Evaluating the Long-Term Performance of Pavements Thermally Imaged During Construction Phase 1: Developing Spatial Tools for Location Identification

Scott Zinke
James Mahoney
Thomas H. Meyer

Final Report – January 13, 2009

Report Number CT-2240-F-08-10

Connecticut Advanced Pavement Laboratory

Connecticut Transportation Institute

University of Connecticut

<table>
<tr><td>1. Report No.
CT-2240-F-08-10</td><td>2. Government Accession No.
N/A</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Evaluating the Long-Term Performance of Pavements Thermally Imaged During Construction Phase 1: Developing Spatial Tools for Location Identification - Final Report</td><td colspan="2">5. Report Date
January 13, 2009</td></tr>
<tr><td colspan="2">6. Performing Organization Code
N/A</td></tr>
<tr><td colspan="2">7. Author(s)
Scott Zinke, James Mahoney,
Thomas H. Meyer</td><td colspan="2">8. Performing Organization Report No.
CAPLAB1-2009</td></tr>
<tr><td colspan="2" rowspan="3">9. Performing Organization Name and Address

University of Connecticut
Connecticut Advanced Pavement Laboratory
Connecticut Transportation Institute
179 Middle Turnpike, U-202
Storrs, Connecticut 06269-5202</td><td colspan="2">10 Work Unit No. (TRAIS)
N/A</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
N/A</td></tr>
<tr><td colspan="2" rowspan="2">13. Type of Report and Period Covered

Final Report</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address

Connecticut Department of Transportation
280 West Street
Rocky Hill, CT 06067-0207</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code</td></tr>
<tr><td colspan="4">15. Supplementary Notes</td></tr>
<tr><td colspan="4">16. Abstract

This research effort was to investigate whether spatial locating equipment or GPS equipment mounted on ConnDOT ARAN Vans could be used to locate areas of distressed pavement. It was desired to determine the repeatability and accuracy of the GPS equipment and its usefulness as a monitoring tool for the progression of distressed areas on roadways throughout Connecticut. Several attempts were made to empirically make these determinations. If the process was in fact accurate and repeatable, it would lend itself useful in conjunction with the downward, frontward and side facing images the ARAN Vehicle collects as a monitoring process partially negating the need for physical monitoring of selected areas of distress.</td></tr>
<tr><td colspan="2">17. Key Words

Asphalt Pavements, ARAN, Pavement Distress, Geographic Positioning, GPS.</td><td colspan="2">18.Distribution Statement

No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.</td></tr>
<tr><td>19. Security Classif. (of report)
Unclassified</td><td>20. Security Classif. (of this page)
Unclassified</td><td>21. No. of Pages
25</td><td>21. Price
N/A</td></tr>
</table>

Form DOT F 1700.7 (8-72)	Reproduction of completed page authorized

Table of Contents

List of Figures

List of Tables

Introduction and Background Summary

In hot-mix asphalt (HMA) pavements, thermal segregation or temperature differentials are hypothesized to create low in-place densities, which lead to water infiltration and shortened pavement life. Thermal segregation in the material occurs when the material loses heat to the air or the metal surfaces of the haul unit. Conversely, the center of the load is insulated by the outer material and is able to maintain higher temperatures for longer periods. However, when HMA material is dumped directly from a haul unit into the paver hopper the cooler material from the outer portions of the load and/or the hopper wings are not mixed thoroughly. The non-uniformity in temperature is hypothesized to generate weak spots in the pavement and shorten pavement life. To investigate the impacts of these temperature differentials on the actual service life of the pavement, the temperature differential should be measured upon placement and the condition of the pavements should be documented periodically. Ideally, these periodic evaluations will be conducted throughout the service life of the pavement. Two studies have been conducted in Connecticut using thermal imaging technology to document temperature differentials observed during the construction of HMA pavements. The first study **[1]**, conducted in 1998 by John W. Henault from the Connecticut Department of Transportation (ConnDOT), documented pavement being placed on six projects. The location of each image was noted by measuring distances from landmarks. The second study **[2]**, conducted in 2000-2003 by the Connecticut Advanced Pavement Laboratory (CAP Lab), University of Connecticut (UConn), used a handheld Geographic Positioning System (GPS) receiver to mark the location where each thermal image was taken. The GPS coordinates were recorded from the exact location where the camera was held to take the thermal image. Figure #1 shows an example of a temperature differential in a thermal image taken during the CAP Lab study.

