STATISTICAL ERROR ANALYSIS
OF
DRAPE ALTITUDE AND RAGE TERRAIN DATABASE

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OUTLINE

LIST OF FIGURES

1. INTRODUCTION

1.1 Background

On March 2003 the UNITECH team was tasked to develop a terrain following algorithm for subscale and full-scale targets. The task was named DRAPE for Derived Radar Altitude Penetration Enhancement. A prime objective of this task is the elimination of the dependence upon an active emitter radar altimeter to reliably conduct low-level operations over diverse terrain. This effort demonstrates that current terrain databases, interfaced with precision threat management architecture, can facilitate “silent” low-level threat presentations.

The UNITECH team is presently using the WSMR Drone Formation Control System (DFCS) and the subscale MQM-107D and full scale QF-4 target to test the DRAPE system. The DRAPE system will eventually reside on a separate DRAPE processor that can be easily interfaced to other target control systems.

The DFCS is a mature control system located in Bldg. 335 at White Sands Missile Range (WSMR) New Mexico. Its mission is to control single and/or multiple unmanned full scale and sub-scale targets for the Army. These targets are used by the Army to test and evaluate new weapons systems. The DFCS can automatically control the QF-4 full-scale target, the MQM-107D sub-scale, and a wide variety of ground targets such as the M60 and T-72 tanks and the M-812 five-ton truck. The DFCS system consists of a DME type data link, 8 drone control consoles, two central RISC type computer control subsystems (CCS), an onboard data link transponder and control subsystem, two co-located interrogator subsystems (ISC) and up to 10 ground interrogator stations (IS) located at strategic mountain peak locations to cover most of White Sands Missile Range airspace.

The UNITECH Team subdivided this effort into 5 major tasks as outlined below:

- Evaluate DFCS Target Position Accuracy
- Evaluate DFCS RAGE terrain database
- Develop Terrain Following Algorithm
- Simulation and Flight Testing
- Documentation

1.2 Scope

This document describes the methodology used to evaluate the target tracking accuracy of the Drone Formation Control System (DFCS) and the accuracy of the RAGE terrain database. This report also provides valuable analysis results comparing the tracking accuracy of DFCS with other tracking systems including GPS and RADAR.

2. APPLICABLE DOCUMENTATION

2.1 WAO-10 DRAPE Requirements, 6 March 2003, WSMR NRO-CR
2.2 WAO-10 Response, 11 March 2003, UNITECH
2.3 DRAPE Analysis Software Requirements, 14 April 2003, UNITECH

3. CONCLUSIONS AND ACTION ITEMS

3.1 Conclusions

- The test data shows that the altitude estimated by DFCS when the barometric altimeter is properly calibrated using DME or the radar altimeter is accurate enough (< 60 feet RMS) to safely support low altitude DRAPE Missions (> 250 feet AGL) over flat terrain.

- The test data indicates that the accuracy of a calibrated QF-4 barometric altimeter is not affected when the target executes moderate climbs and dives at a maximum rate of 100 fps.

- The test data also shows that the target altitude estimated by the GPS system is more accurate than the target altitude estimated by DFCS.

- The DFCS tracking accuracy is in the order of 70 feet RMS in the x-y plane during flight.

- The RAGE DTED level 1 terrain is accurate enough to safely support low altitude drape missions over flat terrain and medium altitude DRAPE missions (>500 feet AGL) over rough terrain. The test data does not show the presence of any altitude bias in the RAGE terrain elevation data. The test data indicates that the registry of the RAGE terrain database is accurate enough to support low altitude DRAPE missions.

- The test data indicates that the present DFCS algorithm used to calibrate barometric altimeter with the radar altimeter and the RAGE terrain database is working as expected.

3.2 Action Items

- Modify the DFCS software to log RAGE terrain elevation data underneath the target all the time.

- Modify the DFCS software to automatically calibrate the barometric altimeter using radar telemetry and RAGE terrain elevation data when the master controller activates the BARO CALIBRATION console button. The DFCS software will automatically use the radar to calibrate the barometric altimeter if the target is at least 2 miles away from the Interrogator Station pre-selected for barometric calibration. The software will automatically turn on and off RADAR navigation mode (DO ON/OFF 1 RADAR). If the target is within 2 miles, in the x-y plane, from the pre-selected interrogator station, the barometer will be calibrated using DME data from the Interrogator Station

- Evaluate the performance of the MQM-107D barometric altimeter during rapid climbs and dives.

- Test RAGE DTED Level 2 data with two QF-4 targets flying at different altitudes over two different flight patterns. The QF-4 targets will be instrumented with GPS Pods.

4. ANALYSIS METHODOLOGY

UNITECH developed the necessary software required to collect and analyze the data needed to evaluate the tracking accuracy of the DFCS system under different operational and flight conditions and the accuracy of the terrain elevation database as specified in Reference 2.3. Subsections 4.1 and 4.2 describe the methodology used to conduct this analysis.

4.1 Evaluation of DFCS Tracking Accuracy

On 23 April 2003 DFCS conducted a QF-4 mission dedicated to evaluate the tracking accuracy of the DFCS system. The QF-4 target was populated with two 5-satellite ASTEK GPS/IMU pods. The QF-4 target was tracked by a WSMR

MOTR radar throughout the flight. Data from a WSMR Kineto Tracking Mount (KTM) System was also collected for a short period.

The barometric altimeter of the QF-4 target was calibrated by over flying at 15,000 feet MSL a QF-4 target over a DFCS DME Interrogator Station. The QF-4 target was flown at different attitudes, altitudes and airspeeds.

The WSMR Real Time Data Processing (RTDPS) collected the GPS and Radar telemetry and send the information to DFCS in real time by Ethernet. The optics data was provided to DFCS on a CD ROM after the mission. During the mission, DFCS displayed and recorded the GPS and radar telemetry information provided by RTDPS.

