Mobile Survey Validation

I15 HOV Lanes

Caltrans District 11

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Table of contents

Executive Summary 4
Overview 5
Mobile Survey System Description 6
Pavement Profile Scanner (PPS) 6
Description
Specifications
Scanning
Data Rate
Accuracy
Data Handling
Position and Attitude Measurement 7
Function
Description
Navigation Solution Generation
Point Cloud Generation 8
PPS/SPAN Synchronization
PPS Data Transformation
Point Cloud Processing 9
Project Work Flow 10
Planing and Setup 10
GPS Coverage
Establish Boresight Line
Base Receiver Setup
Survey Control
Data Collection 10
Initialize Navigation
Perform Mobile Surveys
PPS/SPAN Alignment (Boresight)
Objective
General Procedure
Procedure for this effort
Terminate Navigation
Post Processing 12
I-15 Project Description 13
Location 13
Pavement 14
Project Control / Base Receiver 15

Control Survey 15
Pavement
Boresight Line
Data Collection Workflow 16
GPS Outages and Multipath 16
I-15 Mobile Survey Results 17
Boresight Alignment 17
Absolute Elevation 19
Relative Elevation 24
Background
Approach
Relative Results
Observations and Conclusions 27
Acknowledgements 28
Caltrans 28
Headquarters
District 11
Contact Information
Merrick 28
Contact Information

Executive Summary

This report presents quantitative results of a demonstration project which validates that survey grade mobile survey of in-service highways is now a proven tool that can be applied before and after pavement construction to drastically reduce the exposure of surveyors to the hazardous conditions on and near in-service highways, road closure requirements, and survey related time and costs.

This capability is the result of the convergence of significant developments in laser scanning and GPS Inertial Navigation. Phoenix Scientific Inc. (PSI) has developed the most accurate and fastest laser specifically to scan roads at highway speed while they are in-service with no disruption to normal traffic flow. The original application was pavement strength testing from a moving heavy truck which required very high accuracy. The resulting technology proved ideally suited to precision mobile survey. PSI integrated GPS Inertial Navigation with its pavement scanner technology to measure the scanner position and attitude and then transform the scanner profile points into a point cloud in the appropriate project geodetic coordinate system. Finally, PSI adapted commercial aerial Lidar point cloud software to view and analyze the point cloud and extract the 2D information required for the pavement construction work flow.

Caltrans District 11 envisioned both the potential and the importance, in terms of increased safety and operational efficiency, of mobile survey, With this motivation, they collected extensive control survey data on a section of the reversible I-15 HOV lanes and made it publicly available for validation of this capability, We scanned a six mile stretch of the HOV lanes that included the surveyed control section a total of 8 times. The results show that with control points located in the shoulder of a multi-lane structure at intervals on the order of 1,000 feet, the mobile survey results can be processed to have an absolute (geodetic) elevation accuracy that is better than ±0.03 feet (±1 cm).

Due to the high accuracy of PSI's scanner technology and the Inertial attitude measurements, the results provide data that is well matched to the specifications and work flow required to measure, design and construct roads with tightly controlled cross slope and grade.

This integrated technology is now available from PSI as a service and the system can also be purchased by organizations that are prepared to invest in the personnel and training required for the operation and data processing associated with both laser scanning and GPS Inertial Navigation.

Overview

Phoenix Scientific has developed laser radar scanning technology optimized to the demanding requirements of pavement surface profile measurement at highway speeds in traffic for deflection, rutting, ride quality, texture and distress. The initial application of PSI's Pavement Profile Scanner (PPS) to road survey occurred in late 2005 as the enabling technology in a project for BMW. In 2007 an extensive feasibility test was conducted on I15. ThI15 work led to the first production job for Kansas DOT. Due a tight schedule associated with the Kansas project, the I-15 analysis and report were never published. Throughout 2007 and 2008, PSI developed an enhanced version of the PPS. The most notable feature being the increase of the phase ambiguity from 4 inches (10 cm) to 10.7 feet (3.25 m) for reliable scanning of shoulders and rough terrain. In early 2009, PSI back to the I-15 project and redid the work with the latest PPS version to establish definitive grounds to support deployment of this system for precision mobile survey of the highest grade. This report covers this latest I15 project.

The first section provides a description of the Mobile Survey System, including the PSI PPS, Navigation Systems and post-processing software for Point Cloud Generation and Analysis.

The second section describes the Work Flow associated with the PSI Mobile Survey solution, beginning with pre-survey preparation, then the data collection during the actual mobile survey and then finally the post-processing.

The specific details of the I-15 project are presented in the third section, which covers the location, pavement characteristics, and survey control. Also the specifics of the workflow for this project is presented. And finally, the locations in the project where overpasses caused brief GPS outages are identified.

Finally, in the fourth section, the results of the data analysis are covered, starting with the stationary bore-sight at Miramar Way. Next the results in the 0.9 mile (1,400 meter) section with absolute and dense survey control is covered, and finally the precision of repeat runs over the full 6 mile (9.7 Km) route is presented. The results are followed by the brief Conclusions section.

Mobile Survey System Description

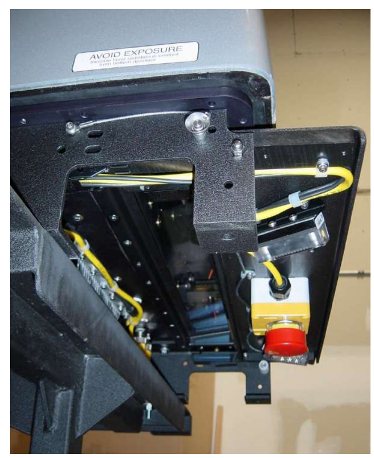
The Mobile Survey System made up of two integrated hardware subsystems, the scanner and navigation system, and the software for the subsystems and post-processing to generate and evaluate the survey data. A block diagram if the system is shown below in the Point Cloud subsection.

Pavement Profile Scanner (PPS)

Description

The primary component of the PPS system is the scanner unit shown here on the PSI test vehicle. The scanner measures the distance to the pavement using phase measurement of a modulated laser beam as the optical path is scanned transversely across the pavement by a rotating polygon.

The scanner is built on an Aluminum plate mounted to two C-channels that provide a mounting foundation for the scanner. Only 4 bolts are required to secure the scanner to a support foundation. A fiberglass cover encloses the scanner electronics and optics with a watertight seal.



The system scans through a window in the bottom of the plate. The window cover slides forward and locks in place during scanning. When unattended the cover can be locked in the closed position to protect the window for tampering. The emergency-off mushroom switch and warning LEDs are mounted to the window cover, so the scanner is a unit with no assembly required. The optics can be seen through the window in the bottom view. The PPS requires just 160 watts operating and 70 watts when quiescent, however a active thermal control subsystem, which operates directly off the vehicle battery, was designed for operation at extreme temperatures.

Specifications

See the PSI website for the detailed specifications of the PPS. The following overview of the key specifications is tailored to provide an understanding of the performance of the PPS.

Scanning

The laser measurement spot is scanned across the pavement through a 90° field-of-view centered straight down, 1,000 times per second. For this project, the PPS was mounted with the polygon 8 feet above the pavement which resulted in a scan width of 16 feet. At the typical speed of 60 M.P.H., the scans were separated by about 1 inch. With the average lane width of 12 feet, this provides 2 feet of overlap to adjacent lanes while minimizing the chance of passing vehicles obstructing the beam and causing spurious data.

Data Rate

Each scan is made up of 945 points sampled at a constant rate of 1.258 million points per second. Since the polygon rotates at a constant rate also, the profile points are closer together at the center of scan and further apart at the edges. For this project, with a 16 foot long scan line, the average spacing between points is 0.2 inches.

Accuracy

PSI's Laser Radar technology measures the range to the pavement with a precision on the order of 0.004 inches (0.1 mm) and when scanning through the 90° FOV, the overall absolute shape accuracy is within ±0.02 inches (±0.5 mm) peak. While this accuracy can be improved with advanced calibrations, it is well within the specifications required for mobile survey.

Data Handling

The advantage of the high PPS data rate is that the data can be used to recognize fine features such a lane markings, raised markers, and pavement defects and also it can be processed statistically to assure precision and coverage at the control points. The PPS system software provides the facility to grid the data within each scan at what ever spacing is desired. For this project, a grid of 6 inches was selected, which produced nominally 32 points per scan. Further, scans can be selected and intervening scans skipped so that the scans are spaced at a suitable distance from each other. In this project the drive speed was fairly constant at about 65 M.P.H. Every 6th scan was selected resulting in nominally a 6 inch separation between lines of gridded points. The PPS also records a wheel encoder input and hence the scans can actually be selected to be at a constant spacing independent of vehicle speed.

The final density of data produced for this project was a 6 inch rectangular grid. The percent reduction from the raw data density was just 0.6% (32/945/6*100%). For this project, the PPS system software was used to export the data in the data into PSI Scanner data D1 and D2 files which are text tab delimited structures for elevation and intensity respectively. The first line of each file consists of the lateral offset positions and then each successive line contains the values from one scan.

Position and Attitude Measurement

Function

The PPS data is relative to the scanner polygon. In order to locate the points in the project coordinate system, it is necessary to measure the instantaneous position and attitude of the polygon.

Description

There are a number of commercially available GPS Inertial Navigation systems on the market that meet the performance requirements of Mobile Survey. In our first mobile survey project which was done for BMW in 2005, we integrated the Applanix POS-LV system as shown in the photo to the right. Other customer owned or specified systems could also be integrated with the PPS. However, PSI chose the Novatel solution when it came time to buy hardware because the product is structured specifically for the integration by Original Equipment Manufacturers (OEMs) such as PSI.

Novatel's SPAN™ (Synchronized Position Attitude & Navigation) Technology combines GNSS (Global Navigation Satellite Systems including but not limited to the US GPS system) and measurements from an Inertial Measurement Unit (IMU) to provide continuous operation with accurate position and attitude measurements. The foundation of SPAN Technology is its tightly and deeply coupled design that affords exceptional GNSS performance in addition to superior bridging capability when GNSS reception is restricted. Tight integration means satellite data is utilized even when a GNSS position is unavailable. Deeply coupled means that SPAN Technology delivers dramatically faster GNSS signal reacquisition resulting in more GNSS measurements available to aid the inertial solution. Further information can be found at: http://www.novatel.com/products/span.htm.