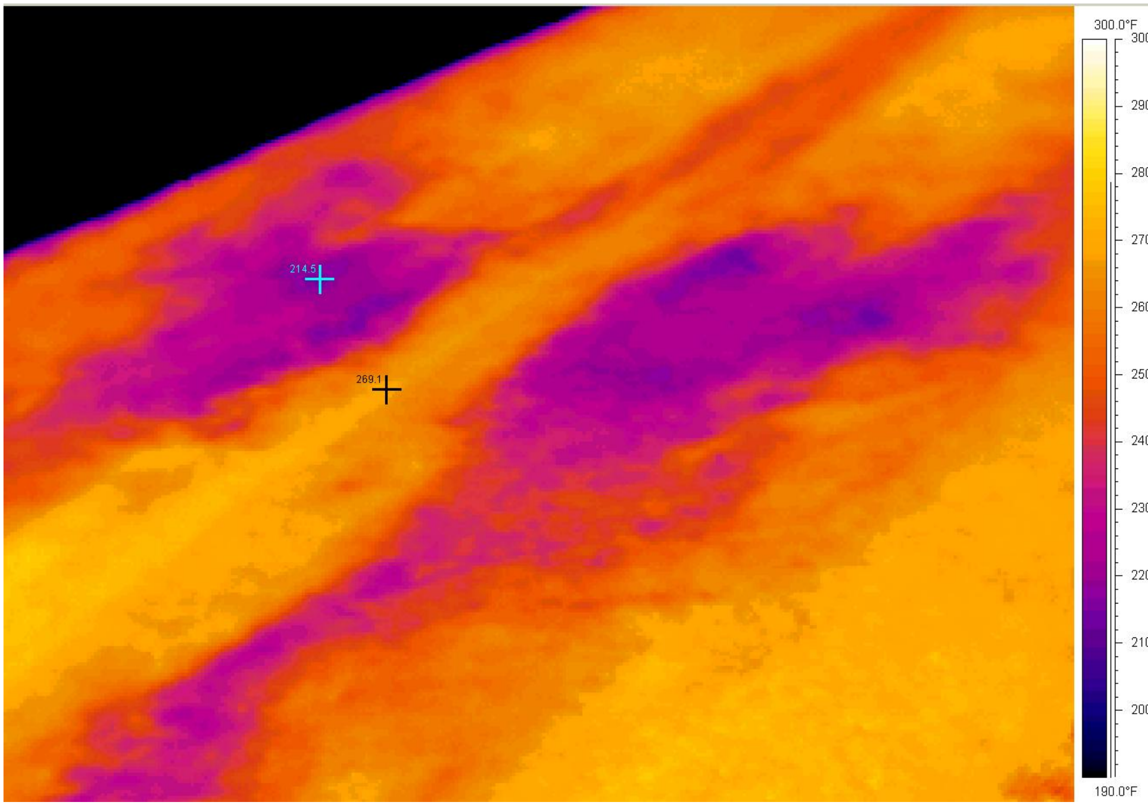


Figure #1. Temperature Differential from Thermal Image

The GPS unit used was a *GeoExplorer 3* manufactured by Trimble. Use of GPS in the second project allowed greater accuracy in locating the image as well as ease of location documentation. The CAP Lab study involved forty separate paving projects on which thermal and spatial data were collected. In both studies, the temperature of HMA, when placed, varied up to 50-60°F over distances of 1-2 feet on the pavement prior to compaction efforts when the end dump method was used to transfer the HMA into the paver hopper.

The effects that temperature differentials at the time of construction have on the long term performance of the pavement are not known and this study is the first to attempt to track such effects. Observations over time will indicate if thermal imaging can be a valuable tool for quality assurance as well as for prediction of the long term performance of HMA. The collection of thermal images and GPS coordinates of locations with observed thermal segregation allow the researchers to track the performance of these locations.

One tool already used by ConnDOT to annually monitor the condition of all state roads is the Automatic Road Analyzer (ARAN) Survey vehicles (Figure #2). ConnDOT's ARAN van also uses GPS in conjunction with multiple other sensors to monitor pavement condition and road geometry. The annual photo logging process includes capturing continuous still images of the road surface (Figure #3) using downward-facing cameras as well as side-facing and forward facing cameras which can be used to find landmarks and track the condition of the roadside (Figure #4).

Figure #2. ConnDOT ARAN Van

Figure #3 ARAN Downward Facing Image

Figure #4 ARAN Forward Facing Image

The data captured by the ARAN vehicles may provide an excellent tool for long-term evaluation of the condition of the pavement at the locations where thermal images were taken. This would provide a safe, cost-effective and efficient methodology to screen projects for premature failure caused by temperature differentials observed at the time of construction. If the spatial data collected by the ARN van could be linked to spatial data collected in the thermal imaging project there would be no need to physically visit the site for evaluation each year and close the road to traffic. However, comparison of images captured by the ARAN vehicle with the thermal images collected during the CAP Lab study relies on an untested spatial alignment methodology using the two GPS sources. Investigating and documenting these methodological issues for GPS location matching between the ARAN van and handheld GPS are the focus of this report.

Objectives

Prior to being able to track the condition of these thermally imaged locations, the repeatability of the data collection process, the ARAN GPS system and the handheld GPS specifically, needed to be determined. It was recognized by the research team that accurate matching of the two GPS data collection systems could not be accomplished unless each system itself was in fact repeatable. The research team sought to develop a plan consisting of several runs of the ARAN over areas/locations of known coordinates to determine if there was an offset, whether that offset was consistent in both distance and direction and finally whether that offset varied with speed and/or acceleration. Another item to be determined was whether or not the ARAN employed real time post processing of collected coordinates or if that was a function that took place after the runs were completed.

The handheld GPS unit also needed to be tested for accuracy. This would be a simple process of collecting a set of spatial coordinates utilizing the handheld unit. Those locations would be marked exactly. Over time, those coordinates would be used as waypoints and revisited to determine how close the hand held unit could return a user to the exact location which it determined coordinates for.

The final task which needed to be completed by the research team was the post processing of the thermal image coordinates taken during the CAP Lab Thermal Imaging Study. This would allow a user to re-enter those coordinates in the handheld GPS unit as waypoints and return to those locations to examine the condition of the pavements. This would also ease the process of matching the ARAN GPS coordinates with those collected from the handheld units as post processing improves the spatial accuracy.

ARAN GPS Repeatability Work Plan and Experimentation

The research team recognized that several repeated runs along a roadway with the ARAN van could yield safety issues. Because of this, the research team contacted the Consumers Union and obtained permission to perform any ARAN testing for this project on the Consumers Union Automotive Test Division Test Track which is located in Colchester Connecticut. This eliminated contending with vehicle traffic as well as with pedestrians. It also allowed the ARAN van to be run at all of the desired speeds, accelerations and decelerations.

