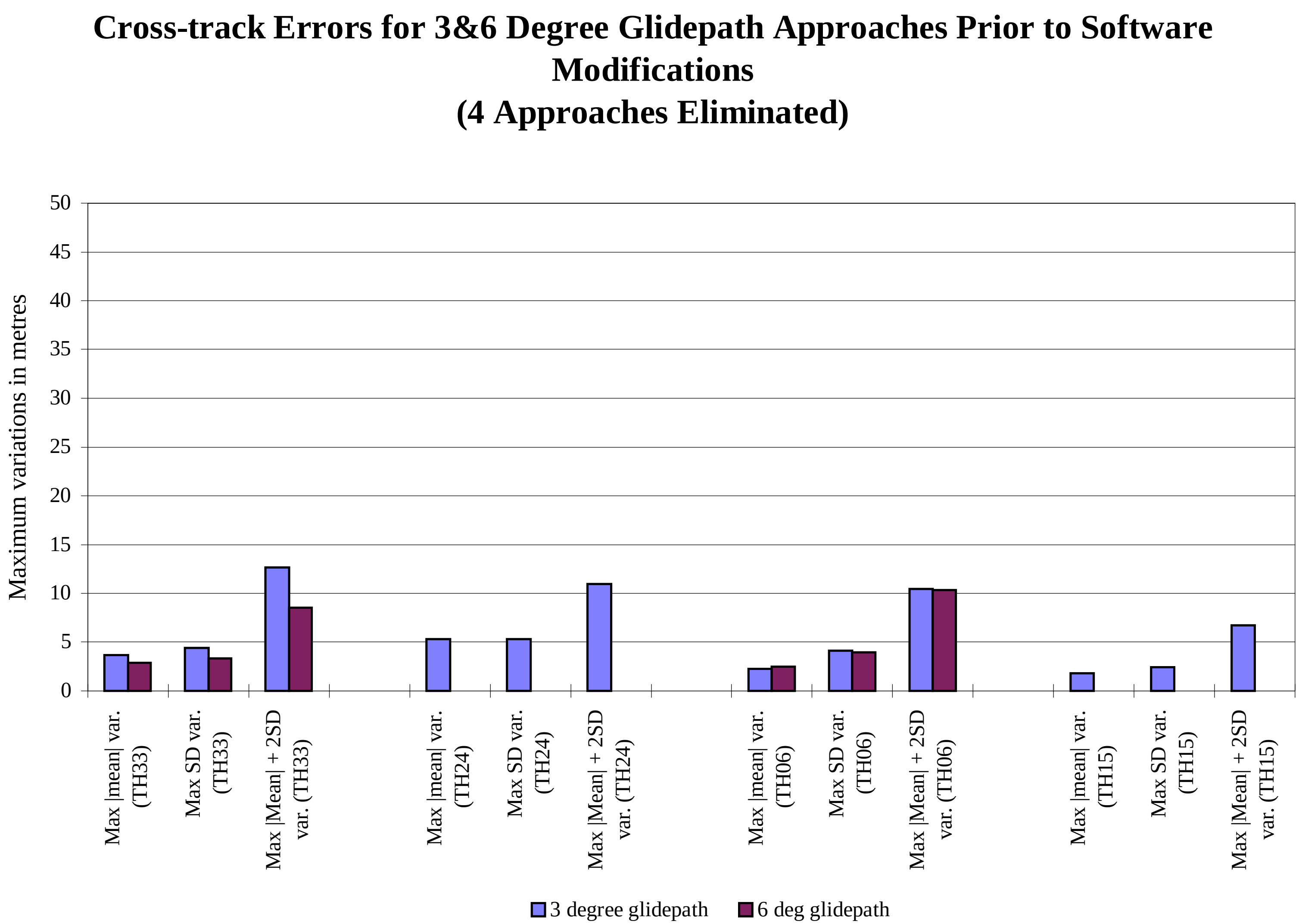

Cross-track Errors for 3&6 Degree Glidepath Approaches Prior to Software Modifications
(4 Approaches Eliminated)
Maximum variations in metres
50
45
40
35
30
25
20
15
10
5
0
Max |mean| var. (TH33)
Max SD var. (TH33)
Max |Mean| + 2SD var. (TH33)
Max |mean| var. (TH24)
Max SD var. (TH24)
Max |Mean| + 2SD var. (TH24)
Max |mean| var. (TH06)
Max SD var. (TH06)
Max |Mean| + 2SD var. (TH06)
Max |mean| var. (TH15)
Max SD var. (TH15)
Max |Mean| + 2SD var. (TH15)
3 degree glidepath
6 deg glidepath