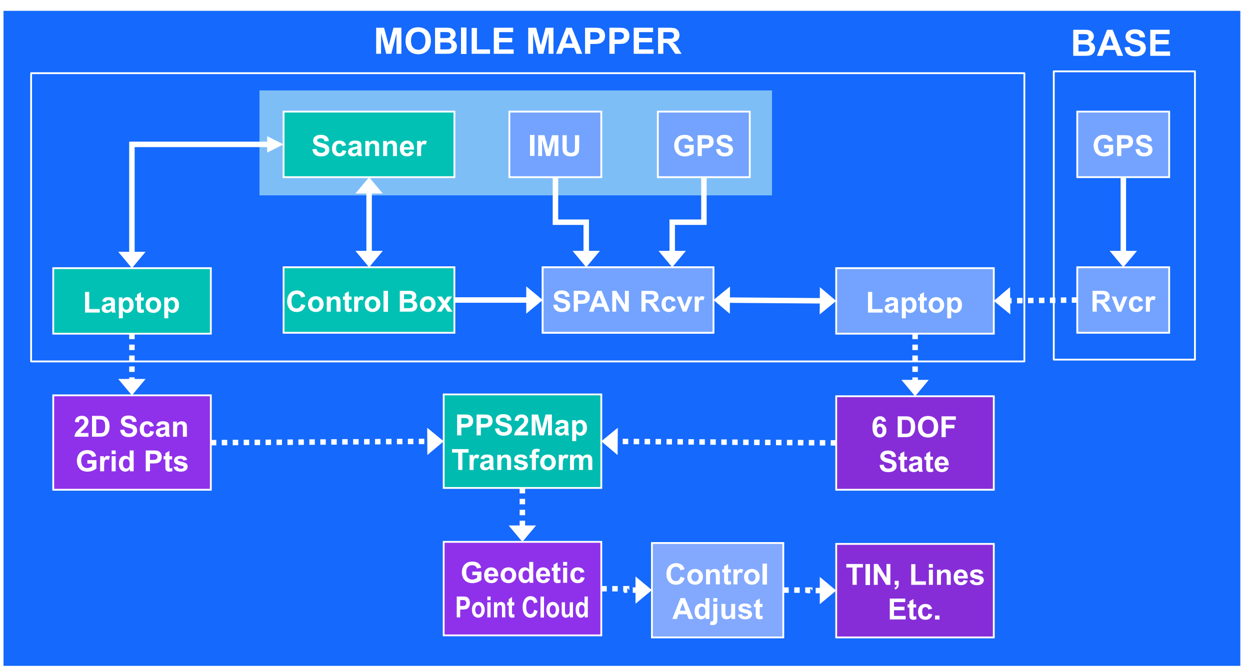
Navigation Solution Generation

The maximum possible position and attitude accuracy are obtained by post-processing the navigation data, including a GPS base station data located in the project area with the most advanced differential GPS and inertial navigation Kalman filtering with forward and reverse smoothing. PSI accomplishes this with the Novatel Waypoint Inertial Explorer package. Once a satisfactory navigation solution is computed, the results are exported as a navigation solution file consisting of GPS time, 6 degrees of freedom solution, horizontal velocity and local grid angle at a 100 Hz data rate. This navigation file covers the entire period of time when the mobile surveys were performed.

Point Cloud Generation

PPS/SPAN Synchronization

PSI has developed a tight integration between the PPS and SPAN which assures that the time when each mobile survey data collection begins is recorded in GPS time to within 0.001 seconds. The GPS start time is then used to synchronize the conversion of the gridded scanner data into Geodetic Coordinates using the navigation solution file.



PPS Data Transformation

PSI has developed a program, PPS2Map, which transforms the gridded scanner transverse profile points from the scanner coordinate system, using the navigation solution, vehicle velocity, local grid angle, and boresight corrections into the desired Geodetic Coordinate system. Typically this is the local East-North-Up (ENU) used by the customer for the specific project.

For this project, we used CCS-83 Zone 6 (refer to: http://www-group.slac.stanford.edu/met/Align/GPS/CCS83.pdf and http://spatialreference.org/ref/epsg/2230/).

PPS2Map has options to export the results as either text tab delimited format of LAS format which is an open binary standard developed in the aerial lidar field. For this project, the data was exported in both formats so that either could be used by Caltrans and others to evaluate the results. The LAS format was used for the analysis presented in this report.

http://www.lasformat.org/

http://www.asprs.org/society/committees/lidar/lidar_format.html

http://www.commission3.isprs.org/laser07/final_papers/Samberg_2007.pdf

Point Cloud Processing

Merrick Advanced Remote Sensing (MARS®) software is a stand-alone, Windows®-based application specifically designed for processing, analyzing, and managing terrain data. MARS® provides unparalleled application and visualization performance for massive LiDAR data sets and includes a modular tool suite that is used to manage field collection, data analysis, quality assurance, production, and client deliverable workflows. See the following link for more information about MARS: http://www.merrick.com/index.php/services/geospatial-solutions/mars-software. There is a free view that can be downloaded.

MARS was used to process the LAS files for the following steps:

- Merger of multiple mobile survey runs
- Point Cloud visualization
- Plotting cross section profiles
- Control Error Report Generation
- Elevation Shifting
- Outlier Reclassification - not done for this project
- 2D Extraction - not done for this project

Project Work Flow

This section gives an overview of the workflow associated with mobile survey. The details of the I-15 project will be presented in the following sections.

Planing and Setup

This section addresses the critical activities that should be completed before starting a mobile survey

GPS Coverage

The DOP (dilution of Precision) which is a measure of the quality of the GPS solution that can be expected, largely as a function of the GPS satellite configuration, should be plotted for the periods of time when mobile survey may be conducted. This will allow the survey team the ability to avoid performing surveys during the times when the coverage is not optimal.

Establish Boresight Line

Typically, the boresight occupation occurs when convenient between mobile survey runs. As such it is vital to set up the line in advance of commencing mobile survey. See the Boresight section below for details of how to establish the Boresight line.

Base Receiver Setup

The base receiver must be positioned at a stable location along the route such that the distance from the base to the extremes of the route is not more than 8-10 miles. The antenna should be located relative to a stable marker on the ground.

Survey Control

Survey control is not required to perform the mobile survey collection, however it is required during the data processing, so this should be accomplished as close as practical in time to the time the mobile survey is conducted. As a minimum the survey should include one point in the should every 1,000 feet along each set of lanes. If practical, a second control point on the opposite shoulder at the same station as the points in the other shoulder is desirable. Optionally the customer may elect to survey points at other locations for independent QC checks.

Survey control should also be established for the base antenna marker and as a minimum, the end points of the boresight line.

Data Collection

Initialize Navigation

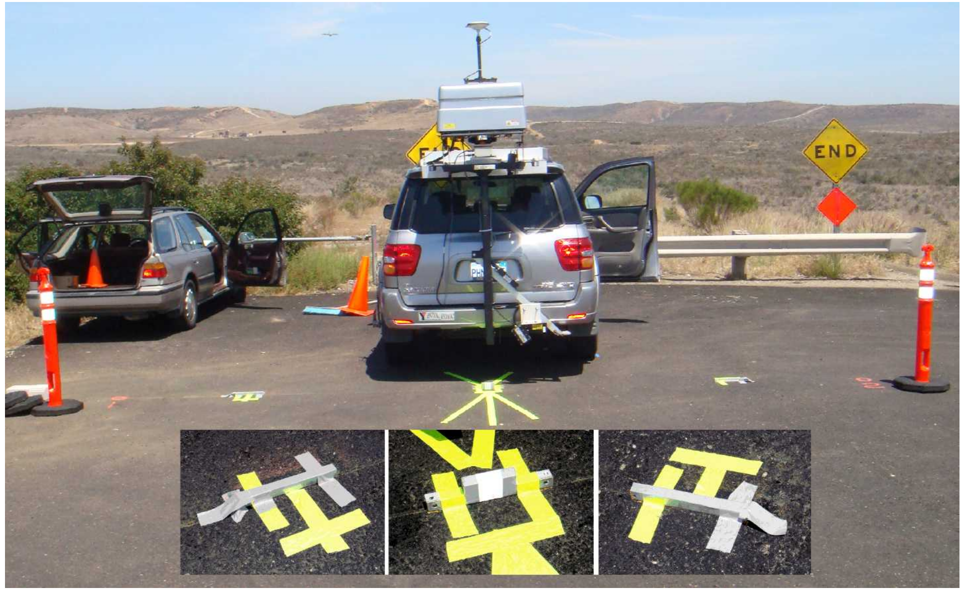
Once in the vicinity of the route to be surveyed, the SPAN system must be started and the IMU aligned. Then with the vehicle sitting stationary, SPAN data recording is started, after a minimum of 2 minutes and nominally 5 minutes, the vehicle can be moved and mobile survey commenced.

Perform Mobile Surveys

The PPS should be operated in Run Control Mode. In this mode, the Run Control switch is used to start and end each mobile survey segment. The Run Control switch causes the Navigation System to record the precise GPS time when each PPS run starts. Proceed to perform mobile surveys and static boresight surveys as appropriate for the project. The boresight process is explained in the next section.

PPS/SPAN Alignment (Boresight)

Objective



The objective is to convert PPS points to the project coordinate system accurately. To accomplish this, careful alignment and measurement is required. Position and attitude is measured by the navigation system relative to the center of the IMU. The offsets from the center of the IMU to the GPS antenna reference point (ARP) must be measured and are used by the Navigation Software to accomplish this. Then the solution is transfered from the center of the IMU to the center of the polygon using the offsets between the IMU and the polygon when the solution is exported. Finally, angular misalignment between the IMU and the scanner coordinate system must be measured and corrected. This part is traditionally referred to as boresighting.

General Procedure

PSI has developed a static boresight process which involves surveying a line, nominally 20 feet long, running either east-west or north-south, and then positioning the vehicle to scan the line my marking the line with raised marks that can be recognized in the real-time PPS profile display as feedback to know that the scan line is positioned on the boresight line. When the profiles measured with the vehicle pointing in opposite directions are coincident, then the proper boresight angles have been established.

Both end points of the line should be marked by steel nail of other stable means, and the end point positions established by accurate conventional survey. Additional points between the endpoints can be established in the same manner or with a horizontal level reference between the endpoints using a laser level or taught string as a reference from which to make vertical measurements.