The first attempt to try to determine the accuracy and repeatability of the ARAN GPS equipment was made in 2004. The plan was to locate two points on the track which the ARAN VAN would pass over at speeds of 60 mph, 45 mph, 30 mph, 15 mph and a crawl. One run would require the ARAN to stop between points while other runs would require the ARAN to accelerate and decelerate through the two points. Once testing had completed the results would be analyzed and determinations made as to the accuracy of the ARAN GPS equipment. The two points were marked on the test track and located with several available handheld GPS units. The ARAN then made runs over the points. Shortly after this testing there were problems with conflicting data points with respect to the handheld units and it was realized that the locations on the test track could not be considered accurate for comparison purposes given the level of inconsistency between the located points. These points could not be relocated after this realization because at the request of the CU they were not marked permanently and thus could not be found if revisited.

The second attempt to collect data at CU was made in the summer of 2005. Given the problems experienced during the first trial, the experiment protocol was changed by the research team. It was realized that if there were three located points as opposed to two, the ARAN operators would be able to regulate their speed more efficiently. Three points were then located with different distances in between. First the start point was selected and the mid point was selected ~ 1000 feet in the direction the ARAN Van would be traveling. The third point was selected ~ 400 feet from the mid point in the direction the ARAN Van would be traveling. These distances were approximated utilizing a rolling wheel and then measured exactly by the research team with a Total Station and finally confirmed by inversing using the GPS-determined positions. It was decided that each run would be assigned a number according to the run schedule in Appendix A. The run number would be placed on a clip board at the start point which would be photo logged for each run as the ARAN Van passed over it (see Figure #5).

Figure #5 ARAN Passing Located Point on Test Track

This would negate any confusion as to which run was being viewed or at which speed the other two points on the track were passed over. The three locations were located by Tom Meyer of the Department of Natural Resource Management & Engineering (NRME) at the University of Connecticut utilizing survey grade GPS equipment which could locate the three points to well within one inch which was above and beyond the needs of the research team.

After the runs were completed and the GPS files were later being viewed it was determined that the data collection equipment on the ARAN van had failed to operate correctly and the experiment would need to be rescheduled and repeated.

The third and final attempt to collect the data necessary to make the ARAN GPS accuracy and repeatability determination took place in the summer of 2006. There were no changes made to the experimental protocol as the protocol used for the second attempt was decidedly sufficient so long as all the data was collected as planned. Tom Meyer of NRME at the University of Connecticut was again on hand to locate the three points with the survey grade equipment shown in Figure #6.

Figure #6 Survey Grade GPS Equipment Used to Locate Points at CU Test Track

The equipment and overall process used to locate the points is very complex. The report submitted to the research team by Tom Meyer of NRME explaining the equipment, the process, and the accuracy of the locations is presented in Appendix B.

ARAN GPS Repeatability Results

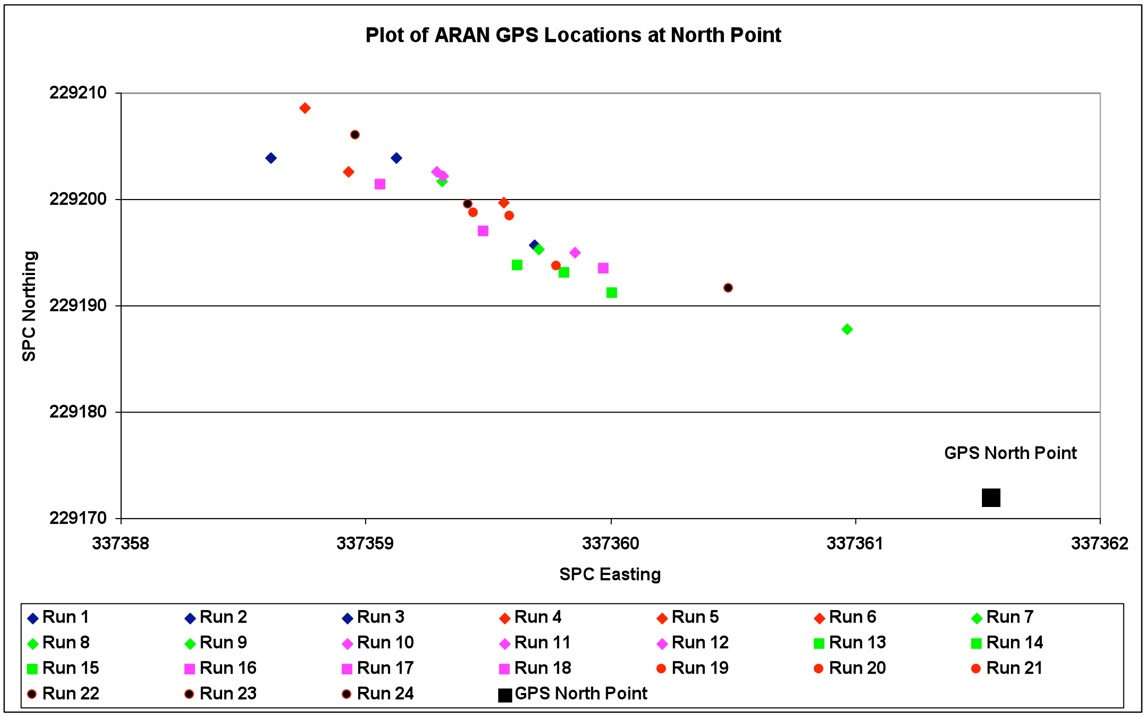
Once the data had been collected and the files obtained by the research team, it was necessary to sort through the downward facing images and retrieve only those containing an image of one of the three points located on the Test Track. Thus for each run there were three downward facing images which could be used for comparison purposes. Along with each image was a number which indicated the chainage distance from the start of that particular run. This chainage distance was also present in the GPS coordinate files. The chainage in the image with a marked point from the test track was then linked with the same chainage in the GPS files to determine which set of coordinates corresponded to which image. It was then necessary to convert the GPS coordinates to a frame on which they could be analyzed and compared. The ARAN GPS system reports geodetic longitude and latitude coordinates referred to the NAD 83 reference frame whereas the report in Appendix B reported coordinates in Connecticut State Plane grid system (SPC 0600 CT), which is much more user friendly and comprehendible than geodetic longitude and latitude. The coordinates were converted to SPC 006 CT from geodetic longitude and latitude via the National Geodetic Survey online conversion tool *Geodetic to SPC* **[3].** Once this conversion took place for all of the images, comparisons were made between the known locations of the three points located at the CU Test Track and the locations as measured by the ARAN GPS system. It was quickly noticed that there was a significant gap between the northing measurements as measured by the ARAN GPS and the actual locations of the points. This is shown plotted in Figures #7, #8 and #9. Immediately preceding those plots is the schedule of runs with the corresponding speed, acceleration, deceleration or constant speed over each of the points shown in Table #1.