Figure 9

- C.) Investigating categories in 0.1 nm increments from the threshold:
  - 3 & 6 degree glidepath approaches,
  - 200 & 100 ft decision height approaches,
  - 50&70 knot approaches.

Figure 10: example of ***horizontal*** error bars for 3 degree glidepath approaches prior to firmware modifications.

Figure 11: example of ***vertical*** error bars for 3 degree glidepath approaches prior to firmware modifications.

Analysis of results

- A.) Investigating all data without categorizing them

Mean of the cross-track errors	**17** approaches **(23%)** fall into the bin size ranging from **0.0 to 0.5** metres
	42 approaches **(58%)** fall into the bin size ranging from **-0.5 to 1.0** metres
Standard deviation of the cross-track errors	**22** approaches **(30%)** fall into the bin size ranging from **0.5 to 1.0** metres
	35 approaches **(48%)** fall into the bin size ranging from **0.5 to 1.5** metres
Mean of the vertical errors	**11** approaches **(15%)** fall into the bin size ranging from **1.0 to 1.5** metres
	29 approaches **(40%)** fall into the bin size ranging from **0.0 to 1.5** metres
Standard deviation of the vertical errors	**15** approaches **(21%)** fall into the bin size ranging from **1.0 to 1.5** metres
	35 approaches **(48%)** fall into the bin size ranging from **1.0 to 2.5** metres

Cross-track Errors (2 Sigma) for 3 Degree Glidepath Approaches Prior to Receiver Software Modifications (TH06)