To assist the driver in the effort to precisely maneuver the vehicle to align the scan line to the boresight line, yellow tape was positioned orthogonal to the boresight line and a video camera mounted to the back of the vehicle provided visual cueing to the driver.

The boresight process not only determines the boresight angles but also provides a check of the GPS to IMU and IMU to Polygon offsets and verifies proper registration of results to the project coordinate system. Once a stable alignment has been accomplished for a given vehicle installation, it is not necessary to repeat the process. However, it is advisable to perform it at least once for each project, as this gives an opportunity to establish that the system is able to produce results precisely aligned to the project coordinate system.

Procedure for this effort

In this project the boresight line was located on the east end of the Miramar Way I-15 interchange, ran nominally north-south. The line was scanned with the vehicle facing east as shown in the top photo on the previous page of the original efforts in 2007 and also facing west as shown in the lower photo on the previous page as configured for the mobile surveys covered by this report. As is obvious, different vehicles were used in 2007 and 2008/9 and the antenna position and scanner height were different as well.

During the final alignment for the results presented in this report, the line was occupied in each direction for 12 minutes. During the navigation post-processing, the boresight occupation times were flagged and processed as static data. This resulted in a very accurate position solution.

Terminate Navigation

Once all mobile and static surveys for a given session are completed, park the vehicle and remain stationary for a minimum of 2 minutes and nominally 5 minutes. Then stop recording navigation data on the mobile system and go to the base and stop recording data there and transfer the base data along with the mobile data to the PC to be used for processing.

Post Processing

The following summarizes the steps involved for the purpose of having an overview of the work involved. This is not intended to be a detailed operational procedure.

- Process the Navigation Data
- Process the PPS Data
- Extract the Boresight navigation results
- Use PPS2Map to transform the Boresight scans
- Iterative adjust Boresight angles in the PPS2Map parameter files until satisfactory boresight results are obtained,
- Use PPS2Map to transform the individual mobile surveys and produce LAS files
- Use MARS to determine Control Point Offsets
- Interpolate Point Cloud to remove elevation offsets
- Process Point Cloud to produce product:
  - 2D profile cuts: transects, edge of lanes/pavement
  - TIN
  - DEM
  - Contours

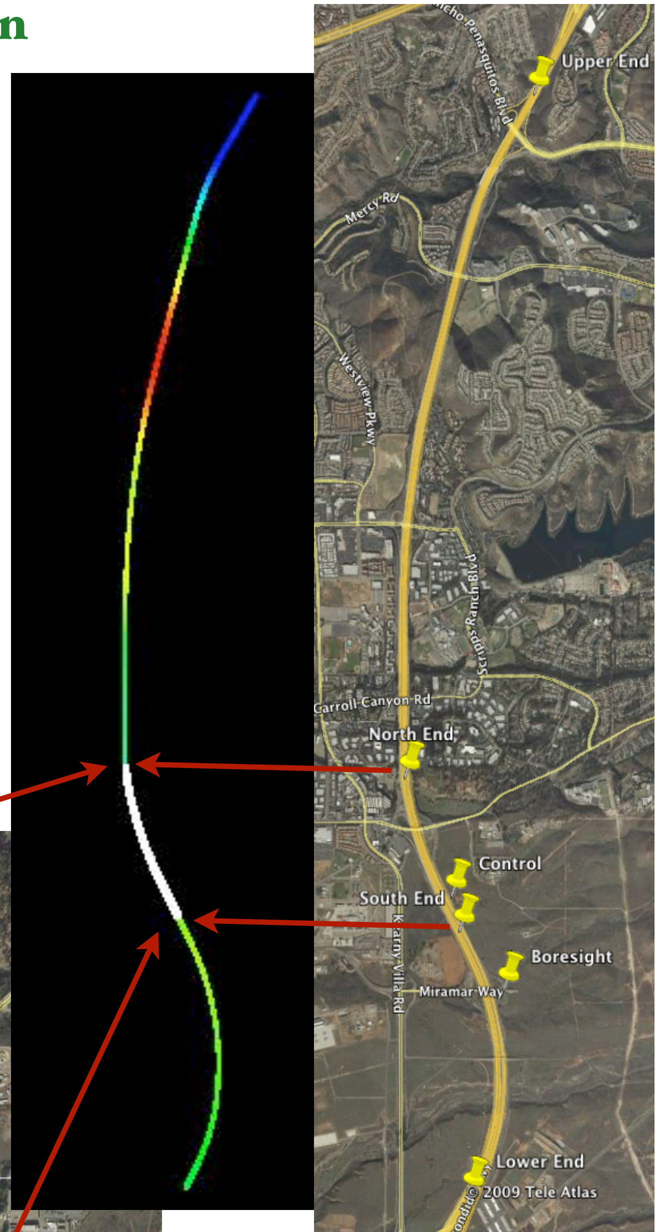
I-15 Project Description

Location

The location selected for this project was a 0.9 mile (1400 km) length of the two reversible HOV Lanes of I15. The southern end of the survey control area was at the toll transponder location just north of Miramar way and it extends north passing under Miramar Road, thereby assuring a GPS outage.

Several features made this location attractive:

1. The control survey could be performed during the mid-day period when the lanes were closed before reversing directions
2. The mobile survey could be performed in both directions
3. Extensive control had been previously establish to support past experimental activities and ongoing construction.



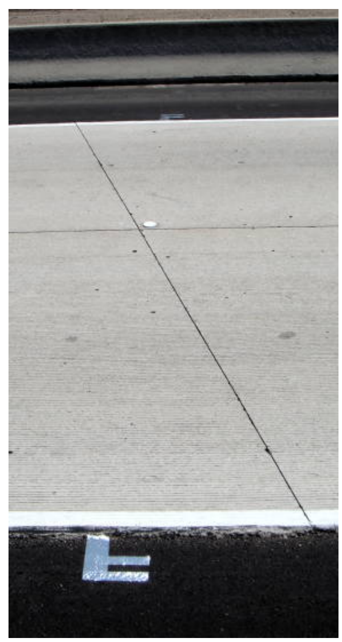
The surveyed section appears white in the point cloud display above due to the dense distribution of control points being displayed.

In order to drive over the surveyed section, it was necessary to drive a 6 mile length of the HOV lanes. This was accomplished by driving a loop where the return was on the regular I15 lanes in the opposite direction. Direction reversal occurred at Kearny Villa Road at the southern end and Ted Williams Freeway (56) at the northern end.

Pavement

The I15 HOV lanes are PCC jointed slab construction. The photographs were taken under the toll transponders at the southern end of the surveyed section.

Some features to note are that:

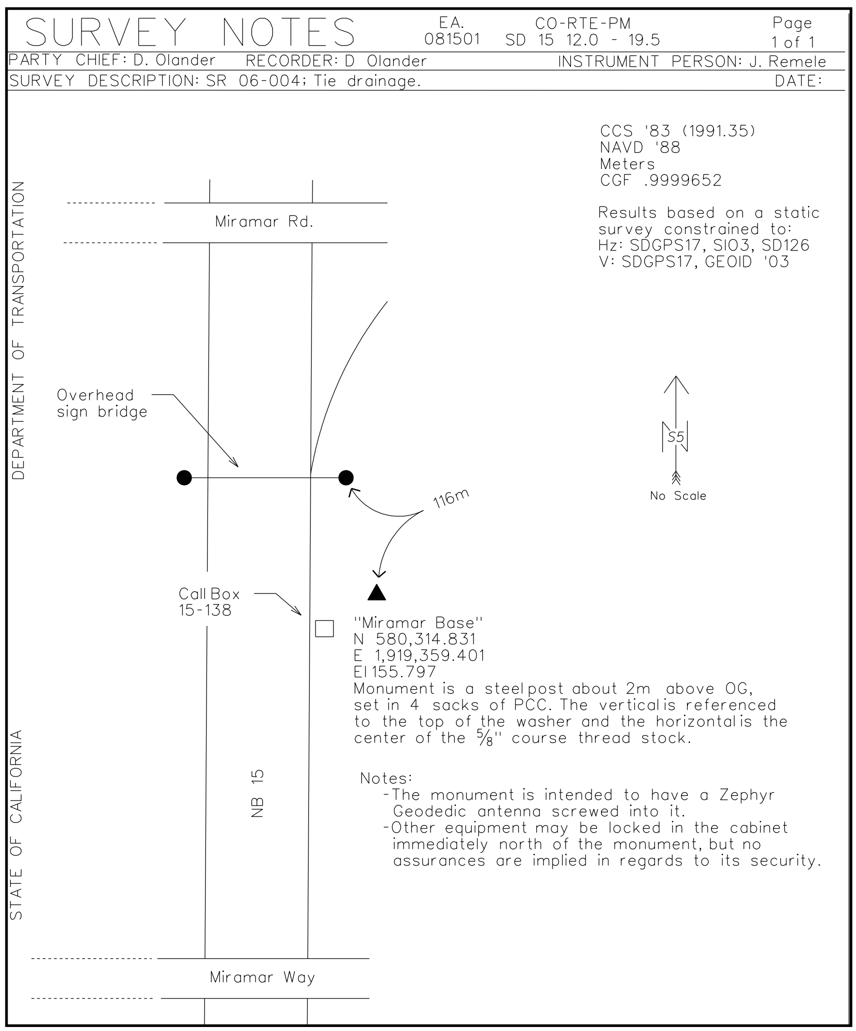


- the pavement has uniform longitudinal grooves,
- the transverse joints and the longitudinal lane separation are wide and deep such that the scanner will measure into the joints,
- the transverse joints are on a diagonal
- there are Bott's Dots dividing the two lanes but no marking between the lanes,
- the PCC is still relatively clean and white in contrast to the black asphalt shoulders,
- there are good quality lane markings painted on the outer edge of each lane

Project Control / Base Receiver

The very stable GPS antenna mount shown in the photograph at the right had been previously established by Caltrans, and is referred to as the “Miramar Base”. Its location is denoted in the views shown in the “Location” section above. It is located about 0.2 miles (300 m) north of the southern end of the surveyed section and 1.7 miles (2,700 m) north of the southern end of the 6 mile section of the HOV lanes that made of the loop driven to scan the surveyed section.

Caltrans furnished the position of the antenna reference point (ARP) in CGS 83 as shown in the drawing to the right.



Control Survey

The control survey of the pavement and boresight line were performed by different surveyors at different times with a different approach to vertical control.