Table #1. ARAN Van Run Schedule.

RUN #	START (mph)	POINT 1 (mph)	dV	POINT 2 (mph)
1	40	40	CONSTANT	40
2	40	40	CONSTANT	40
3	40	40	CONSTANT	40
4	45	45	CONSTANT	45
5	45	45	CONSTANT	45
6	45	45	CONSTANT	45
7	20	20	CONSTANT	20
8	20	20	CONSTANT	20
9	20	20	CONSTANT	20
10	30	30	CONSTANT	30
11	30	30	CONSTANT	30
12	30	30	CONSTANT	30
13	20	20	ACCELERATE	45
14	20	20	ACCELERATE	45
15	20	20	ACCELERATE	45
16	30	30	ACCELERATE	45
17	30	30	ACCELERATE	45
18	30	30	ACCELERATE	45
19	45	45	DECELERATE	20
20	45	45	DECELERATE	20
21	45	45	DECELERATE	20
22	45	45	DECELERATE	30
23	45	45	DECELERATE	30
24	45	45	DECELERATE	30

- Start point was located 1000 ft. from point #1 to allow adequate time to achieve speeds as accurately as possible.
- Point #2 was be located 400 ft. from point #2

Figure #7. ARAN GPS Plot of CU Locations (North Point). Coordinates in meters.



The data series' were configured and grouped according to the run schedule in Table #1. It should be noted that the speeds for the north point are only approximate as the ARAN Van was attempting to get up to speed through this point.

Figure #8. ARAN GPS Plot of CU Locations (Mid Point). Coordinates in meters.

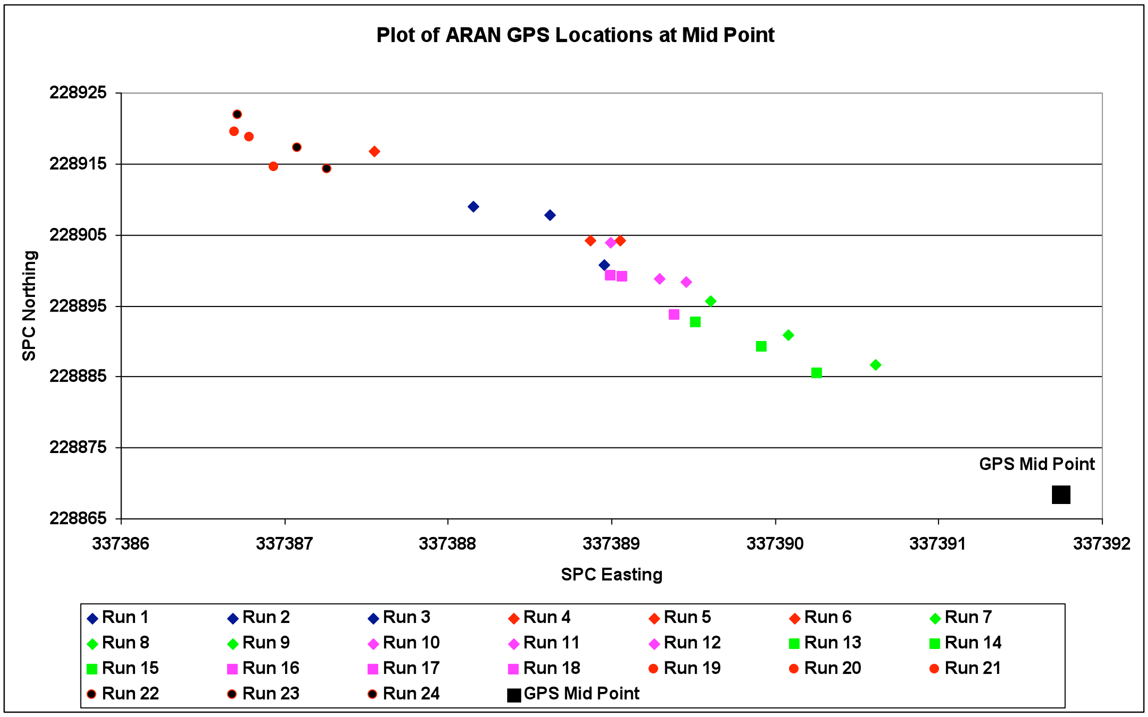
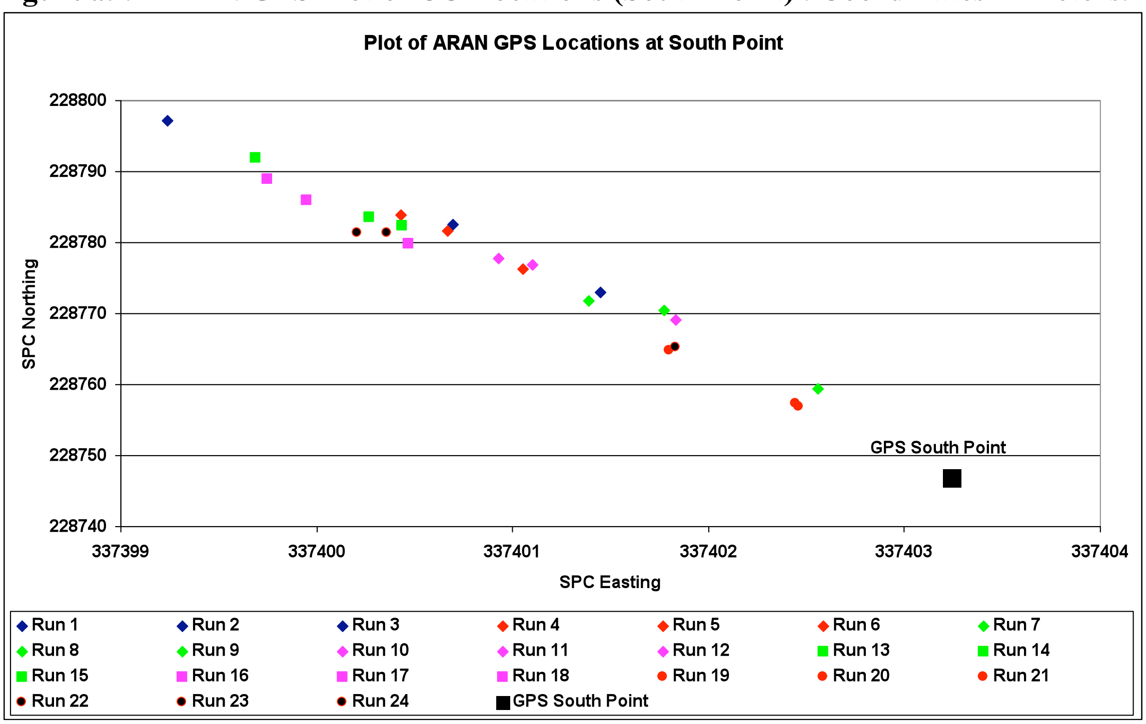