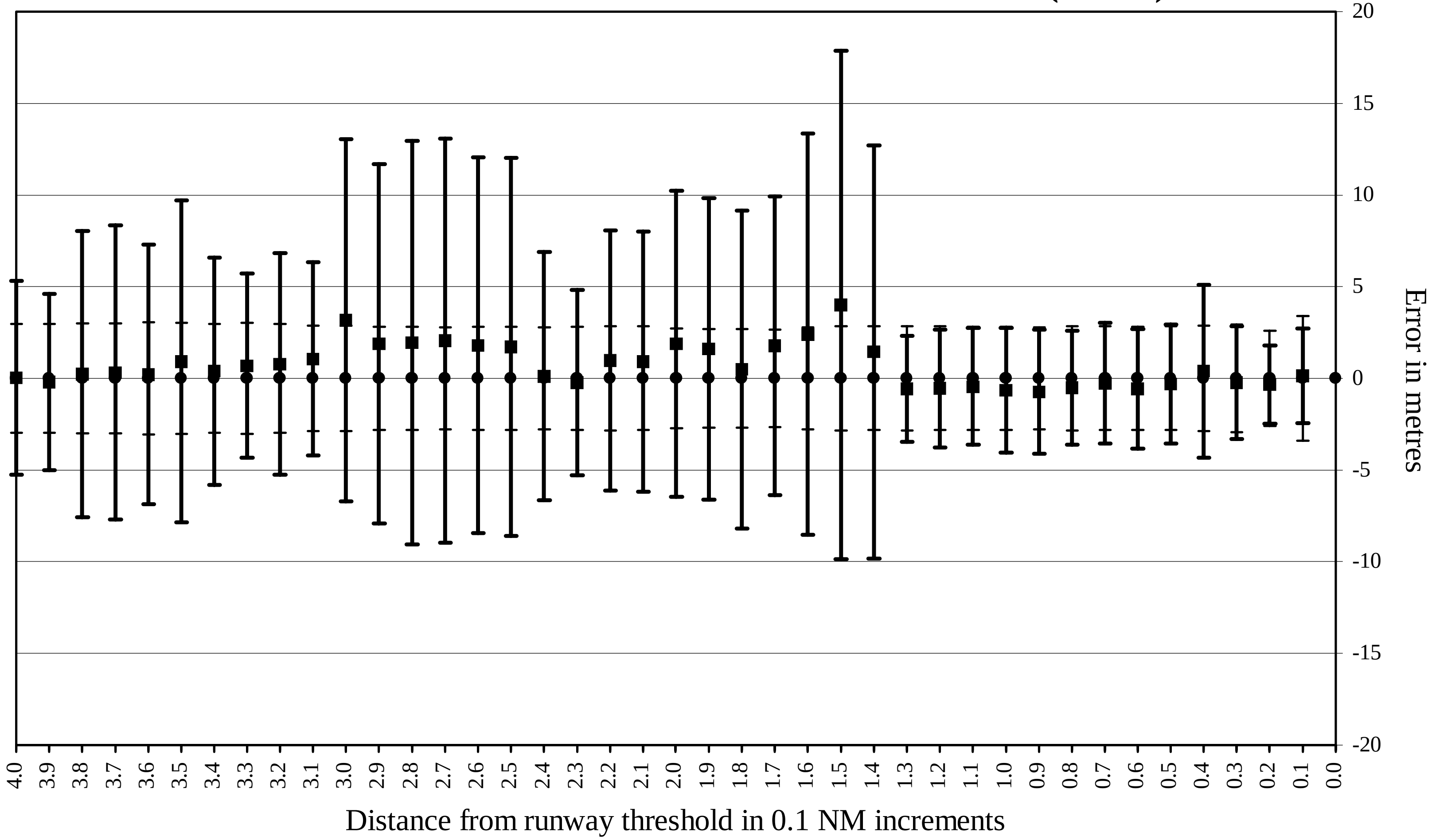


Figure 10

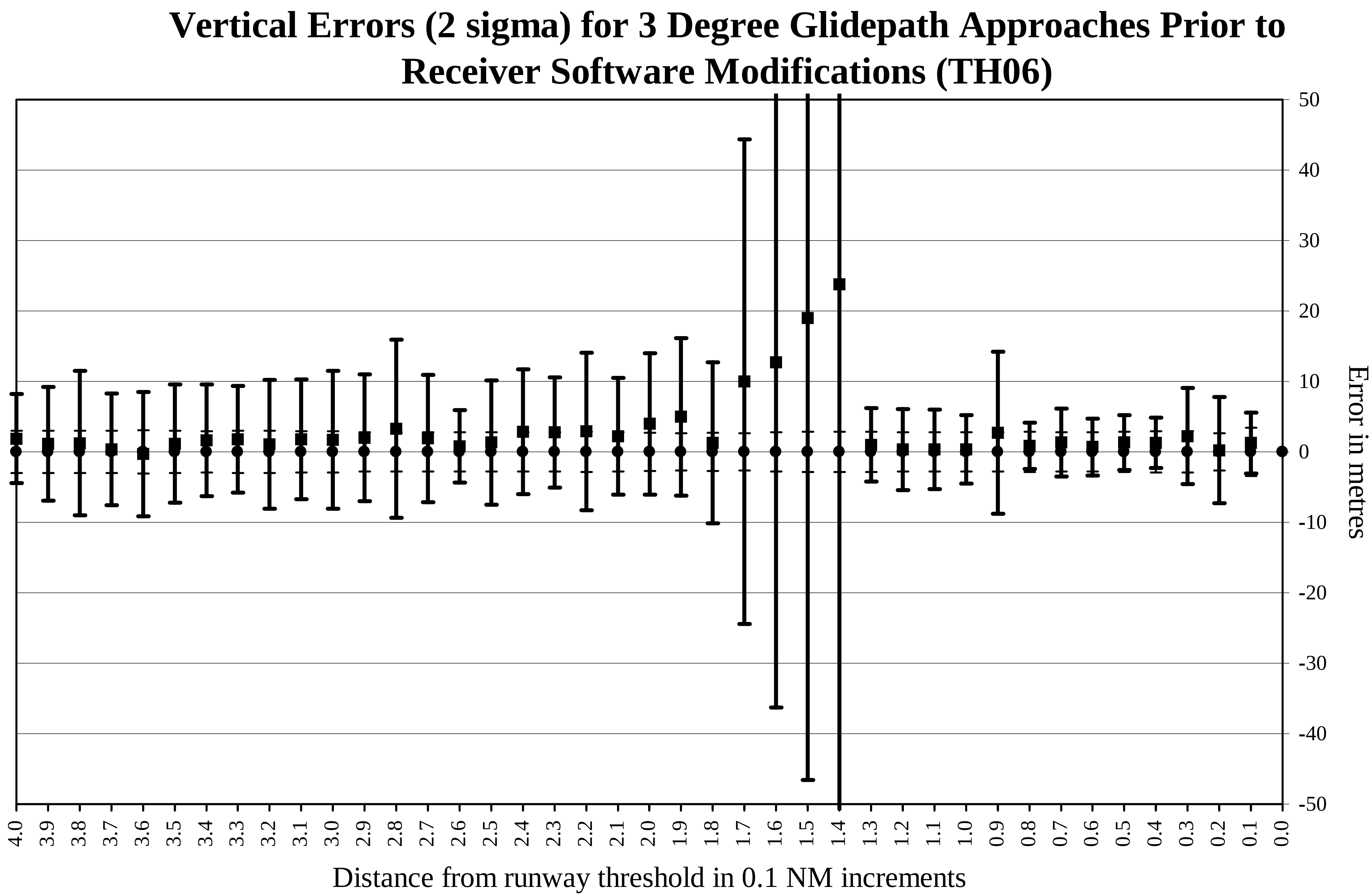

Vertical Errors (2 sigma) for 3 Degree Glidepath Approaches Prior to Receiver Software Modifications (TH06)
50
40
30
20
10
0
-10
-20
-30
-40
-50
Error in metres
4.0
3.9
3.8
3.7
3.6
3.5
3.4
3.3
3.2
3.1
3.0
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Distance from runway threshold in 0.1 NM increments

Figure 11

- B.) Investigating the categories and looking at *maximum mean variation*, *maximum standard deviation variation* and *maximum |mean|+ 2sigma variation* (all data, all data minus 4 approaches).

  Figure 12: shows the three statistics of *horizontal* errors for the four thresholds, 6 categories, prior to and after the firmware modifications.

  Figure 13: shows the three statistics of *vertical errors* for the four thresholds, 6 categories, prior to and after the receiver firmware modifications.

- C.) Investigating the categories in 0.1 nm increments from the threshold (all data minus 4 approaches).

  Figure 14: shows the *horizontal* error statistics to compare the individual categories, thresholds, prior to and after receiver firmware modification.

  Figure 15: shows the *vertical* error statistics to compare the individual categories, thresholds, prior to and after receiver firmware modification.