Pavement

The pavement survey was conducted by GPS RTK constrained to the single point "Miramar Base". The elevations of the instrument control points used to measure the pavement were established by differential levels from the “Miramar Base”. Thus the accuracy of the pavement survey control points is approximately .01m horizontal and .003m vertical with respect to "Miramar Base" at the 2 sigma confidence level. Using those points as control, the pavement survey was then conducted with traditional topographical measurement methods using 3" total stations. The observations were kept within 120 meters of the instruments. Those observations added a couple millimeters vertical and nominally 5 mm to the horizontal, but it is difficult to estimate the errors in the horizontal because they are highly related to how attentive the field tech is to the plumbness of his prism pole. All of the equipment was calibrated immediately prior to this survey.

Boresight Line

At the time when the boresight line endpoints were surveyed, it was not clearly specified that absolute elevation was a consideration, and as such, the end points were surveyed directly by GPS RTK, without referencing to the "Miramar Base". As such, the end points, have an accuracy of about .03m in the vertical and .01m in the horizontal with respect to the GPS base. However they do have a precision of .003m vertical and .003m horizontal in between the end points of the the boresight line. As presented later in the results, there was an average 0.027 elevation offset in the mobile pavement survey after alignment to the boresight. It is possible that a level run between "Miramar Base" and the boresight points would confirm that the offset was built into the boresight elevations, but Caltrans was not able to dedicate the time for such a task before this report was completed.

Data Collection Workflow

The final data presented in this report was collected on February 5, 2009. The mobile surveys started at 10:42 AM. Four runs were performed driving southbound, first in the west lane and then alternating in the east, west and finally east lane. They were completed by Noon. Then while the lane directions were closed for reversal, the boresight surveys were performed between 12:56 and 1:35 PM. Finally 4 northbound surveys were completed between 1:57 and 2:49 PM, starting in the east lane and then alternating in the west, east and finally west lanes. Hence including the static navigation periods at the beginning and end, the boresight and mobile survey of 48 miles (8 six mile segments) was accomplished in 4.5 hours, including a break for lunch.

GPS Outages and Multipath

The performance of the during and after periods when the GPS signals are blocked and/or multipath is encountered is critical to successful mobile survey. Through out the 6 mile route there are seven overpasses where the GPS signals are completely block for a brief period. The position of those seven overpasses are listed in table below. Also included in the table are the HOV Toll Transponder structures since that are a potential source of multipath. There are other sign bridges along the route but they have not been tabulated.

The Latitude and Longitude were derived from Google Earth and then converted use the utility in Inertial Explorer to Easting and Northings so that they can be flagged the plots of data from the full length route.

Index	Overpass or Structure	Latitude	Longitude	Eastings (m)	Northings (m)
8	Ranch Penesquito Blvd / Poway Rd	32° 56" 53.53'	117° 6" 21.40'	1919965	587003
7	Mercy Rd / Scripps Poway Pkwy	32° 56" 12.27'	117° 6" 40.55'	1919457	585736
6	Mira Mesa Blvd	32° 55" 01.44'	117° 6" 57.70'	1918994	583558
5	Carol Canyon Road	32° 54" 12.35'	117° 6" 58.53'	1918960	582046
4	Miramar Road	32° 53" 35.44'	117° 6" 54.57'	1919053	580908
3	HOV Toll Transponder Structures	32° 53" 06.35'	117° 6" 39.81'	1919429	580009
2	Miramar Way	32° 52" 49.99'	117° 6" 30.45'	1919668	579503
1	NCSA Miramar Minor Road	32° 52" 30.86'	117° 6" 25.93'	1919781	578921

I-15 Mobile Survey Results

First the boresight results are presented and then the mobile results are presented in two sections. The first set of mobile results cover just the area surveyed by Caltrans and are relative to an absolute reference. The second set of mobile results covers the entire 6 mile project, but are limited to performance of three runs relative to a fourth run in each lane which was used to generate control.

Boresight Alignment

The final results of the boresight alignment are plotted in the figure on the next page, Note from the plan view in the top plot that the boresight line was not perfectly aligned north-south. There is nominally a 0.36 meter cross slope over the 4.8 meter scan line. Hence the line is rotated 4.3 degrees from north, This is the first boresight line we had ever established. It was established in the spring of 2007 when we began rigorous development of the mapping system and the value in more precisely aligning the line to be closer to orthogonal to the local coordinate system.

The middle plot is also a plan view plot of the same data as in the top plot, but in this case the deviation of the measured line from the survey line is plotted to remove the bias caused by the misalignment of the boresight line. In this plot it can bee seen that the two lines are within 1 cm of each other and at a slight angle, 0.1 degrees, relative to each other. This under scores the precision with which the mobile vehicle must be maneuvered to position the scan line on the blocks.

Note that when facing east, the scan line must have been partially off of the blocks and hitting the pavement. This caused the east-west position to shift since the range was biased to be longer than expected. Unfortunately this affect was so subtle that it was not visible in the real-time cross profile display, as the magnitude is just 2 mm in the lateral orientation.

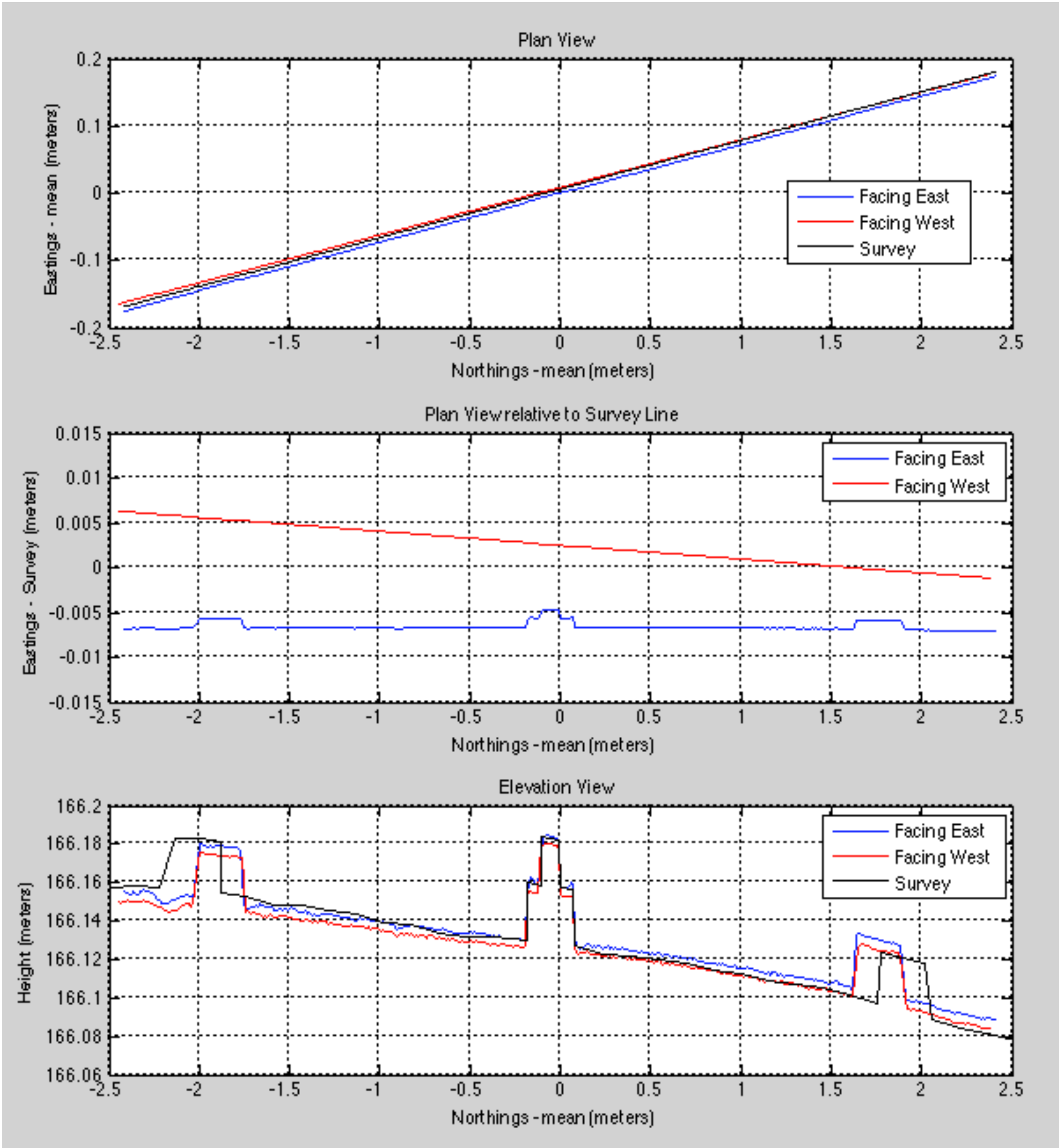
The plan view is used primarily to adjust for yaw and pitch misalignment. The bottom plot, which is the cross section view, is used to adjust roll misalignment. Note that the outer blocks were placed so that they were centered on the location where during the reference survey in 2007, the inner edges of the blocks were placed. This change does not affect the ability to inspect the alignment of the profiles relative to each other and the survey line.

In this case, it was decided to align the east and west lines to each other, which resulted in them being rotated relative to the survey line by about 0.06 degrees. An alternative approach would have been to increase the roll correction such that the survey lines would have been rotated in opposite directions from the survey line by ±0.03 degrees.