Figure #9. ARAN GPS Plot of CU Locations (South Point) . Coordinates in meters.



It should be noted that Figures #7, #8 and #9 are plotted such that the x-axis is scaled 1 to 1 and the y axis is scaled 1-10. This was done because the offset for the northing in each run was substantially larger than the offset in the easting. The offsets in the northings for each of the locations ranged from 10 meters to in excess of 53 meters while the offsets for the eastings ranged from 0.6 meters to 5 meters. This could be due in part to the direction of travel primarily taking place in the North to South direction. The driver of the ARAN Van was very careful not to drift to the left or right while traveling down the test track over the three located points as well. This effort was confirmed while viewing the downward facing images which the vehicle collected during each run which showed the marked located points as well as the run number which was displayed on clip boards immediately adjacent to the marked points as shown in Figure # 10.

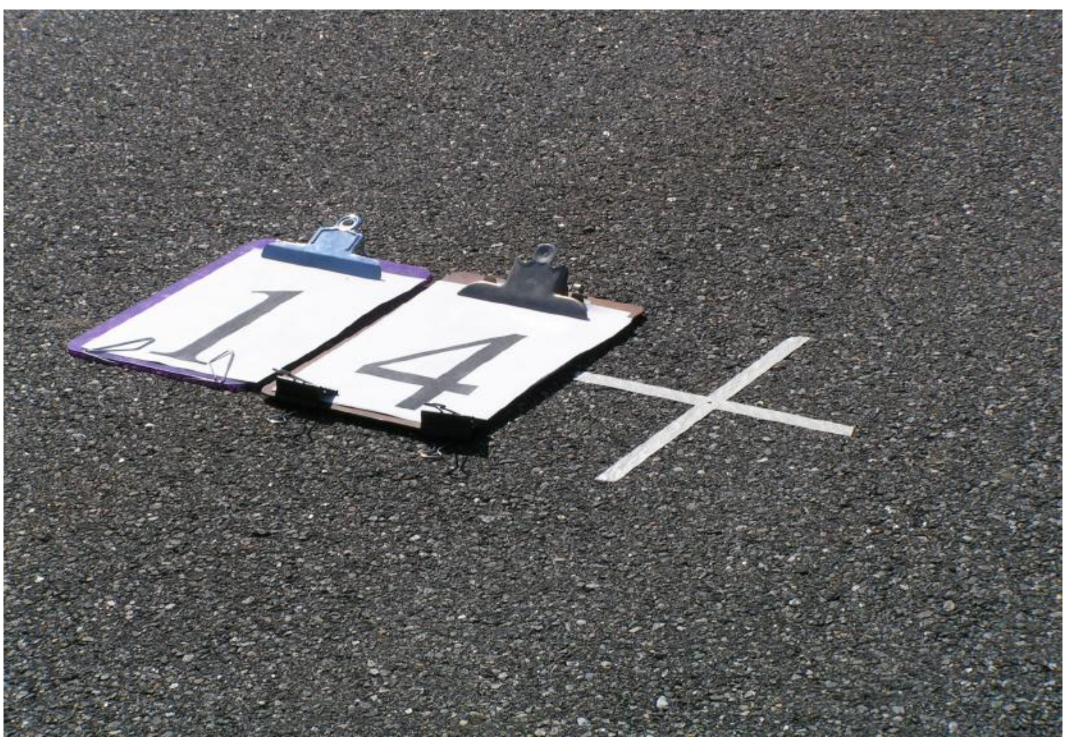


Figure #10. Located Point and Run Indicator

Movement in the East to West direction while traveling the Test Track is very minor as the track runs more North to South as shown in Figure #11 which is an extraction from Google Earth.