CROSS-TRACK ERRORS (ALL DATA USED) UNITS IN METRES [MIN,MAX]												
Approaches prior to the receiver software modifications												
Thresholds/ Type of approach	**TH33**			**TH24**			**TH06**			**TH15**		
	Max mean var.	Max s.d. var.	Max |mean| + 2s.d. var.	Max mean var.	Max s.d. var.	Max |mean| + 2s.d. var.	Max mean var.	Max s.d. var.	Max |mean| + 2s.d. var.	Max mean var.	Max s.d. var.	Max |mean| + 2s.d. var.
3 deg glidepath	[-0.32,3.65]	[0.47,4.42]	[1.26,12.49]	[-2.69,0.63]	[0.53,15.08]	[1.27,32.85]	[-2.17,2.23]	[0.62,10.34]	[1.75,20.99]	[0.62,1.83]	[2.21,2.46]	[5.04,6.75]
6 deg glidepath	[-0.02,2.86]	[0.97,3.33]	[2.12,8.50]				[-0.86,2.49]	[0.72,3.97]	[1.7,10.43]			
DH 200	[-0.32,3.65]	[0.47,4.42]	[1.26,12.49]	[-2.69,0.63]	[0.53,15.08]	[1.27,32.85]	[-2.17,2.49]	[0.62,10.34]	[2.44,20.99]	[0.62,1.83]	[2.21,2.46]	[5.04,6.75]
DH 100	[1.32,2.86]	[1.9,3.33]	[5.46,8.5]									
Missed approach: landing	[-0.02,2.86]	[1.67,3.34]	[3.77,8.5]	[0.37]	[1.36]	[3.09]	[-1.20,1.62]	[0.62,0.88]	[2.44,3.88]			
Missed approach: left-right	[0.18,0.76]	[0.83,2.28]	[2.42,5.31]	[-0.35,-0.25]	[1.6,5.31]	[3.45,10.97]	[-1.2]	[1.41]	[4.02]			
Missed approach: straight-180 deg	[1.57,1.73]	[1.48,2.07]	[4.69,5.71]	[-0.03]	[1.02]	[2.07]	[-2.17,2.49]	[0.72,10.34]	[1.7,20.99]	[0.62]	[2.21]	[5.04]
50 knots	[-0.02,2.53]	[0.83,3.33]	[2.42,8.5]				[-1.36,2.49]	[0.72,3.55]	[2.8,9.59]			
60 knots							[-2.17,-0.86]	[0.8,0.88]	[2.46,3.18]			
70 knots	[1.32]	[2.08]	[5.48]				[0.26,2.23]	[1.64,10.34]	[3.54,20.99]			
80 knots	[2.86]	[2.51]	[7.88]				[-1.2]	[0.62]	[2.44]			
90 knots				[-0.88]	[0.55]	[1.98]						
120 knots	[1.73]	[1.48]	[4.69]									
Approaches after the receiver software modifications												
Thresholds/ Type of approach	**TH33**			**TH24**			**TH06**			**TH15**		
	Max mean var.	Max s.d. var.	Max |mean| + 2s.d. var.	Max mean var.	Max s.d. var.	Max |mean| + 2s.d. var.	Max mean var.	Max s.d. var.	Max |mean| + 2s.d. var.	Max mean var.	Max s.d. var.	Max |mean| + 2s.d. var.
3 deg glidepath	[0.15,1.9]	[0.66,2.42]	[1.47,6.74]	[-0.15,1.32]	[2.23,6.3]	[4.61,13.92]	[-0.39,1.62]	[0.76,15.81]	[3.07,35.61]	[-0.03,2.91]	[1.29,7.56]	[2.61,18.03]
6 deg glidepath	[-0.59,0.66]	[0.58,0.86]	[1.21,2.38]				[-0.19,5.40]	[0.80,5.95]	[2.04,17.3]			
DH 200	[-0.15,0.66]	[0.66,0.86]	[1.47,2.38]				[-0.19,5.4]	[0.91,5.95]	[2.95,17.3]			
DH 100	[-0.59,1.9]	[0.58,2.42]	[1.21,4.9]				[-3.99,0.95]	[0.76,15.81]	[2.36,35.61]			
Missed approach: landing	[-0.05,0.66]	[0.58,0.86]	[1.75,2.38]	[0.19]	[5.16]	[10.51]	[-3.99,0.78]	[0.76,15.81]	[2.39,35.61]			
Missed approach: left-right							[0.40]	[0.98]	[2.36]	[-0.19,-0.03]	[1.29,2.05]	[2.61,4.29]
Missed approach: straight&180 deg	[-0.59,1.9]	[0.66,2.42]	[1.91,4.9]	[-0.15,-0.03]	[2.23,6.3]	[4.61,13.92]	[0.17,1.62]	[0.8,1.78]	[2.04,4.02]			
50 knots	[-0.15]	[0.66]	[1.47]				[0.17,1.49]	[0.8,2.32]	[2.04,4.83]			
60 knots	[-0.59,-0.05]	[0.58,0.80]	[1.21,2.19]				[0.77,0.78]	[1.09,1.88]	[2.95,4.54]			
70 knots	[0.06,1.09	[0.77,2.42]	[3.44,4.9]	[-0.15,0.19]	[2.23,5.16]	[4.61,10.51]	[[0.07,5.4]	[0.91,5.95]	[2.95,17.3]	[-0.19,2.91]	[1.29,7.56]	[2.61,18.03]
80 knots				[1.32]	[6.3]	[13.92]	[-3.99,0.75]	[1.09,15.81]	[3.25,35.61]			
90 knots							[-1.55]	[0.76]	[3.07]			
DH 50				[0.19,1.32]	[5.16,6.3]	[10.51,13.92]				[-0.19,2.91]	[1.29,7.56]	[2.61,18.03]
DH 150							[1.49]	[0.9]	[3.29]			
65 knots	[0.66]	[0.86]	[2.38]									