DFCS used the MATLAB/SIMULINK program to compare the target position (x, y and MSL altitude) estimated by DFCS to the target position estimated by the GPS, RADAR, and OPTICS systems. Error statistical parameters such as Mean, Standard Deviation and Root-Mean Square were also calculated. It should be noted that the best we could do was to assess the target positional accuracy of the DFCS system relative to the position accuracy of the other systems.

Because of the different coordinate systems used by DFCS, GPS, RADAR and OPTICS, a considerable amount of analysis was made to insure that computational errors were not introduced during the coordinate conversion processes. Special attention was dedicated when the altitude estimated by DFCS was compared to the altitude predicted by the GPS system because of the fact that GPS uses a WGS-84 GEOID model and DFCS utilizes a fix radius of the earth model to compute the target altitude above mean sea level. The data provided by OPTICS deviated from other sources. The cause of this excursion continues to be investigated.

Subsection 5.1 summarizes the tracking analysis results obtained during the test mission conducted on 23 April 2003

4.2 Evaluation of RAGE Terrain Elevation Accuracy

On 24 June 2003, DFCS conducted a QF-4 mission dedicated to evaluate the accuracy of the DFCS RAGE terrain database. The QF-4 target was populated with two 5-satellite ASTEK GPS/IMU pods. The target was flown at 15,000 feet MSL over two distinct flight patterns.

The barometric altimeter of the QF-4 target was calibrated by over flying at 15,000 feet MSL a DFCS DME Interrogator Station. The QF-4 target was flown at different attitudes, altitudes and airspeeds.

The AGL altitude of the target was derived by subtracting the altitude of the terrain underneath the target from the target MSL altitude estimated by DFCS and GPS. This AGL altitude was then compared to the radar telemetry down linked by the QF-4 target. The difference between these two measurements indicates a possible error in the terrain elevation database.

The terrain elevation underneath the target was calculated by subtracting radar down linked telemetry from the MSL altitude estimated by the DFCS and GPS systems.

Additional terrain altitude accuracy missions were flown on October 9 and 18 of 2003 with the QF-4 and MQM-107D targets, respectively. For these missions, the barometric altimeter was calibrated using the radar altimeter and the RAGE terrain elevation data.

Subsection 5.2 describe in detail the data analysis conducted to evaluate the altitude accuracy of the RAGE terrain database.

5. DETAILED ANALYSIS

5.1 DFCS Tracking Accuracy

5.1.1 DME Barometric Calibration

For the first test, DFCS calibrated the barometric altimeter by over flying an interrogator station at 15000 feet MSL. DFCS has the capability to calibrate the Barometric Altimeter when the target is flown over a data link Interrogator Station (IS). The principle is very simple. The barometric altimeter is calibrated using the position of the interrogator station and the time the speed of light takes to travel from the target to the IS and from the IS back to the target. Figure 5-1 shows a time plot of the estimated target altitudes by GPS (black), Radar (red) and DFCS (blue) systems. The plot clearly shows, with vertical line, the time when the barometric altimeter is calibrated. It should be noted that the error between DFCS and the GPS estimated altitudes is virtually reduced to zero feet after the barometric altimeter is calibrated. The error becomes larger after the target flies away from the Interrogator Station. The HDOP increases as the distance between the target and the interrogator station increases.

The DFCS barometric calibration logic assumes that the BARO error changes linearly with target altitude. Equation 1 shows that DFCS computes two parameters to calibrate the barometric altimeter. The parameter M represents the slope of the line and the parameter B the altitude at which the line intercepts the z-axis.

$$HM = HBIASM * H + HBIASB \quad \textbf{(Equation 1)}$$

Where:

HM	-	Calibrated barometric altimeter
H	-	Altitude of the target estimated by the DFCS navigation Filter using HM, Radar (if enabled), and DME data.

The DFCS navigation filter uses DME, radar and calibrated barometric data to estimate the target altitude. The terrain database was not available for this test; therefore, the radar altimeter could not be used to enhance the target altitude estimation of the DFCS navigation filter. Figure 5-1 also shows the mean and standard deviation errors between GPS and DFCS before and after the calibration of the barometric altimeter. The mean error was reduced from 78 feet to 22 feet after barometric altimeter calibration. As expected the STD error did not change that much since the target flight conditions did not vary.