The final boresight angles that were used to produce these results and process the rest of the data in the subsequent analysis presented below were:

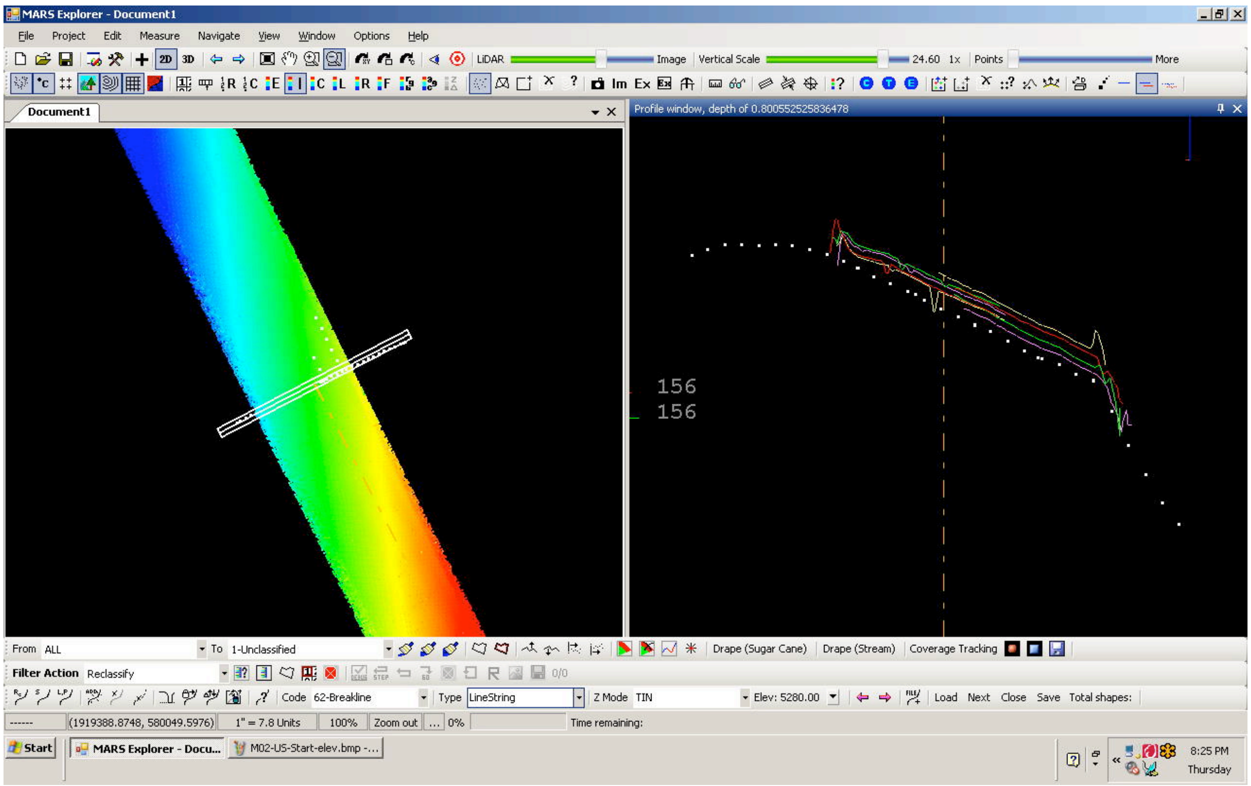
- Roll -1.250°
- Pitch -0.250°
- Yaw -0.010°

Given that the IMU is mounted flush to the optical strong back of the scanner which defines the scan plan, it is not surprising the the Yaw correction is quite small.


Plan View
Eastings - mean (meters)
Northings - mean (meters)
Facing East
Facing West
Survey
Plan View relative to Survey Line
Eastings - Survey (meters)
Northings - mean (meters)
Facing East
Facing West
Elevation View
Height (meters)
Northings - mean (meters)
Facing East
Facing West
Survey

Absolute Elevation

All 8 survey runs were loaded into MARS along with the master control file. The following screen capture of MARS shows the plan view of the collective point cloud in the region of the southern end of the 0.9 mile (1,400 km) surveyed control section in the left half. The narrow white rectangle in the plan view selects the data that is "cut out" for display in the cross section view in the right half. At the southern and northern ends and approximately 1/3 and 2/3 in between, there is a dense control cross profile that runs between the outer edges of the shoulders, which was essential from K-rail to K-rail, which established the HOV lanes confinement. Note that all 8 runs are parallel to each other and the control line, and that they are all scattered above the control line.



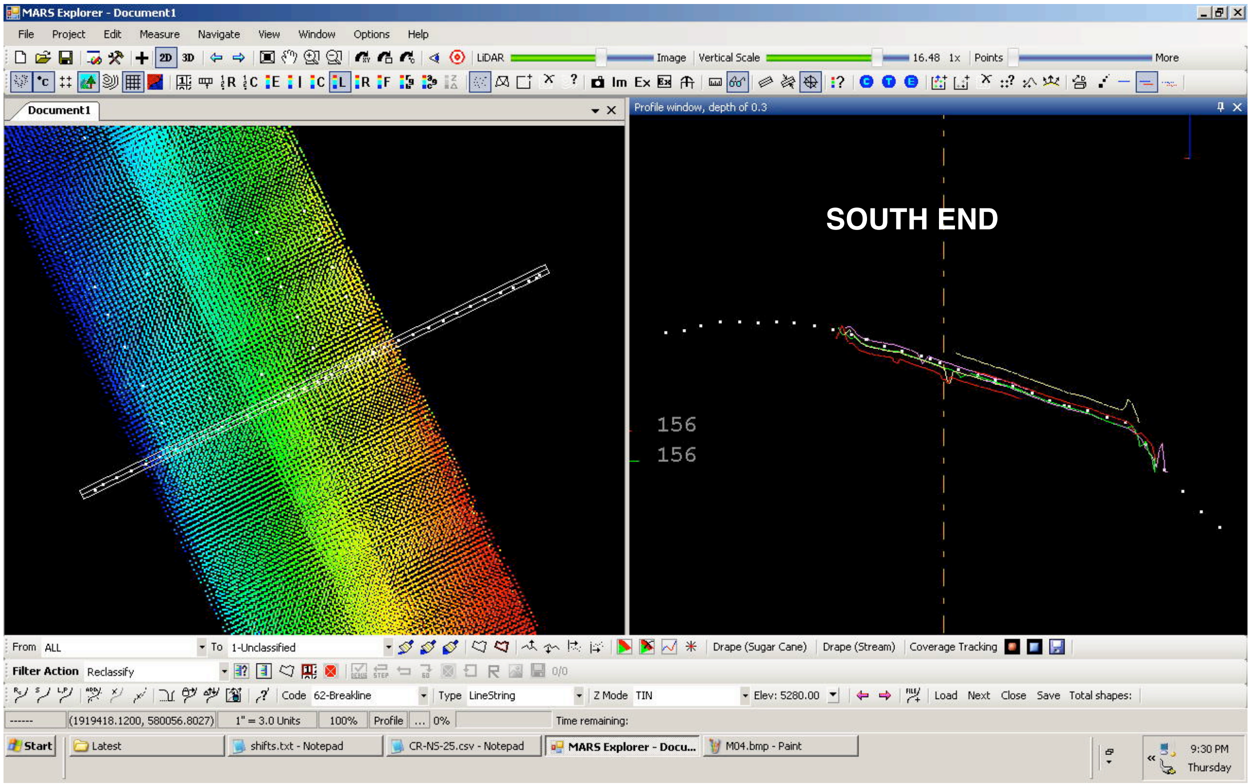
One run at a time was enabled in MARS and a control Report was generated for each run.

The average elevation error for each run computed by the control report is summarized in the table at the right. The average elevation bias relative to the control was 0.089 ft (2.7 cm). Individual survey run averages ranged from 0.055 to 0.131 ft (1.7 to 4.0 cm), which is a spread of 0.075 ft (2.3 cm).

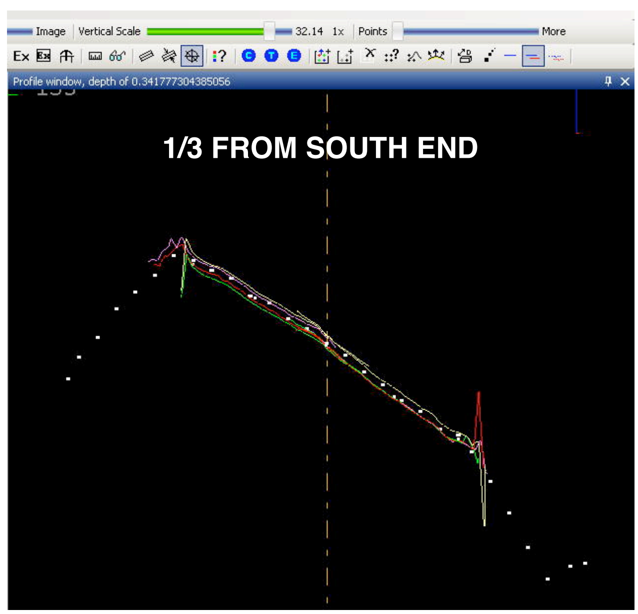
The base station, pavement, and boresight line surveys were all performed at different times and by different people. Further the pavement and bore sight line surveys were completed by RTK without base so this type of relative elevation offset for the pavement results after the boresight was adjusted to match, is not unreasonable.

Run #	Drive Direction	Lane	Elevation Bias (cm)
10	South	West	1.7
11		East	2.5
12		West	2.8
13		East	4.0
22	North	East	2.5
23		West	1.8
24		East	3.9
25		West	2.5
Overall Elevation Bias			2.7

For all further analysis, the individual average elevation bias values were applied to each survey run LAS file as a constant correction for all the points with in the run. This was very easily done within MARS as a single quick step. It seemed as though it was simply a matter of noting the value in the file header. All further analysis is based on the average shifted LAS files. The shifted data at the southern end as shown in the following figure is now tightly clustered about the control, with the exception of two survey runs. The plan view magnification has been increased some to reveal the discreet survey points and the more sparse white control points can be seen outside the cut rectangle.