Figure 12 .Statistics for cross-track errors of all categories (all data used)

VERTICAL ERRORS (ALL DATA USED) UNITS IN METRES [MIN, MAX]												
Approaches prior to the receiver software modifications												
Thresholds/ Type of approach	**TH33**			**TH24**			**TH06**			**TH15**		
	Max mean var.	Max s.d. var.	Max |mean| + 2s.d. var.	Max mean var.	Max s.d. var.	Max |mean| + 2s.d. var.	Max mean var.	Max s.d. var.	Max |mean| + 2s.d. var.	Max mean var.	Max s.d. var.	Max |mean| + 2s.d. var.
3 deg glidepath	[-6.64,2.87]	[1.02,18.8]	[2.55,38.74]	[-0.39,29.86]	[1.11,106.67]	[2.61,243.2]	[-2.93,3.12]	[0.83,18.09]	[4.27,38.22]	[0.98,2.82]	[2.70,2.83]	[6.38,8.48]
6 deg glidepath	[-2.72,5.01]	[1.56,13.84]	[4.34,30.4]				[0.56,7.73]	[1.71,16.03]	[4.12,39.79]			
DH 200	[-6.64,2.87]	[1.02,18.8]	[2.55,38.74]	[-0.94,29.86]	[1.11,106.67]	[2.61,243.2]	[-2.93,7.73]	[0.83,18.09]	[4.27,38.22]	[0.98,2.82]	[2.7,2.83]	[6.38,8.48]
DH 100	[-2.72,5.01]	[4.21,13.84]	[8.6,30.4]									
Missed approach: landing	[-2.72,5.01]	[1.82,18.27]	[4.93,37.92]	[0.94]	[6.48]	[13.9]	[0.56,2.61]	[0.83,1.78]	[4.12,4.27]			
Missed approach: left-right	[-6.64,-1.22]	[1.31,8.88]	[4.39,24.4]	[1.14,3.26]	[1.59,3.23]	[6.44,7.6]	[1.05]	[2.54]	[6.13]			
Missed approach: straight-180 deg	[-4.34,0.18]	[3.5,4.21]	[8.6,11.34]	[1.23]	[1.31]	[3.85]	[0.33,4.29]	[2.06,18.09]	[4.45,38.22]	[2.82]	[2.83]	[8.48]
50 knots	[-2.72,0.18]	[1.38,18.27]	[4.39,37.92]				[0.33,7.73]	[1.78,16.03]	[4.12,39.79]			
60 knots							[2.67,3.07]	[1.71,2.23]	[6.49,7.13]			
70 knots	[0.87]	[8.08]	[17.03]				[2.04,4.29]	[3.43,18.09]	[9.98,38.22]			
80 knots	[5.01]	[10.01]	[25.03]				[2.61]	[0.83]	[4.27]			
90 knots				[0.12]	[1.43]	[2.98]						
120 knots	[-4.34]	[3.5]	[11.34]									
Approaches after the receiver software modifications												
Thresholds/ Type of approach	**TH33**			**TH24**			**TH06**			**TH15**		
	Max mean var.	Max s.d. var.	Max |mean| + 2s.d. var.	Max mean var.	Max s.d. var.	Max |mean| + 2s.d. var.	Max mean var.	Max s.d. var.	Max |mean| + 2s.d. var.	Max mean var.	Max s.d. var.	Max |mean| + 2s.d. var.
3 deg glidepath	[0.17,0.37]	[1.14,2.48]	[2.55,5.33]	[-0.24,1.43]	[1.77,7.12]	[4.76,8.64]	[-4.56,3.83]	[0.92,11.11]	[2.72,26.78]	[0.75,16.13]	[1.1,29.62]	[2.95,75.37]
6 deg glidepath	[-1.44,1.9]	[1.16,2.1]	[3.07,5.64]				[-2.03,2.79]	[1.15,43.5]	[3.48,89.79]			
DH 200	[-1.44,0.17]	[1.45,2.1]	[3.07,4.37]				[-4.56,2.75]	[1.06,11.11]	[2.46,26.78]			
DH 100	[-0.25,1.9]	[1.14,2.48]	[2.55,5.33]				[-1.91,3.83]	[0.92,43.5]	[2.72,89.79]			
Missed approach: landing	[-1.44,1.9]	[1.16,2.1]	[4.22,5.64]	[1.43]	[7.12]	[15.67]	[-4.5,3.83]	[0.92,43.5]	[2.72,89.79]			
Missed approach: left-right							[1.27]	[2.09]	[5.45]	[0.29,0.75]	[1.1,3.29]	[2.95,6.87]
Missed approach: straight&180 deg	[-0.25,0.27]	[1.14,2.48]	[2.55,5.33]	[-0.24,1.22]	[1.77,4.2]	[4.76,8.64]	[-2.03,1.74]	[1.38,6.61]	[2.46,13.26]			
50 knots	[0.17]	[1.45]	[3.07]				[-1.09,1.72]	[1.15,3.8]	[4.02,8.33]			
60 knots	[-0.25,1.9]	[1.16,1.41]	[3.07,4.22]				[-4.56,0.04]	[6.61,11.11]	[13.26,26.78]			
70 knots	[0.27,0.37]	[1.14,2.48]	[2.55,5.33]	[1.22,1.43]	[1.77,7.12]	[4.76,15.67]	[-2.03,2.79]	[1.29,43.5]	[4.49,89.79]	[0.29,16.13]	[1.1,29.62]	[2.95,75.37]
80 knots				[-0.24]	[4.2]	[8.64]	[-0.34,3.83]	[1.06,1.55]	[2.46,6.93]			
90 knots							[0.88]	[0.92]	[2.72]			
DH 50				[-0.24,1.43]	[4.2,7.12]	[8.64,15.67]				[0.29,16.13]	[1.1,29.62]	[2.95,75.37]
DH 150							[-.72]	[1.38]	[3.48]			
65 knots	[-1.44]	[2.1]	[5.64]									