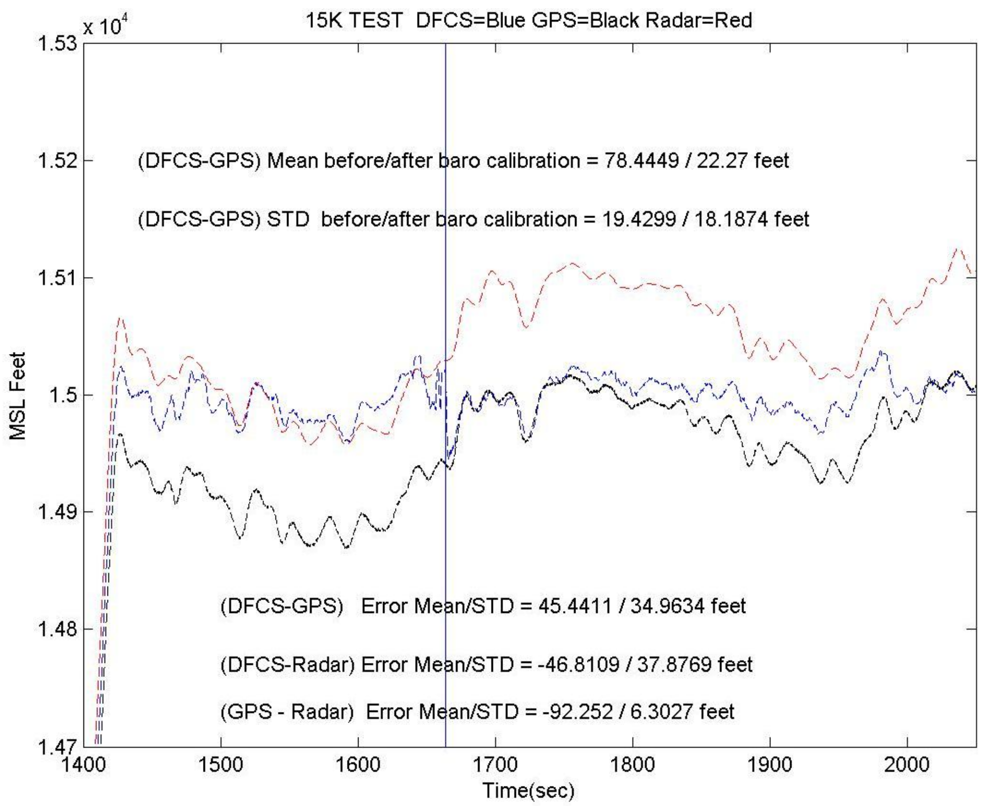

Figure 5- 1 Barometric Calibration

5.1.2 DFCS Altitude Accuracy

The target was flown at 3 different altitudes. The purpose of this test was to assess how accurate is the DFCS barometric calibration logic in predicting what the barometric altimeter error will be at different altitudes. Figure 5-2 shows time plots of the target altitude estimated by the DFCS (blue), GPS (black) and RADAR (red) systems. Data was collected at 9000 feet, 12000 feet, 15000 feet MSL for a period of 40 minutes (x-axis). The overall RMS error between DFCS and GPS was 42 feet. The blue vertical lines indicate that the barometric altimeter was calibrated twice, the first time at 12000 feet MSL and the second time at 15000 feet MSL. Figure 5-2 also shows that the barometric altimeter accuracy was not degraded when the target dived from 15K feet MSL to 9K feet MSL and when it climbed from 9K-12K-15K feet MSL at 100 fps. The plot also shows that the RADAR system tracked the target at a slightly higher altitude than GPS and DFCS did. The overall RMS error between DFCS and the RADAR altitudes was 73 feet. It should be noted again however that the DFCS and GPS agreement was maintained.

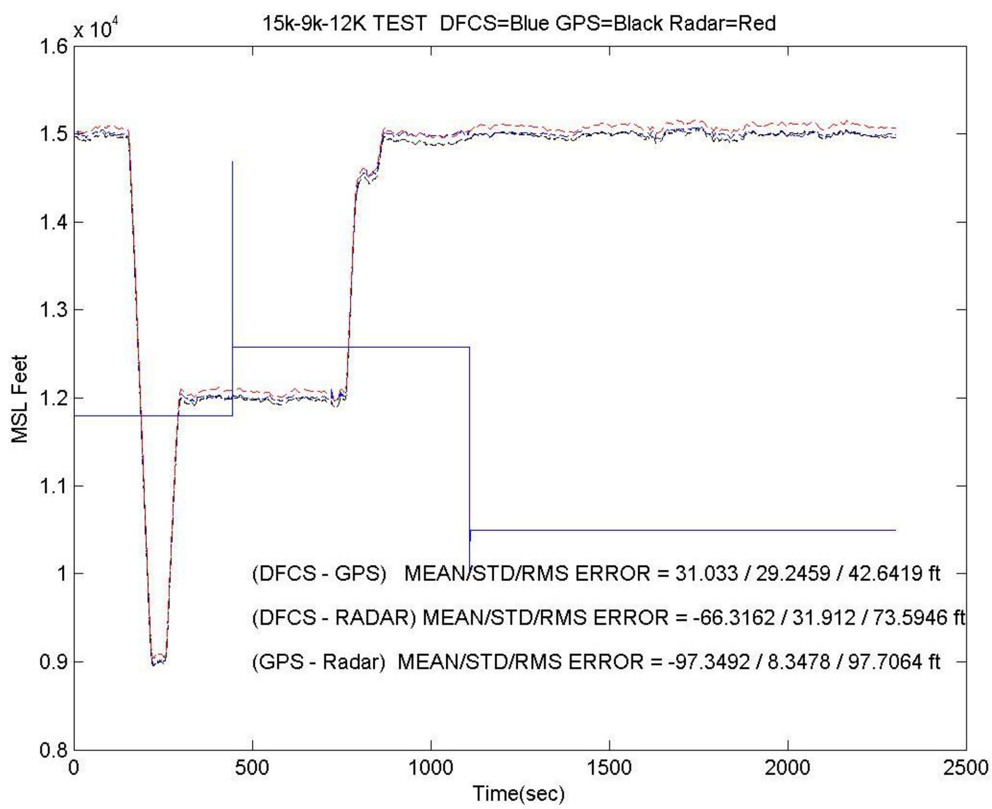

Figure 5- 2 DFCS Altitude Accuracy

5.1.3 DFCS X, Y Accuracy

Because the DRAPE algorithm needs to determine what is the altitude of the terrain underneath and in front the target, it is imperative that DFCS can track the position of the target accurately. DFCS uses a flat plane East-North Cartesian Coordinate system to track the target. DFCS assumes that the earth is a perfect sphere to estimate the target altitude above MSL. Figure 5-3, subplots 1 and 2 show the errors in the X (East) and Y (North) axes between DFCS and GPS. Subplot 3 is a time plot of the normal acceleration of the target in number of GS. Figure 5-3 shows that large DX, DY errors were detected during high bank angle turns (GS >> 1.0). The overall RMS error in the X-axis was 51 feet and 75 feet in the Y-axis. It should be noted that the flight pattern was an oval shape pattern that extended mostly from North to South. Therefore, most of the time the target was either traveling straight north or south. That is, the target velocity was approximately the derivative of the target position on the Y-axis (YDOT). Any timing error between the GPS and DFCS data would introduce an error in the Y-axis direction. That would explain why the overall RMS error in the Y-axis is larger than in the X-axis.