Figure #11 Consumers Union Automotive Test Division Test Track. Colchester, CT.

The only real noticeable trend with the run plots is at the midpoint in Figure #8. The magnitude of the error clearly increases as speed increases and the speed groupings show this. This does not to indicate the error was by any means mitigated, it simply indicates that as speed increases for the speed groups, the error increases as well. This does not hold steady for the end or south point as the speed groups are far more dispersed and there is no discernable trend as shown in Figure #9.

<u>Handheld GPS Unit Repeatability Work Plan and Experimentation</u>

The determination of the accuracy of the GPS handheld unit (Trimble GeoExplorer 3) was not nearly as intensive as the testing for the ARAN GPS system. For the handheld unit, it was simply desired to obtain a rough estimate of how close to a known waypoint location the user could get. This was done very quickly and without much effort. The handheld unit was taken out onto the large field immediately north of the Connecticut Advanced Pavement Laboratory and three locations were marked and their locations measured with the handheld unit. One location was in wide open space, one adjacent to a tree and another along side of a large brick building. The coordinates were downloaded, post processed and entered as waypoints back into the handheld unit. Two members of the research team then attempted to locate the marked locations to determine how close the unit would bring them.

<u>Handheld GPS Unit Repeatability Results</u>

Over two days the research team located the three points several times to gain insight as to the change in accuracy and repeatability of the hand held unit due to PDOP and changes in satellite geometry. The handheld units were accurate to within ~2 to 4 meters each time. The research team also followed up on a few cold spot locations from the CAP Lab thermal imaging study [2], whose locations were known exactly and the handheld units were accurate to within a few meters on some spots and up to 20 meters in other spots. This could be due in part to different satellite geometries or being on a heavily wooded roadside or PDOP fluctuations or a combination thereof. Meyer, et al. [4] indicate that there is a loss of accuracy with GPS coordinates per percent of sky obstruction. That study was conducted with survey grade equipment so it could be theorized that less intricate equipment such as the handheld unit used in this study would have an even more pronounced loss of accuracy given a set of sky obstruction conditions.

Conclusions and Recommendations

The level of error in the coordinates collected at the CU Test Track as shown in Figures #7, #8 and #9, indicate that there is currently no useful way to employ the ARAN GPS data in revisiting sites and locations of known distress or for monitoring purposes. The error found by the research team is thought to be systematic and is believed to be correctable. This data and problem were forwarded to the manufacturers of the ARAN GPS equipment by ConnDOT and this represents the state of this research at the present time. It is recommended that further investigation be conducted to determine the root cause for the errors found as well as to correct this issue and further pursue the use of the ARAN GPS data for documenting and utilizing geospatial data as needed for monitoring of distressed areas on Connecticut's pavements. The ARAN Vehicles are a promising means of logging roadway conditions in Connecticut. There is an extraordinarily high volume of data collected by the ARAN Vehicles yearly and if the connection between photo log GPS coordinates and actual physical locations could be established, then that geospatial relationship could be used to link construction data and observed pavement distress over time. This would in turn lead to feasible methods of studying the effect of workmanship and material quality at the time of construction with the rate of deterioration and distress on the roadway.

It is the opinion of the research team that the handheld unit used in this research can at times be extremely useful in locating specific areas of distress so long as post processing has taken place. It is also the opinion of the research team that at other times the handheld unit can only be useful in locating approximate general areas of distress. The number of readings taken to average a set of coordinates during data collection may play a key role in obtaining more accurate relocations.

If the manufacturer addresses the technical problems discovered and documented by this project, future research may be warranted to pursue the development of methodologies to utilize ARAN GPS data to document and monitor distressed pavement areas on Connecticut's highways, as well as for monitoring of experimental pavement study sites.

References

1. Henault, J.W., "Development of Guidelines for Reduction of Temperature Differential Damage (TDD) for Hot Mix Asphalt Pavement Projects in Connecticut – Construction Report," Report No. 2222-1-99-5, November 1999.

2. Mahoney, J., Zinke, S.A., Stephens, J. E., Myers, L.A., and DaDalt, A.J., "Application of Infrared Thermographic Imaging to Bituminous Concrete Pavements - Final Report," Report No. 2229-F-03-7, November 2003.

3. National Geodetic Survey. http://www.ngs.noaa.gov/cgi-bin/spc_getpc.prl. This utility uses NGS program SPCS83 or program GPPCGP to convert NAD83 or NAD27 Geodetic Positions to State Plane Coordinates (SPC).

4. Meyer T.H., Bean J, Ferguson R., and Naismith J.Z. (2002) The Effect of Broadleaf Canopies on Survey Grade Horizontal GPS/GLONASS Measurements. In *Surveying and Land Information Science*, vol. 62, no. 4, pp. 215 – 224.

Appendix A. CU Test Track Location Acquisition – Tom Meyer Report

Report on ARAN GPS survey

Introduction

The ARAN survey was conducted at the Consumer Reports automotive test track in Colchester, CT on April 11, 2006. Topcon HiPer-Lite+, Javad Odyssey and Javad Legacy receivers with 2m fixed-height range poles were used to occupy three temporary marks placed on the test track and one pin set in the ground nearby. The three marks on the asphalt test track were designated North, MID and South, corresponding to their general relative positions. A base station was set up on a 9" steel nail with an aim-point drilled in the top and driven into the ground adjacent to the track. The nail was designated as PIN and occupied by a Topcon HiPer-Lite+ receiver.