Figure 13. Statistics for vertical errors of all categories (all data used)

CROSS-TRACK ERROR STATISTICS IN METRES

Approaches prior to the receiver software modifications

Thresholds/ Type of approach	**TH33**				**TH24**				**TH06**				**TH15**				**All Thresholds**			
	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches
3 deg glidepath	1.38	4.17	14.22	10	-0.19	3.43	10.88	10	0.69	6.59	13.86	8	0.54	3.68	7.41	2	0.61	4.47	14.22	30
6 deg glidepath	2.06	3.38	15.67	7					0.92	4.68	18.76	6					1.49	4.03	18.76	13
DH 200	1.27	4.25	15.19	11	-0.14	3.60	12.30	9	0.62	6.29	12.86	15	0.54	3.68	7.41	2	0.57	4.45	15.19	37
DH 100	2.32	3.49	16.45	6													2.32	3.49	16.45	6
50 knots	1.45	2.66	15.87	8					1.57	4.30	18.76	4					1.51	3.48	18.76	12
70 knots	1.80			1					1.89	5.38	18.07	3					1.84	5.38	18.07	4

Approaches after the receiver software modifications

Thresholds/ Type of approach	**TH33**				**TH24**				**TH06**				**TH15**				**All Thresholds**			
	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches
3 deg glidepath	0.38	2.50	15.20	3	-1.45	6.86	24.50	3	0.66	4.00	11.08	6	-0.05	1.81	6.26	3	**-0.11**	3.79	24.50	15
6 deg glidepath	0.14	1.76	5.35	3					0.65	2.04	3.57	11					0.40	**1.90**	**5.35**	14
DH 200	0.22	1.75	4.08	2					1.00	3.00	8.83	8					0.61	**2.38**	**8.83**	10
DH 100	0.22	2.34	14.23	4					0.17	2.45	3.35	8					**0.20**	2.40	14.23	12
50 knots	-0.37			1					0.52	2.10	3.76	6					**0.08**	**2.10**	**3.76**	7
70 knots	1.36	2.80	4.47	2					1.05	3.08	10.34	6	-0.05	1.81	6.26	3	0.79	2.56	10.34	11

Figure 14. Statistics for cross-track errors of 6 categories using readings sampled at 0.1 NM increments