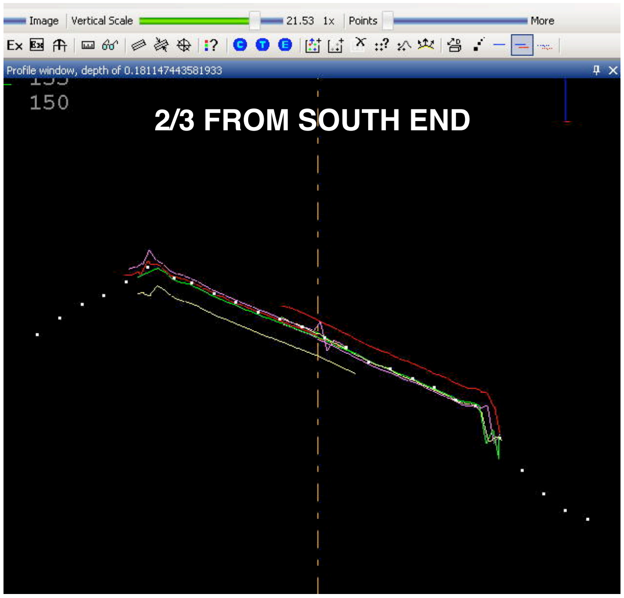


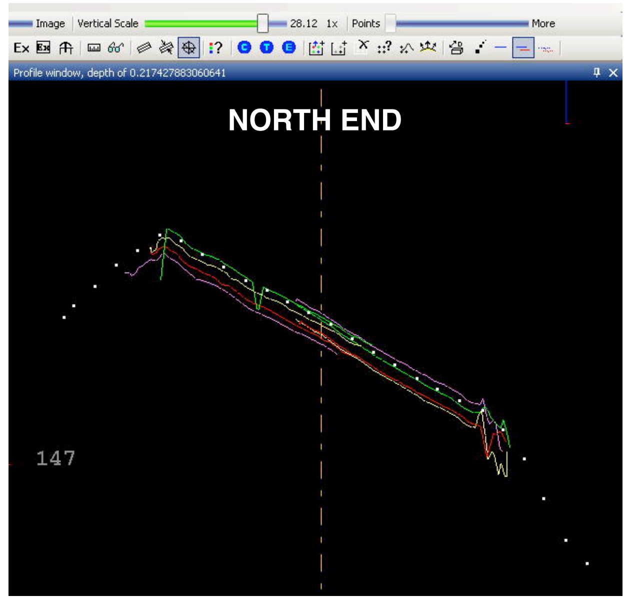
The display at the right shows the shifted profiles at the station 1/3 of the way north of the southern end where the profiles are clustered about the control.



The displays at the top of the next page show the results at 2/3 north of the southern end and at the northern end where as at the southern end some of the survey runs are outliers.

These cross profile displays reveal that all the survey profiles are parallel to the control, indicating that the system reliably measures cross slope. However this is a relatively small sample of the total set of mobile survey results. To more clearly present all the results, the entire set of error values from each control report have been plotted.

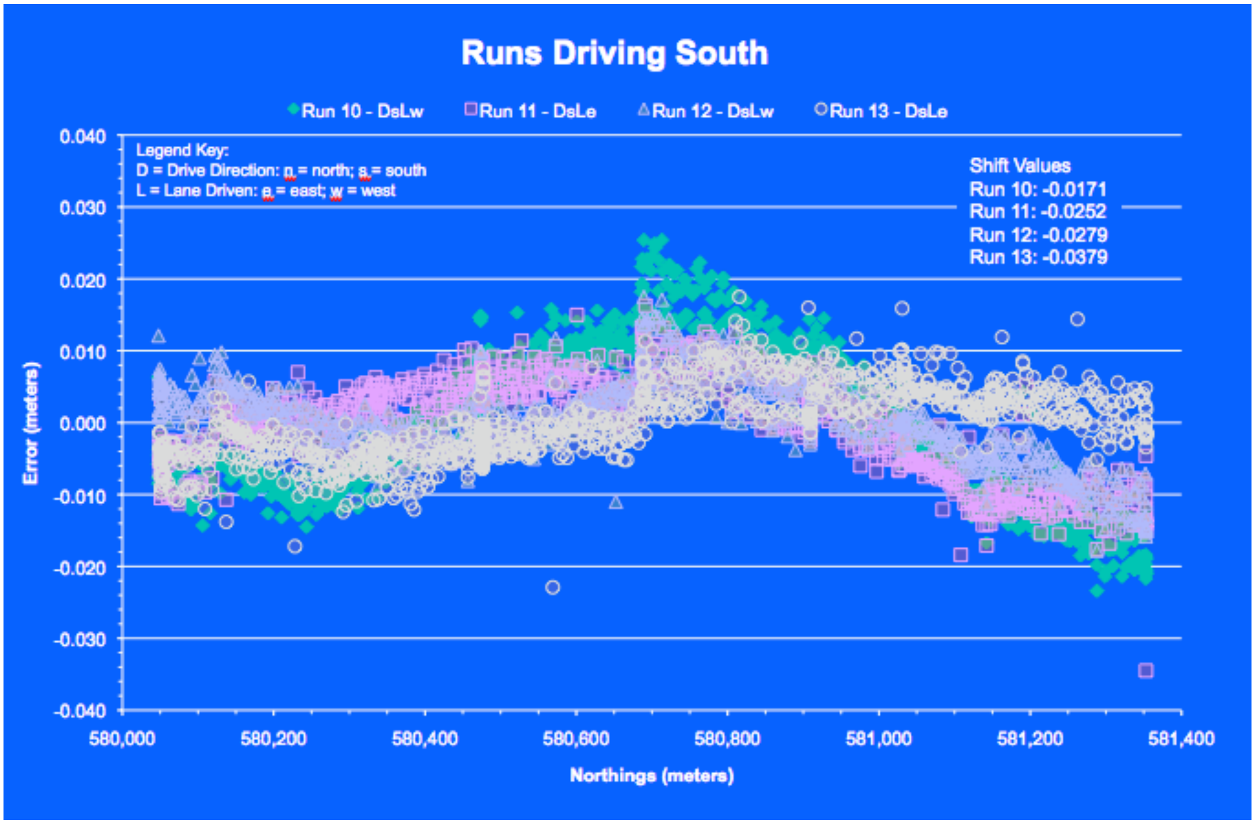


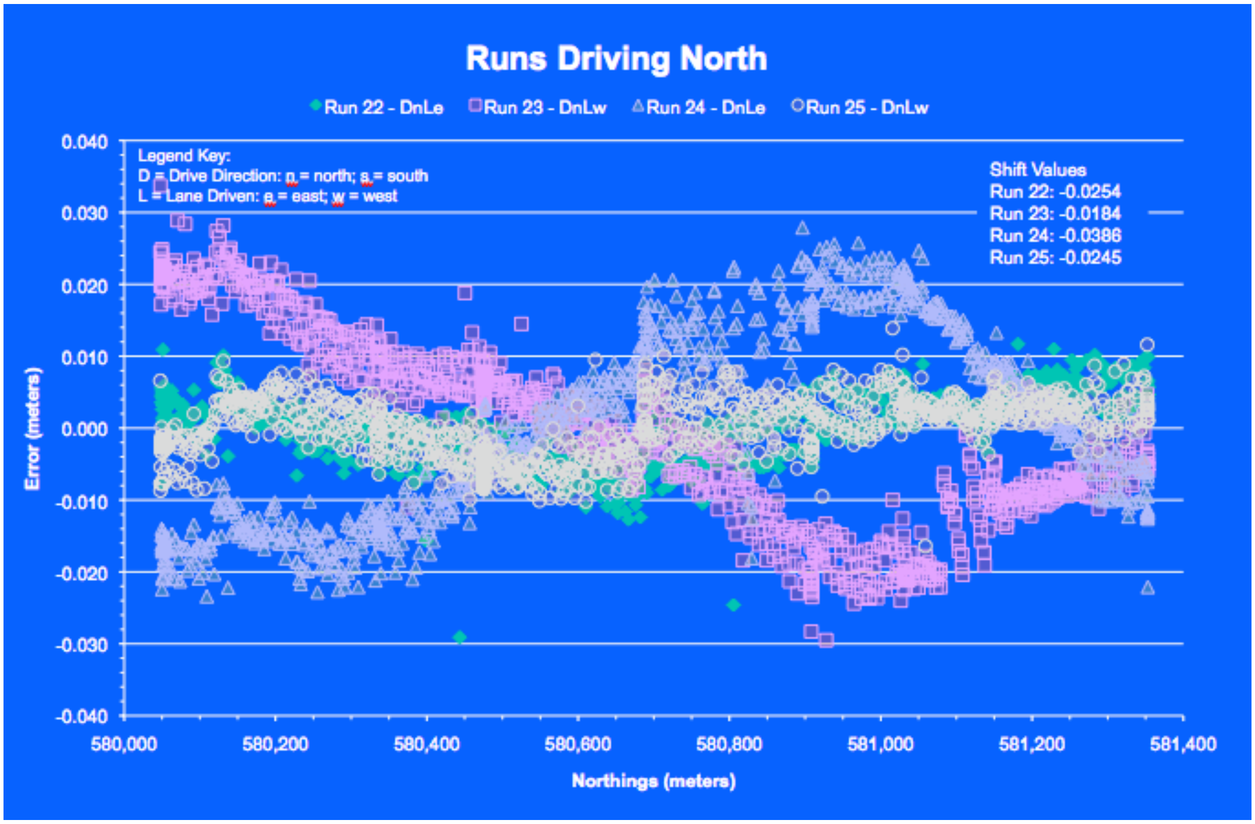


The first plot on the next page presents the deviations from control in the survey runs that were performed while driving south. Note the 0.033 foot (1 cm) discontinuity at about 580,670 meter northings. This corresponds to the location of the overpass for Miramar Road, which would cause a brief GPS outage. All south bound survey runs show a remarkably similar pattern even though two were performed in the morning and two in the afternoon. The second plot on the next page shows the north bound survey runs. Two of those runs, 22 and 25 are nearly identical and the peak-peak range neglecting outliers is just ± 0.033 foot (±1 cm). However the other to runs show a low frequency undulating deviation on the order of ±0.13 feet (±4 cm). It is these results which made it clear that the relative analysis presented in the next section was essential to understand the performance of the system.