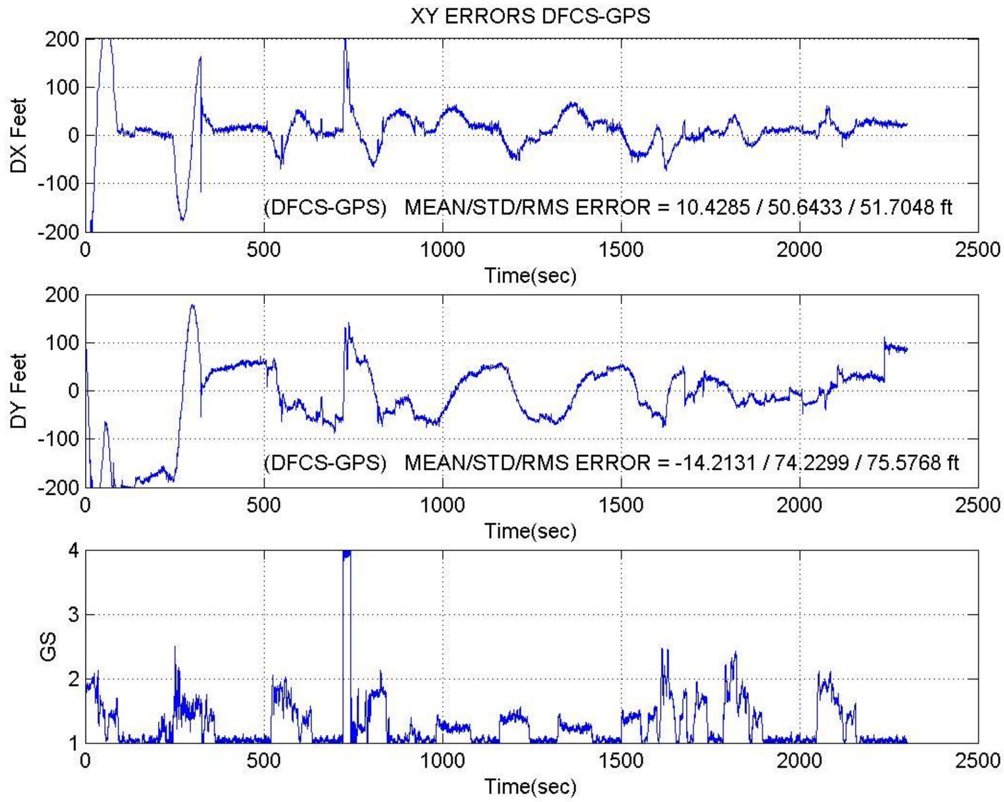

Figure 5- 3 DFCS-GPS Accuracy in the X-Y Plane

Figure 5-4, subplots 1 and 2 show the errors in the X (East) and Y (North) axes between DFCS and RADAR. Subplot 3, in Figure 5-4, is a time plot of the normal acceleration of the target (GS). Figure 5-3 shows that large DX, DY errors were detected during high bank angle turns (GS >> 1.0). The overall RMS error in the X-axis was 54 feet and 69 feet in the Y-axis.