Occupations began at 8:43 AM EDT and ended at 9:57 AM EDT, with a total time span of 1h and 14 minutes. The test track has nothing obstructing sky visibility above our elevation mask (10 degrees) and the weather was dry and calm. Handheld weather station (Kestrel) readings gave a relative humidity of 42%, a starting temperature of 56 F, and the atmospheric pressure at 1007 hPa.

Occupation data were processed with Topcon Pinnacle processing software. Three Continuously Operating Reference Stations (CORS), CTDA, CTMA and TRS were chosen to control the survey. All control coordinates were in NAD 83 (2002.0). The coordinates at antenna reference point (ARP) are CTDA (N $41^0$03'57.06987'', W $73^0$30'25.94233'', -13.27m), CTMA (N 41^0 43' 52.91709'', W 72^0 12' 38.87753'', 55.18m) and TRS (N 41^0 29' 20.15819'', W 71^0 31' 39.77855'', 45.69m).

GPS data were processed by the Topcon Pinnacle post-processing software to determine baseline vectors from differencing phase observations. Our solution vectors were determined from L1-L2 double differencing. Carrier phase ambiguity fixed/float ratio was nearly 100% for all vectors; see Table 1. Offsets from the ground marks to the ARP of GPS antenna and offsets from antenna phase center to ARP were carefully set during the processing of the data in order for the offset to be zero at the marks for the

CORS stations. ARP-to-phase-center offset measurements for each receiver were taken from the GPS antenna calibration site of National Geodetic Survey (NGS).

Table 1. Vector Solution Characteristics

Vector		Common span	Solution		Observations		Am big. fix /flo	Min fix rati o	Result/rms m/mm		
From	TO		code	type	total/ discar ded	RMS DD			X	Y	Z
MID	South	00:17:30	OTDDFX	Static	10551/ 14	0.049	39/0	100	34.848/0.8	-73.472/1.6	-91.121/1.3
North	MID	00:22:40	OTDDFX	Static	15937/ 13	0.045	42/0	100	88.580/0.9	-183.442/1.4	-227.016/1.2
North	South	00:15:00	OTDDFX	Static	8324/7	0.024	72/0	100	123.428/0. 5	-256.912/1.0	-318.137/0.9
PIN	MID	00:27:06	OTDDFX	Static	94824/ 66	0.030	216/ 0	98	68.002/0.5	-100.638/0.8	-131.096/0.7
PIN	North	00:32:15	OTDDPF	Static	22375/ 25	0.044	62/1	100	- 20.579/0.7	82.802/1.2	95.921/1.1
PIN	South	00:17:30	OTDDFX	Static	10543/ 18	0.050	57/0	100	102.849/1. 0	-174.109/1.7	-222.217/1.6

Results

Geodetic coordinates for the marks in NAD83 (2002.0) are reported in Table 2 (ellipsoid height is shown at 5mm confidence).

Table 2. Geodetic coordinates determined for occupied marks (NAD 83 (2002.0)).

Points	Latitude	Longitude	height(m)	Sigma (mm) s(N)	Sigma (mm) s(E)	Sigma (mm) s(U)
MID	41°31'16.36053"N	72°21'34.32145"W	145.090	2.0	1.5	3.7
North	41°31'26.20267"N	72°21'35.56467"W	144.605	2.0	1.5	3.7
South	41°31'12.41789"N	72°21'33.84944"W	145.020	2.0	1.5	3.8
PIN	41°31'22.04540"N	72°21'35.80107"W	144.760	2.0	1.5	3.7

Table 3 reports the mark coordinates in SPC83 coordinate system (zone CT0600). The results show a very small standard deviation that is probably optimistic. It is known that fixed-integer solutions have better-than-real error statistics and we believe 5mm to be more realistic. Ellipsoid height is reported at 5mm confidence in Table 3. The projection scale factor at the test track is 0.999983.

Table 3. SPCS83(CT0600) coordinates

Points	Northing(m)	Easting(m)	Height (m)	Sigma (mm) s(N)	Sigma (mm) s(E)	Sigma (mm) s(U)
MID	228868.467	337391.747	145.090	2.0	1.5	3.7
North	229171.969	337361.552	144.605	2.0	1.5	3.7
South	228746.885	337403.240	145.020	2.0	1.5	3.8
PIN	229043.692	337356.650	144.760	2.0	1.5	3.7