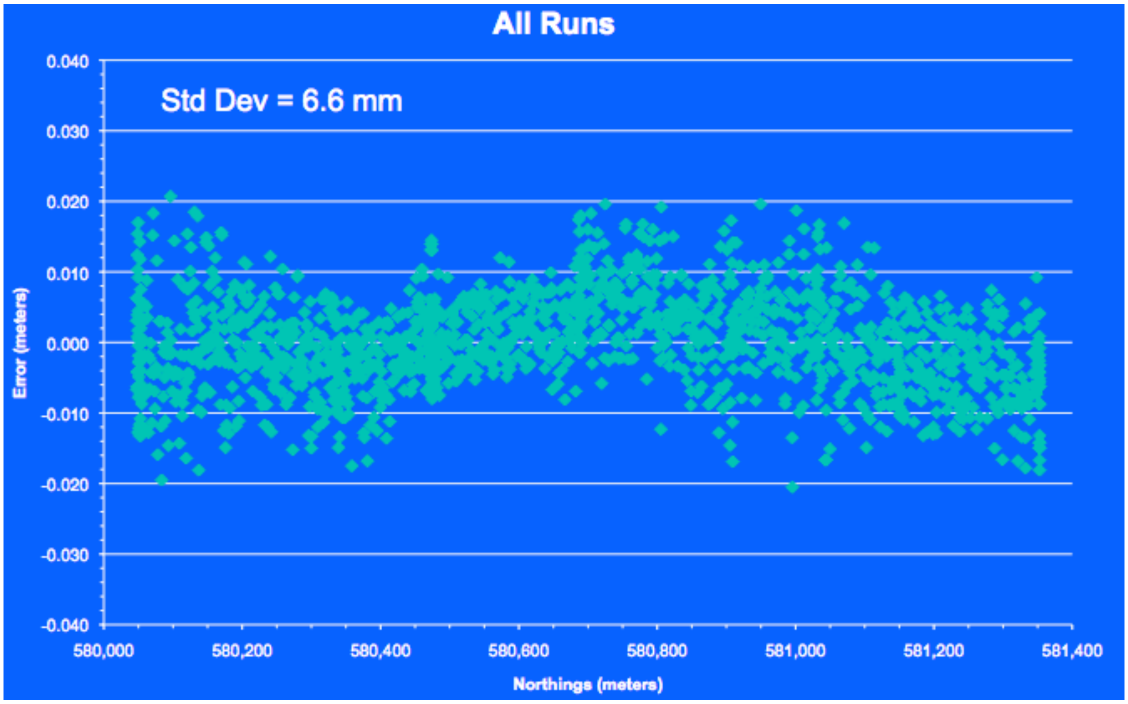
The peak-peak ranges, standard deviations and other details for this data is summarized in the table below. Many of the outliers can be attributed to the large open gaps between pavement slabs, but considering the large number of control points, the number of outliers are small and have a minimal affect on the statistics.

Run Number	10	11	12	13	22	23	24	25	All	6 of 8	5 of 8
Direction	South				North				Both	Both	Both
Lane	West	East	West	East	East	West	East	West	Both	Both	Both
Time (sec)											
Start	414447	415468	416459	417503	424372	425433	426453	427523	n/a	n/a	n/a
End	414497	415518	416509	417547	424417	425482	426504	427572	n/a	n/a	n/a
Duration	50	50	50	44	45	49	51	49	n/a	n/a	n/a
Control Points, Total	1702										
No. with Coverage	940	957	958	956	956	958	956	957	1606	1606	1604
% of Total	55.2%	56.2%	56.3%	56.2%	56.2%	56.3%	56.2%	56.2%	94.4%	94.4%	94.2%
Error Statistics											
Average Offset	0.0171	0.0252	0.0279	0.0379	0.0254	0.0184	0.0386	0.0245	0.0000	0.0000	-0.0001
Maximum	0.0254	0.0163	0.0175	0.0175	0.0117	0.0337	0.0279	0.0139	0.0207	0.0214	0.0161
Minimum	-0.0234	-0.0345	-0.0178	-0.0229	-0.0291	-0.0295	-0.0234	-0.0164	-0.0205	-0.0184	-0.0143
Range	0.0488	0.0508	0.0353	0.0404	0.0408	0.0632	0.0513	0.0303	0.0412	0.0398	0.0304
Standard deviation	0.0104	0.0069	0.0056	0.0052	0.0047	0.0129	0.0129	0.0043	0.0066	0.0054	0.0044

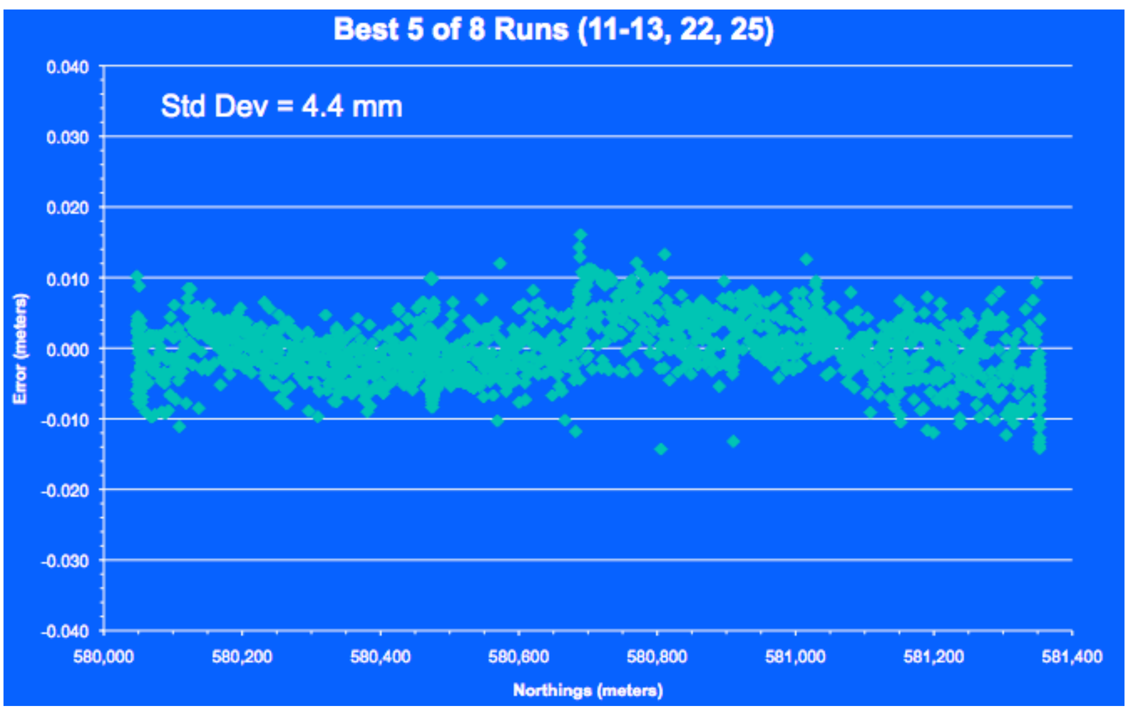

Runs Driving South
Run 10 - DsLw
Run 11 - DsLe
Run 12 - DsLw
Run 13 - DsLe
Legend Key:
D = Drive Direction: n = north; s = south
L = Lane Driven: e = east; w = west
Shift Values
Run 10: -0.0171
Run 11: -0.0252
Run 12: -0.0279
Run 13: -0.0379
Error (meters)
Northings (meters)


Runs Driving North
Run 22 - DnLe
Run 23 - DnLw
Run 24 - DnLe
Run 25 - DnLw
Legend Key:
D = Drive Direction: n = north; s = south
L = Lane Driven: e = east; w = west
Shift Values
Run 22: -0.0254
Run 23: -0.0184
Run 24: -0.0386
Run 25: -0.0245
Error (meters)
Northings (meters)

Note that the standard deviations of Runs 22 and 25 are less than 0.016 feet (5 mm). Next a control report for the data for all 8 survey runs combined was computed and it is plotted below.



Then a control reports for the best 6 runs, eliminating Runs 23 and 24 was computed and finally a control report for the 5 best runs , eliminating 10, 23 and 24 was computed and it is plotted below. The standard deviation for this data is again less than 0.016 feet (5 mm) and the peak range neglecting outliers is ± 0.033 foot (±1 cm).



Relative Elevation

Background

Based on the results from the 0.9 mile (1,400 meter) section where undulations in elevation of ±0.01 feet (±3 cm) were measured, the natural next question was concerned with how much greater the elevation errors would become if measured over additional time and distance. This question was anticipated based on experience during the development process and the first commercial job done for Kansas DOT in 2007. Hence for these surveys, data collection was performed for the complete 6 mile stretch of the I15 HOV lanes between the entrance and exit points were we were able to turn around. These extremes are denoted on the aerial project view with push pins labeled Lower End and Upper End on page 13.

When it was decided that mobile survey of the full 6 mile route would be performed, the potential for Caltrans to survey additional control along the full route at a lower density, compared to the original 0.9 mile stretch, was explored, but resources for such an effort were not available. So instead, an analytical plan was developed to allow quantification of the precision or repeatability component of accuracy for the mobile surveys.

Approach

Four repetitions of mobile survey were performed in both the east and west lanes of the 6 mile route. One of the four surveys of in each lane were selected to form a base line to which the others could be compared, so as to determine the range of variability in the measurement of elevation. Fundamentally, the survey run selected could be selected on a random basis, however since Run 22 in the east lane and 25 in the west lane exhibited the best absolute elevation results (see the lower graph on page 22), they were used for the baselines in their respective lanes.

Control files that could be read by MARS were developed for both Run 22 and 25. First each run was reprocessed by selecting one scan every 16 feet (5 meters) and gridding each scan with points separated by 1.6 feet (0.5 meters) with 6 inch wide bin averaging. This resulted in 7 points per scan located at 0, ±1.6, ±3.2, and ±4.9 feet (0, ±0.5, ±1.0, ±1.5 meters) in the scanner coordinate system. Since the surveys were performed with the vehicle nominally centered in the 12 foot (3.7 meter) wide lanes, these points are located within and nominally centered in the lanes. Even at this relatively sparse density, these output files contained nominally 13,80 points per lane.

Next PPS2Map was used to transform these points into the project coordinate system using the same navigation solution used for the Absolute Elevation analysis. However instead of generating LAS files, the option to generate text tab delimited files was selected.

Then the text tabbed files were opened in Excel and a column was added at the beginning of the file and a unique control point number, starting from one and increments by 1 to the end of each file, was created in the new column. Finally, the files were saved a comma delimited (.CSV) at which point they can be opened by MARS as control files.

Relative Results

The control files were opened in MARS and then a control report was generated for all eight survey runs, one at a time. The results are summarized in the table on the next page and they are shown plotted on page 26. Note that the GPS outage events caused by overpasses identified in table on page 16, are identified on the plot by numbered double ended arrows between the upper and lower graphs.

Based on the actual lengths of Runs 22 and 25, the control files contain 13,818 and 15,169 points respectively. The statistics of Runs 22 and 25 are for those runs relative to control derived from themselves. The coverage is nearly 100%. A few points at the ends did not have coverage. The average offsets are essentially zero as expected. The range, which is simply the maximum minus the minimum values, are significantly large, 10 and 8 cm for Runs 22 and 25 respectively. By inspection of the plot, it is apparent that this id due to a handful of outliers which probably result from some control points being skewed by profile measurements into the wide deep slab joints. But most reassuring is that the standard deviations are 1.5 and 1.2 mm for runs 22 and 25. They have been highlighted yellow in the table to make them more obvious. This residual is most likely an artifact of the binning to create the control versus the triangulation interpolation process conducted by MARS to generate the control report.