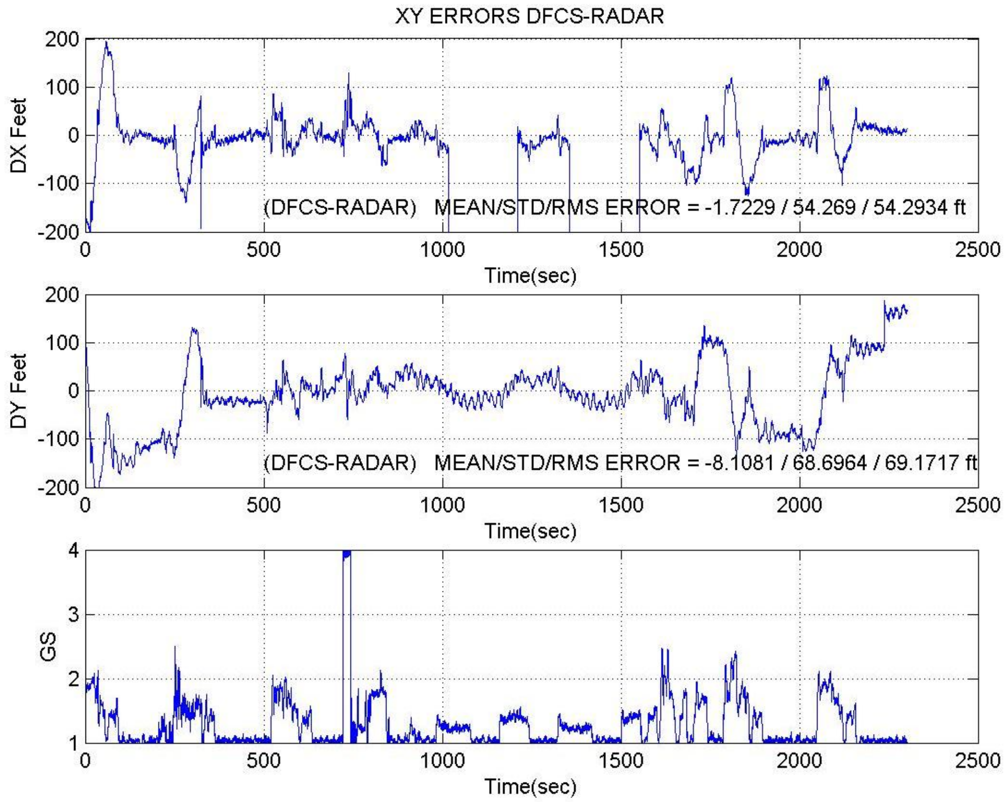

Figure 5- 4 DFCS-RADAR Accuracy in the X-Y Plane

5.2 RAGE Terrain Database Accuracy

<u>5.2.1 DFCS Barometric Calibration using Radar Altimeter</u>

On October 18, 2003 an MQM-107D target was flown for the first time in DRAPE altitude control mode. Before engaging DRAPE, the barometric altimeter was calibrated at 6300 ft MSL by entering the keyboard command DO ON 1 RADAR and pushing the barometric calibration button on the MCC console. Figure 5-5 shows a time-plot of the target estimated MSL altitude, computed by adding terrain elevation underneath the target, radar down linked telemetry, and calibrated barometric altitude data. Also depicted is the trace of DSTAB 19. This DSTAB is set to 1 when DO ON 1 RADAR is active. When DSTAB 19 is set to 1, DFCS starts using radar altimeter, terrain elevation data, barometric altitude and DME data to estimate the MSL altitude of the target (H). Also indicated with a black line is the bias added to the barometric altimeter data as part of calibration logic. Notice a minor navigation altitude excursion during the barometric calibration process. It should be noted that unless the altitude provided by the barometric altimeter is considerably off (error > 1000 feet), DFCS navigation altitude (H) would follow the altitude measured by the barometric altimeter.

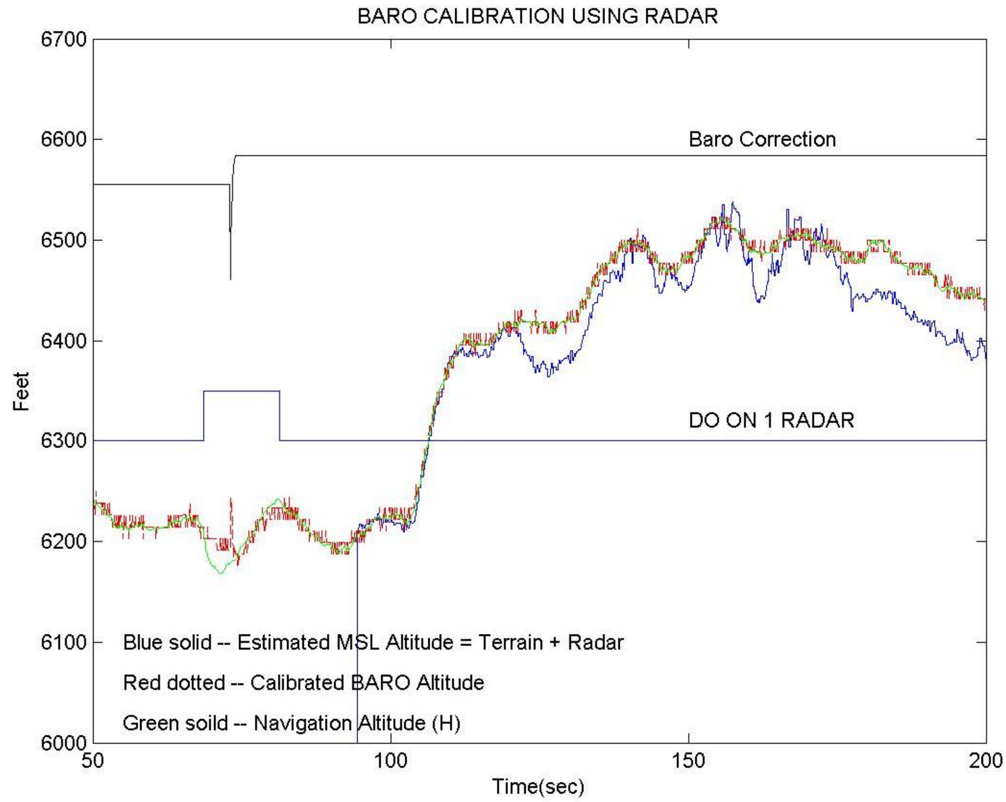

Figure 5- 5 DFCS Barometric Calibration using Radar and Terrain Elevation

5.2.2 Terrain Elevation Accuracy

5.2.2.1 QF4 Mission 24 June 2003

As indicated in Subsection 4, on 24 June 2003 DFCS conducted a dual QF-4 mission dedicated to evaluate the accuracy of the DFCS terrain database. The

QF-4 targets were populated with 5-satellite ASTEK GPS/IMU pods. The QF4 targets were flown at 15,000 feet MSL over two distinct flight patterns. The “red” pattern was flown with target 1, AF211, and the yellow pattern with target 2 , AF214. The name of the pattern file was “be-bc.fltpat” which presently resides in the CCS4 /home/uops/work/ directory. Figure 5-6 illustrates superimposed time plots of the estimated terrain MSL altitude using GPS and DFCS and a time plot of RAGE terrain altitude. An average error of 25 feet was reported between DFCS and GPS. Previous analysis has shown that the target altitude estimated by GPS is more accurate than DFCS. For this test, the barometric altimeter was calibrated by flying the target over an interrogator station. Any error of the target in the x-y plane with respect to the position of the interrogator site will translate into a barometric calibration error. Furthermore, due to the relatively small altitude difference between the Interrogator Stations and the target, DFCS is also more susceptible to bad data link geometry problems (HDOP>>1) than GPS. Assuming that the GPS provided the correct target MSL altitude, the average error between the estimated terrain and the RAGE terrain altitude was 16.3 feet for the entire flight pattern. The standard deviation error using both DFCS and GPS was 119 feet. This is not a coincidence since the same radar altimeter data and terrain database was used to estimate the terrain elevation with GPS and DFCS. It should be noted that most of the error was generated when the target was over the WSMR mountains. This error is due to two factors:

- The data grid of the RAGE DTED Level 1 terrain is approximately a 300 x 300 feet square on the x-y plane. That means that on the average, the target will be flying over terrain that is 150 feet off from the true terrain. The altitude error increases proportionally with the slope of the mountain. That is, if the slope of the mountain is equal to 45 degrees, the altitude error will be approximately 150 feet since the tangent of a 45-degree angle is equal to one.