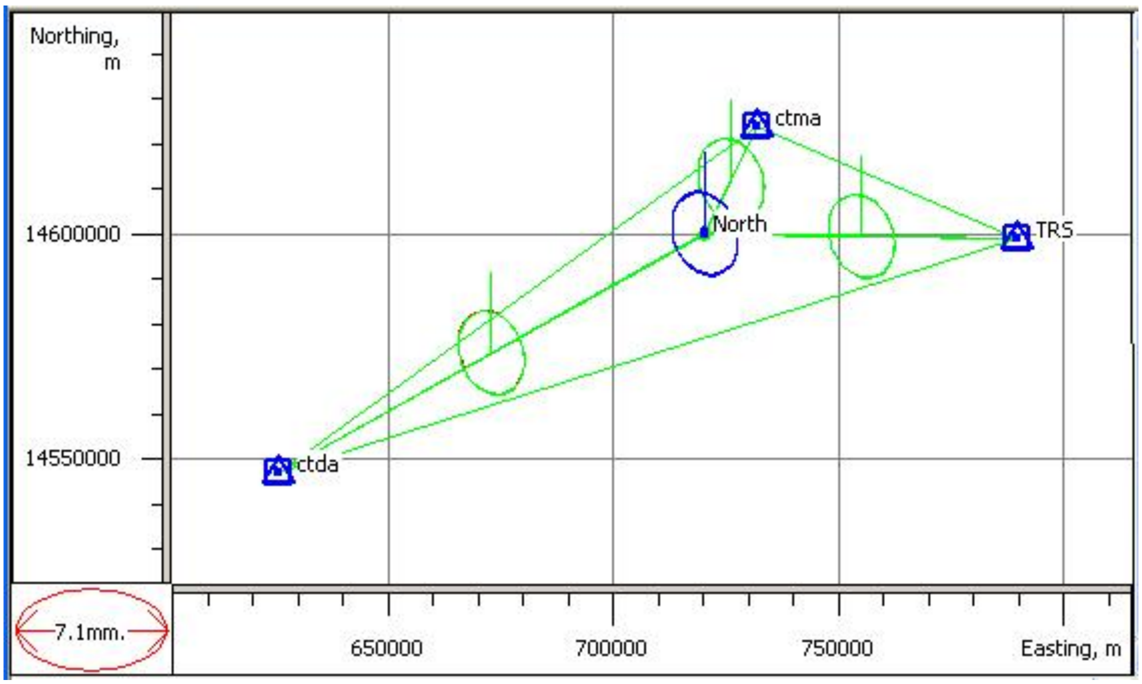
All coordinates are on the ground at the marks. The ground distances between points, given at 5mm confidence and reported in the NAD 83 Earth-Centered, Earth-Fixed terrestrial reference system (XYZ), are given in Table 4. Inversing between SPC coordinates will *not* replicate distances reported in Table 4 due to the projection scale factor and truncation/round-off in the State Plane coordinates. The distances in Table 4 should be used, rather than inversing between State Plane coordinate pairs.

Table 4. Spatial (three-dimensional, straight line distances) separating the marks on the ground. Distances given at 5mm confidence level.

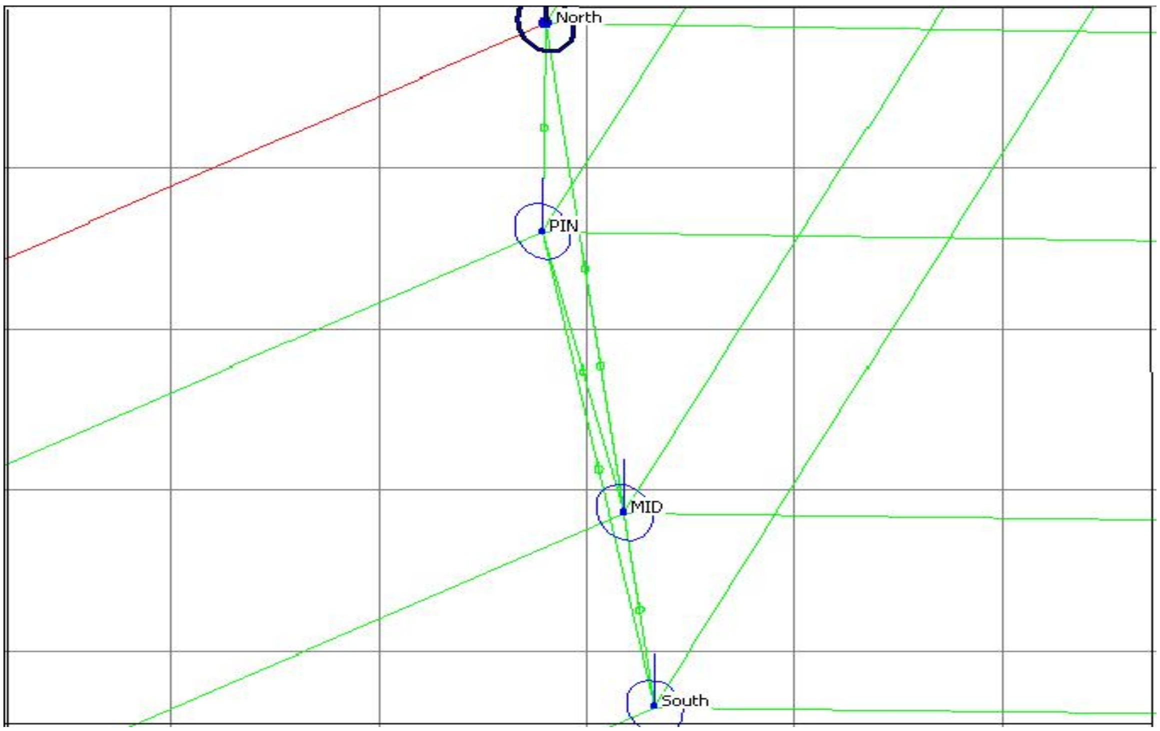
from - to	Coordinates (m)			Length (m)	Sigma (mm)		
	X	Y	Z		s(X)	s(Y)	s(Z)
MID-South	34.848	-73.472	-91.121	**122.130**	0.8	1.6	1.3
North-MID	88.580	-183.442	-227.016	**305.015**	0.9	1.4	1.2
North-South	123.428	-256.912	-318.137	**427.140**	0.5	1.0	0.9
PIN-MID	68.002	-100.638	-131.096	**178.715**	0.5	0.8	0.7
PIN-North	-20.579	82.802	95.921	**128.375**	0.7	1.2	1.1
PIN-South	102.849	-174.109	-222.217	**300.450**	1.0	1.7	1.6

Figures:

A view of complete networking and a closer look of networking among the points are shown below in the following figures. In the first figure, all of the test track markers appear coincident due to their relatively small separation compared with the distances between the control stations. At the scale of the figure, the test track points are too close to be rendered distinctly. Triangles indicate fixed horizontal coordinates and squares indicate fixed vertical (ellipsoid height) coordinates.



A closer view of the marks and the baselines is shown in the following figure.


North
PIN
MID
South