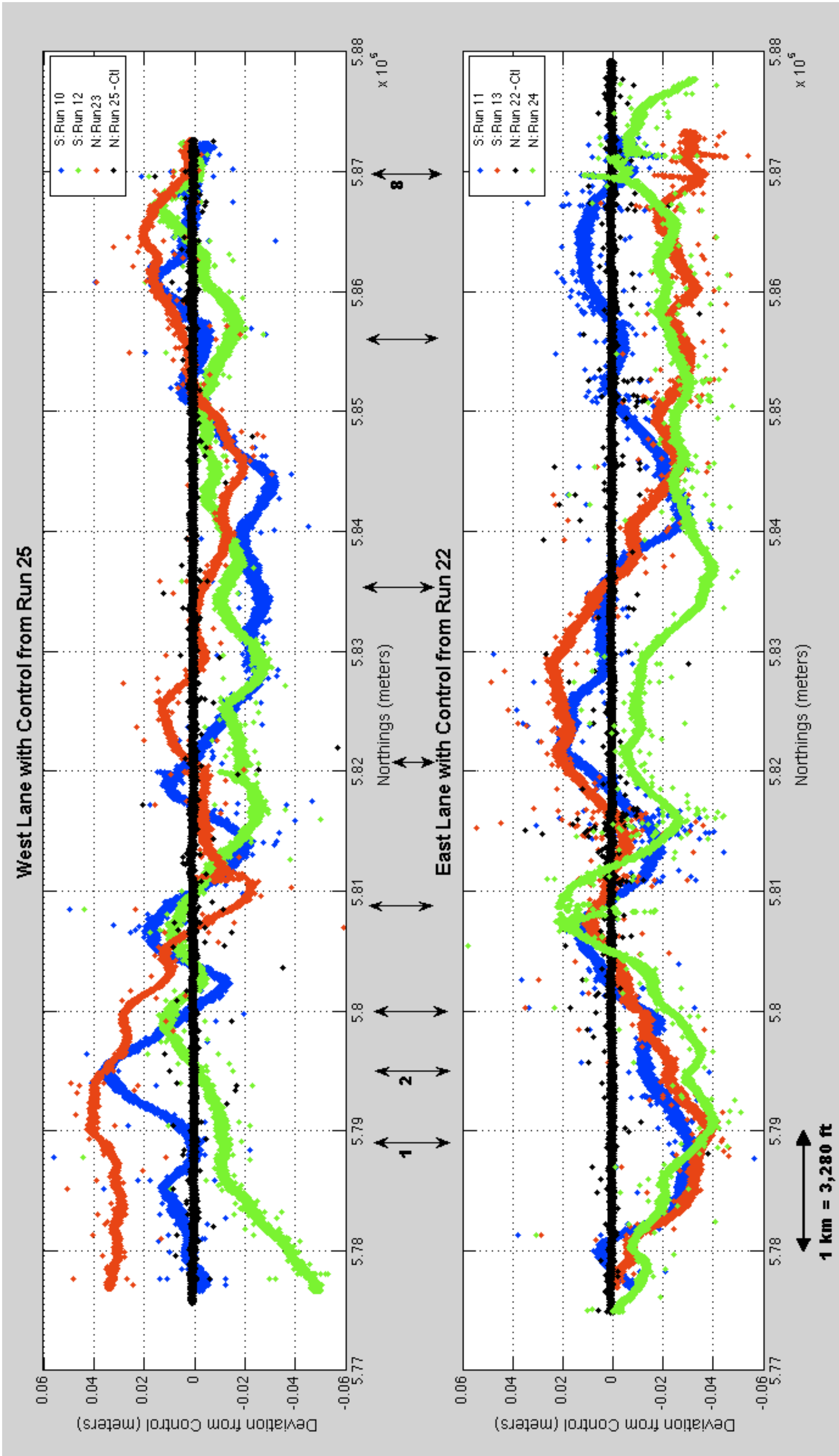
Now examining the control deviations statistics fro the three other runs in each lane relative to the control survey run, the following can be readily noted:

- The average offsets range between -1.8 to -0.9 cm. While not perfectly zero, this shows that the elevation long term error has a minimal bias component.
- Just considering the Range as presented in the table, which is 13.4 cm on average for all the runs with a standard deviation of 1 cm, the performance is not very good. However by inspection of the plot on page 26, which was limited to ±6 cm, it is apparent that the actual range is on the order of 8 cm or ±4 cm, and the statics in the table are affected by the relatively small number of outliers.
- The standard deviations of the individual runs ranges from 1.5 to 2.2 cm, which tends to reflect the range observations arrived at by inspection of the plot.

Run Number	10	12	23	25	11	13	22	24
Direction	South		North		South		North	
Lane	West				East			
Time (sec)								
Start	414249	416268	425358	427440	415271	417305	424289	426366
End	414574	416585	425673	427755	415597	417623	424634	426730
Duration	325	316	315	315	326	319	346	365
Control Points, Total	13818				15169			
No. with Coverage	13549	13548	13587	13813	13685	15164	15164	14875
% of Total	98%	98%	98%	100%	90%	100%	100%	98%
Error Statistics								
Average Offset	-0.0026	-0.0098	0.0091	0.0006	-0.0045	-0.0113	0.0006	-0.0182
Maximum	0.0838	0.0752	0.0890	0.0208	0.0659	0.0662	0.0348	0.0576
Minimum	-0.0469	-0.0655	-0.0594	-0.0567	-0.0618	-0.0539	-0.0682	-0.0764
Range	0.1307	0.1407	0.1484	0.0775	0.12770	0.1201	0.1030	0.1340
Standard deviation	0.0150	0.0162	0.0193	0.0012	0.0142	0.0210	0.0015	0.0222

The underlying quality of these results can be seen by inspection of the plot on the next page. Note that the band of data for the individual runs is only slightly broader that that of the runs 22 and 25 which represents the noise of the process of creating a gridded set of control points with bin averaging and then computing the control report from the same data with the MARS triangulation interpolation process. The standard deviations of Runs 22 and 25 were 1.5 and 1.2 mm, and it is reasonable to estimate that if the low frequency fluctuation if the elevation error were filtered or had the trend removed, that the residual standard deviation of the other runs would be less than 5 mm.

Considering that the main division of the x axis of the plot represents 3,280 feet (1 Km), if there were one control point every 1,000 feet (330 m), that is roughly three points per division, then by linear interpolation of the error between points, it would be reasonable to assume that the error could be controlled to within ±0.033 feet (± 1 cm). PSI has already applied this process to its first commercial job for Kansas DOT although there was not the dense control as in this project with which to establish strong statistical validation of the approach. That job was completed in Excel and was very time consuming. Currently PSI is working out an efficient work plow automation that will make this process very efficient.


West Lane with Control from Run 25
S: Run 10
S: Run 12
N: Run23
N: Run 25-Ctl
Deviation from Control (meters)
Northings (meters)
x 10^5
1
2
8
East Lane with Control from Run 22
S: Run 11
S: Run 13
N: Run 22-Ctl
N: Run 24
1 km = 3,280 ft

Observations and Conclusions

This objective of this section is to provide a brief description of the lessons learned from this project, with particular focus on that which is important to the planning and performance of precision production mobile survey. To be clear, by production it is meant the the surveys are conducted in an efficient, cost-effective, and timely manner as would be required to make this process a backbone of modern road design, construction and rehabilitation.

- Proper planning for performance of the control survey is critical, particularly in that the mobile survey elevation accuracy is only as good as that of the control points. Both the bore sight line endpoints and the pavement control points should be referred by differential level or comparable means to the stable reference point used to position the base receiver.
- Daily plots of GPS coverage quality should be prepared in advance of performing mobile surveys and data collection should be suspended during the typically brief periods when coverage is degraded.
- One control point per 1,000 feet (300 m) is adequate to assure that post-processing can adjust for residual GPS related elevation errors. Typically the control should be located 1-2 feet (0.3-0. m) into the shoulder to minimize risk to surveyors and impact on traffic. When practical and as supported by project budget, matching control points on the opposite should would be desirable as a cross-check. In areas where GPS coverage may be compromised, such as under leaf canopy, or in tunnels or urban canyons, more frequent control may be warranted.
- The focus of this project has been on the accuracy of elevation as this is an obvious critical parameter in the road construction business. Recent project planning related to the support of AC pavement construction and rehabilitation has revealed that cross slope measurement accuracy is also very important. Both by inspection of the cross profile plots in this report and by examination of the potential error sources in this system related to cross slope measurement, it is clear that the this system performance exceeds the typical cross-slope tolerance requirements.

Acknowledgements

The scope of this project was made possible with the following vital support, and we are very grateful to the following individuals and organizations for this support.

Caltrans

Caltrans collected and made available the survey control used in this project. This data is publicly available to any and all entities. Caltrans neither funded or authorized PSI to conduct the mobile surveys.

Headquarters

Kevin Akins is a surveyor who leads the charge at Caltrans headquarters to evaluate and incorporate new technologies such as laser scanning. His vigilance at discovering new technologies and communicating about this to the districts. Kevin was instrumental in making District 11 surveyor Dave Olander aware of PSI's efforts to develop mobile survey in early 2007. Further, Kevin provided useful feedback though his efforts to evaluate preliminary mobile survey results in 2007, well before PSI was able to bring the MARS software to bear on the problem.

District 11

Dave Olander had developed a conviction that mobile survey should be technologically feasible and was looking for a source for this technology to minimize the hazards to Caltrans surveyors tasked with surveying the busy highways of California. When Dave learned from Kevin of our efforts he offered to generate a suitable set of control data so that PSI and any other vendor could evaluate and demonstrate the requisite technology. Dave's management, Ned Salman and Bruce Urguhart in District 11 supported Dave's efforts to generate this data.

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Merrick

Mark Romano and Bill Emison provided access to the MARS software for this project and also evaluated samples of PSI LAS files. which helped us develop the LAS output software. In turn this effort enabled them to evaluate the potential of our scanner technology and drove improvement to MARS to accommodate the higher resolution of the PPS data compared to aerial lidar for which MARS was designed. At the time of this report, Mark Romano has left Merrick to become CTO of Earth Eye.

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