- The data was collected with a QF-4 target flying at 15,000 feet MSL. The accuracy of the QF-4 radar altimeter at high altitude over rough terrain is questionable. The radar altimeter footprint increases directly proportional to the target altitude and the roll attitude angle of the target (footprint radius ~= radar altitude * sin (roll angle)). Therefore, as the altitude of the target increases, the probability of the radar beam hitting exactly the terrain underneath the target decreases. This could also explain a large Standard Deviation (STD) value for the computed altitude errors when the target was flown over rough terrain. DFCS needs to conduct another manned QF-4 mission at a much lower altitude (< 1000 feet AGL) over the mountains using the same flight pattern.

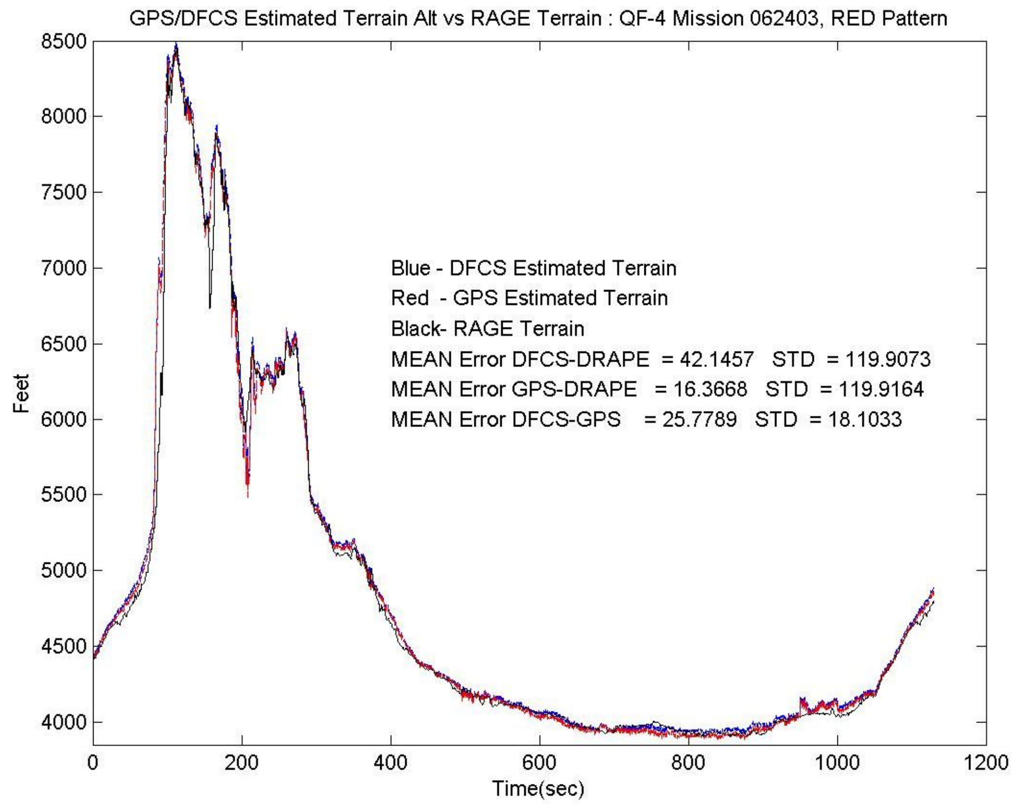

Figure 5- 6 Terrain Accuracy on Red Pattern

Figure 5-7 is snapshot of the of Figure 5-6 showing time plots of the estimated terrain versus RAGE terrain when the target was flown over the basin (time interval from 400 sec to 1000 sec). The data shows an average error between the GPS estimated terrain altitude and the RAGE terrain altitude of only –2.7 feet. The computed standard deviation is less than 31 feet. It should be noted that around second 950, there is a real terrain elevation discrepancy of approximately 100 feet between the terrain estimated by DFCS and GPS and the RAGE terrain elevation. The analysis shows that the discrepancy cannot be attributed to a radar altimeter error due to a high bank angle of the drone or to a barometric altimeter error.