VERTICAL ERROR STATISTICS IN METRES																				
Approaches prior to the receiver software modifications																				
Thresholds/ Type of approach	**TH33**				**TH24**				**TH06**				**TH15**				**All Thresholds**			
	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches
3 deg glidepath	-0.65	13.58	74.16	10	1.11	5.24	27.68	10	3.08	13.07	96.67	8	2.28	3.91	14.11	2	1.46	8.95	96.67	30
6 deg glidepath	0.77	12.73	66.50	7					2.87	10.41	36.66	6					1.82	11.57	66.50	13
DH 200	-0.64	13.79	70.84	11	1.16	5.45	3.91	9	2.32	11.83	66.86	15	2.28	3.91	14.11	2	1.28	8.75	70.84	37
DH 100	0.82	13.97	73.29	6													0.82	13.97	73.29	6
50 knots	-1.13	8.23	87.22	8					0.40	4.02	16.72	4					-0.37	6.13	87.22	12
70 knots	2.25			1					7.98	16.79	113.60	3					5.12	16.79	113.60	4
Approaches after the receiver software modifications																				
Thresholds/ Type of approach	**TH33**				**TH24**				**TH06**				**TH15**				**All Thresholds**			
	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches	Average mean	Average 2 s.d.	Max 2 s.d.	Number of approaches
3 deg glidepath	0.39	3.32	15.91	3	0.73	8.51	33.37	3	-0.56	8.16	49.62	6	0.00	2.36	8.18	3	**0.14**	5.59	49.62	15
6 deg glidepath	-0.67	3.95	10.19	3					0.00	5.85	17.27	11					-0.34	**4.90**	**17.27**	14
DH 200	-0.66	4.37	9.64	2					-0.86	9.83	41.78	8					-0.76	7.10	41.78	10
DH 100	0.28	3.12	14.01	4					0.62	3.88	6.66	8					**0.45**	**3.50**	**14.01**	12
50 knots	0.63			1					0.97	3.84	9.32	6					0.80	3.84	**9.32**	7
70 knots	0.21	1.88	5.56	2					-0.39	5.49	12.99	6	0.00	2.36	8.18	3	**-0.06**	**3.24**	12.99	11

Figure 15. Statistics for vertical errors of 6 categories using readings sampled at 0.1 NM increments

- **Conclusions**

  - Four approaches eliminated (1 for lost VHF link, 3 for inadequate quality of Ashtech "ground truth" data).
  - Worse case scenario: in the case of *horizontal* errors the *maximum |mean|+2sigma* = 18.0 metres due to jumps in the Trimble positions. Fig.12
  - Worse case scenario: in the case of *vertical* errors the *maximum |mean|+ 2sigma* = 89.8 metres due to jumps in the Trimble positions. Fig 13
  - There is a marginal improvement in the Trimble positions after the receiver firmware modifications took place (Fig 14 & 15).
  - In the case of *horizontal errors* (Fig 14):
    - 6 degree glidepath app. proved to have performed better than the 3deg,
    - 200 ft decision height app. proved to have performed better than the 100 ft,
    - 50 knot app. proved to have performed better than the 70 knot.
  - In the case of *vertical errors* (Fig 15):
    - comparing 3 and 6 degree app. is inconclusive,
    - 100 ft decision height app. proved to have performed better than the 100 ft,
    - 50 knot app. proved to have performed better than the 70.

- The number of approaches *vary* from category to category. Also, investigation C.) only takes sample every 0.1 nm so it does not contain all data pertaining to a particular approach. Therefore, jumps in positions provided by Trimble are only reflected in investigation A.) and B.) not in C.).
- The accuracy requirements for CAT 1 precision approaches are:
  - in horizontal sense 17.0 m at 2 sigma level,
  - in vertical sense 7.4 m at 2 sigma level.
- The LDGPS system provided this accuracy for 68 approaches (93%) in horizontal sense but failed to fulfill the vertical requirements for 34 approaches (47%). Why?
  - jumps in Trimble solution,
  - required vertical accuracy is inherently higher than the horizontal.

◆ **Recommendations:**

- More accurate "ground truth" system is required such as by using Ashtech Z-12s.
- More repeated approaches of the same kind and careful design of approaches are needed.