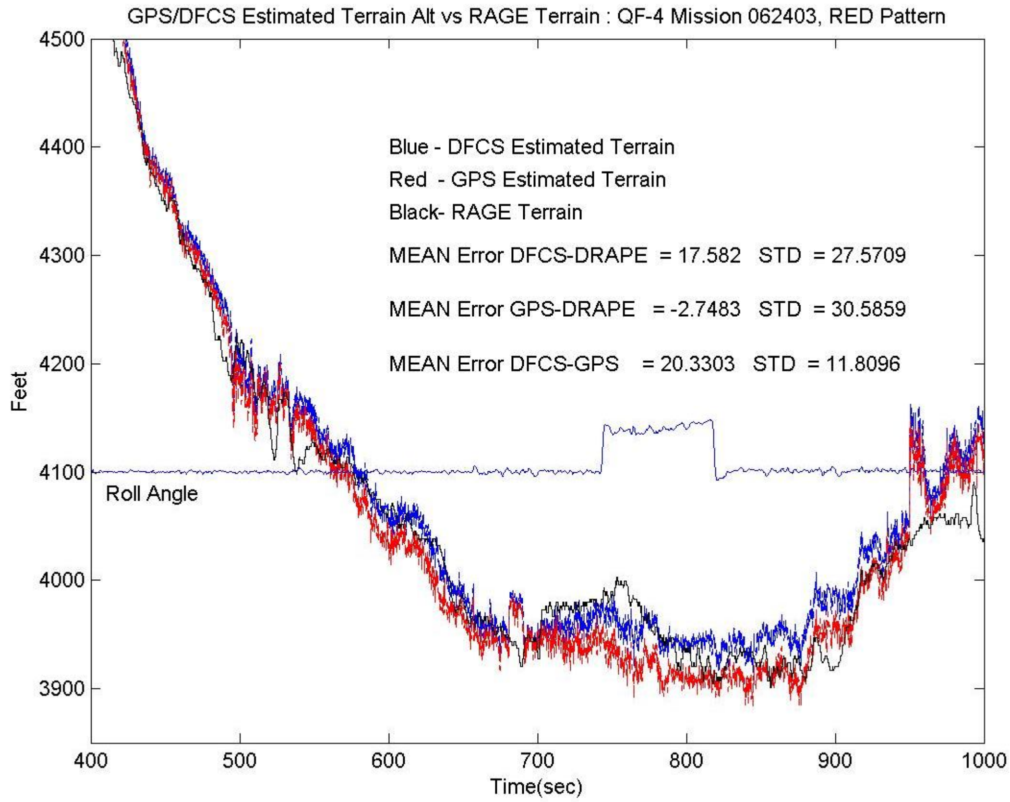

Figure 5- 7 Terrain Accuracy on Red Pattern over Flat Terrain

Figure 5-8 depicts terrain elevation time plots of drone 2 flying over a second flight pattern (yellow pattern). The plot clearly shows that the altitude estimated by DFCS has a bias of approximately 50 feet. DFCS barometric calibration process can be affected by two factors: target distance from the Interrogator Station in the x-y plane and Data Link Geometry during barometric calibration. Any of these two factors could have been the source of the 50 feet altitude bias. It should be noted that on the other hand, the terrain elevations estimated by GPS are very close to the RAGE terrain altitudes. The average error is approximately 37 feet with a standard deviation of 123 feet.

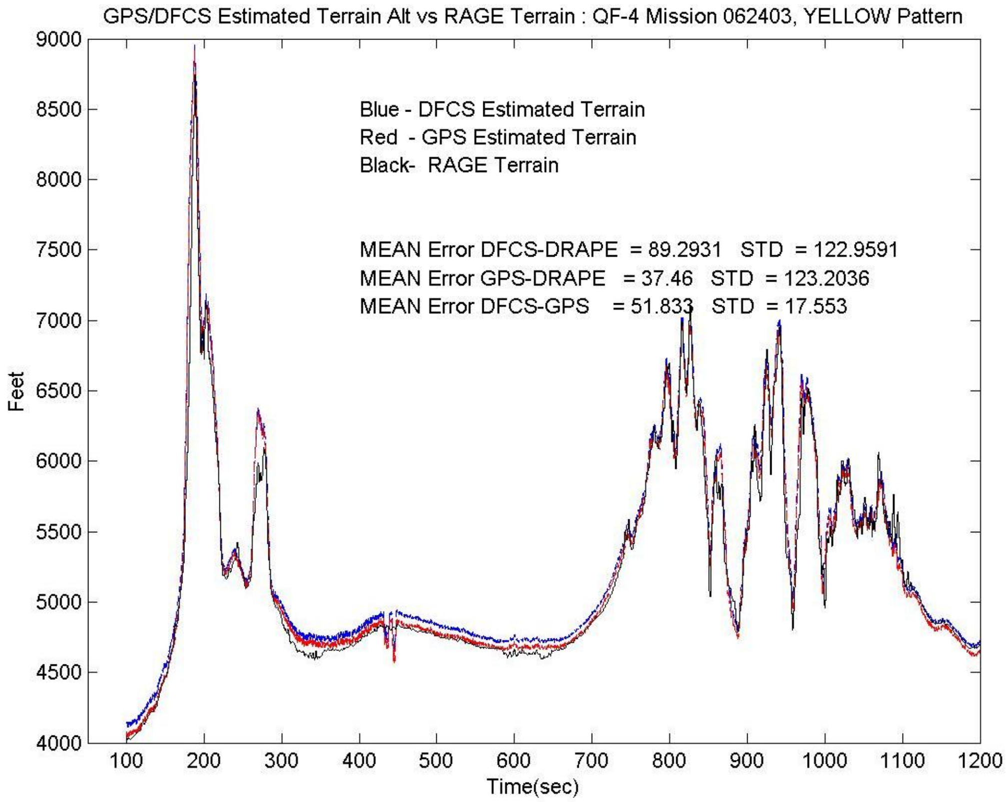

Figure 5- 8 Terrain Accuracy on Yellow Pattern

Figure 5-9 is snapshot of Figure 5-8 depicting time plots of estimated terrain altitude versus RAGE terrain when the target was flying over a semi-flat area (time interval from 300 sec to 1000 sec). The data shows an average error between the GPS estimated terrain altitude and the RAGE terrain altitude of 32 feet. The computed standard deviation is less than 40 feet.

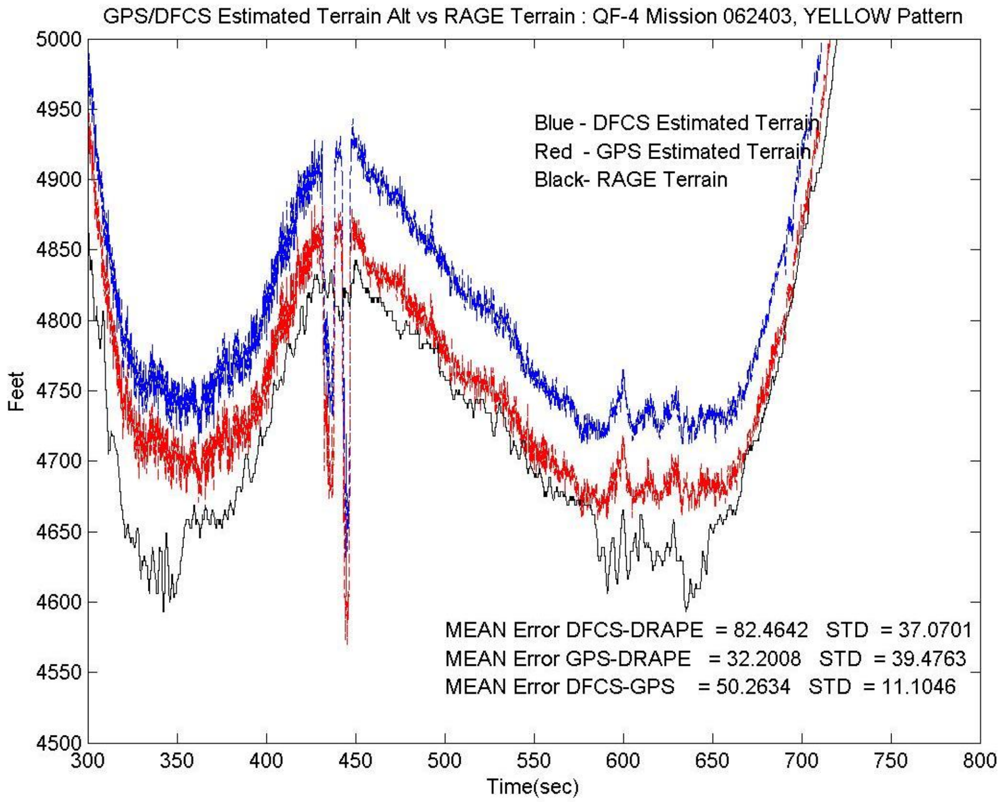

Figure 5- 9 Terrain Accuracy on Yellow Pattern over flatter terrain

<u>5.2.2.2 MQM-107D Mission 18 October 2003</u>

Several missions had been flown to evaluate the accuracy of the terrain elevation data. As mentioned before, one of the missions was conducted with the MQM-107D target on 18 October 2003. The barometric altimeter was calibrated using the radar altimeter and available terrain elevation data. Figure 5-10 shows time plots of the terrain altitude estimated by the DFCS navigation filter (blue line), using MSL navigation altitude minus down linked radar altimeter data and RAGE terrain elevation data. The plot shows that the radar altimeter signal is smoother than the actual terrain. One explanation would be that the radar data is being filtered before it is down linked to DFCS. Also shown is a biased trace of the target roll attitude angle in degrees. The radar altimeter data is not very reliable at high bank angles (i.e. roll angle > 30 degrees). The computed average error between the estimated terrain elevation and the RAGE terrain for 5 minutes of data is approximately 25 feet with a standard deviation of 19 feet.

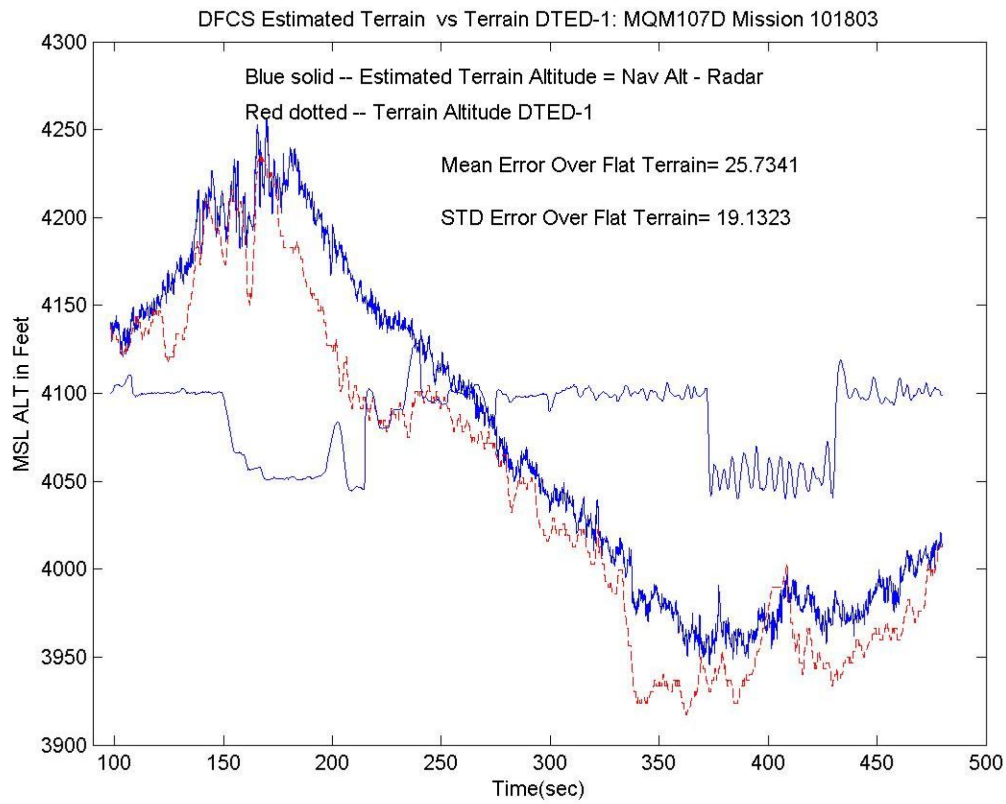

Figure 5- 10 DFCS Barometric Calibration using Radar and Terrain Elevation

GLOSSARY OF TERMS

AGL	Above Ground Level
DFCS	Drone Formation Control System
DME	Distance Measuring Equipment
DRAPE	Derived Radar Altitude Penetration Enhancement
DTED	Digital Terrain Elevation Data
GPS	Global Positioning System
GS	Number of Standard Earth Gravity Units (9.8 m/sec^2)
HDOP	Height Dilution of Precision
IMU	Inertial Measurement Unit
IS	Interrogator Station
ISc	Interrogator Station Co-located
MSL	Mean Sea Level
RAGE	Real Time Advance Graphics Environment
RMS	Root Mean Square
RTDPS	Real Time Data Processing System
STD	Standard Deviation
WSMR	White Sands Missile Range
YDOT	First Derivative of Y