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16. ABSTRACT

Snow Plow driver guidance system has two major components: a roadway relative position determination system (RRPDS) and a human machine interface (HMI). The RRPDS must maintain an estimate of the vehicle state (i.e., position, velocity, heading, and heading rate) relative to the roadway with position accurate to a few centimeters. The HMI presents the data from the RRPDS to the driver in a visually appealing and easily perceivable format. This is a three phase effort with the objective of producing a Carrier Phase (CP) Differential Global Positioning System (DGPS) aided Inertial Navigation System (INS) implementation of the RRPDS that is able to maintain centimeter level position accuracy along highways through mountain environments. The main advantage of the system underdevelopment relative to previously demonstrated systems is that the CP DGPS aided INS approach would not require any alterations of the highway infrastructure. Along the demonstration corridor, the phase II effort demonstrated that: By the use of a single radio modem repeater and differential correction prediction technology, differential corrections could be reliably received to achieve the desired level of performance. Along the vast majority of the highway included in the demonstration, GPS signal reception was sufficient to be able maintain the desired centimeter level system accuracy. The selected portion of the I80 did not include overpasses or overhead street signs due to limitations of the GPS receivers available to the project during Phase II. To achieve this successful demonstration, the Phase II effort: evaluated alternative methods for communication of the base station corrections, selecting the Freewave modem approach for the final demonstration; studied the effect of modem repeaters on system performance and designed a modem/repeater configuration to support the demonstration; developed a Windows based HMI with enhanced features; and advanced the state-of-the-art in GPS aided INS signal processing. In addition, we performed research on the suitability of certain augmentation technologies, most notably Pseudolites, as they relate to the objectives of this project.

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& Innovation

Differential Carrier Phase GPS aided Inertial Navigation for Snowplow Guidance

Final Report

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Final Report

Report No. CA04-0289

December 2008

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Differential Carrier Phase GPS aided Inertial Navigation for
Snowplow Guidance
Final Report

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1 Executive Summary

The project is concerned with the development of vehicle navigation systems to serve as the vehicle location input for driver assistance systems for highway maintenance vehicles. These systems would have value, for example, for safety or law enforcement vehicles traveling in extreme fog or snow removal equipment operating in heavy snowfall. The objective of the navigation system is to reliably maintain cm level accuracy for the vehicle location estimate.

Based on past successful demonstrations at Crows Landing of differential carrier phase global positioning system (DCPGPS) aided inertial navigation systems (INS) maintaining cm level accuracy for vehicle control applications, Caltrans suggested that the approach be further developed and tested to work reliably in more challenging environments, such as that at Donner Pass. A major objective of the first phase of this project was a site survey to assess the feasibility and challenges of working at the Donner Pass location. That analysis is contained herein.

The main conclusions are

1. The GPS signal availability is sufficient for the DCPGPS aided INS to maintain cm level accuracy, except on certain short sections of the tested roadway. These roadway sections are repeatable between runs. This repeatability was a desired outcome. The fact that the roadway sections are repeatable between runs means that at least one of the augmentation methods suggested in the original proposal (e.g., pseudolites, roadway altitude, or magnetometer along isolated road sections) or advances in GPS receiver and satellite technology should yield a reliable working system along the entire roadway from Sierraville to Grass Valley.
2. The Caltrans base station in Donners Pass is sufficient to allow testing of the approach along limited sections of I80; however, certain sections of the roadway do not reliably receive the base station signal. This should be fixable by installing repeaters.

These conclusions are based on analysis of eleven datasets acquired at different times and on different days between August 26–August 28, 2003 on the I80 between the Sierraville and Grass Valley exits.

Based on these conclusions, future project goals are:

1. to investigate and develop the augmentation methods for use with the DCPGPS aided INS;
2. to investigate the use of advanced GPS and INS technologies;
3. to modify the UCR DCPGPS aided INS so that it is able to receive the differential correction data from and operate with the Caltrans base station at Donners Pass; and
4. to investigate alternative sources of differential corrections.

The objective is to begin successful demonstrations of the DCPGPS aided INS on limited sections of the I-80 through Donner Pass in the Phase II of the project. We expect to be able to demonstrate on longer sections of the I80 through Donners and to improve performance and reliability as the augmentation methods are further improved and incorporated over the duration of this project.

2 Introduction

Snowplows typically operate in extreme environments in terms of temperature, humidity, vibration, and visibility. In extreme whiteout or fog conditions, it would be useful to provide the driver information about his roadway relative position. A magnetometer based roadway relative positioning system developed by PATH and AHMCT has previously been demonstrated in the snowplow guidance application with Caltrans sponsorship. The existing approach has two main components. The first component is a magnetometer based roadway-relative vehicle position sensor. The second component is a display of the roadway relative position to the driver.

The utility of a snowplow/snowblower driver guidance system is clear. Such a system can provide the driver with roadway relative position and velocity information when the driver's visual perception of these quantities is impaired by weather conditions. Such a driver guidance system has two major components: a roadway relative position determination system (RRPDS) and a human machine interface (HMI). The RRPDS must maintain an estimate of the vehicle state (i.e., position, velocity, heading, and heading rate) relative to the roadway with position accurate to a few centimeters. The HMI presents the data from the RRPDS to the driver in a visually appealing and easily perceived format. Previous CALTRANS-supported projects have demonstrated a magnetometer based snow-plow/snowblower RRPDS and a HMI. Previous CALTRANS research under the PATH program has developed and demonstrated a CPDGPS aided INS RRPDS that has been successfully demonstrated in lateral vehicle control applications [2, 4]. CALTRANS research under the PATH program has also developed and demonstrated a magnetometer and CPDGPS aided INS RRPDS that has been successfully demonstrated in lateral vehicle control applications [5, 7]. The motivation for this project is to apply the CPDGPS aided INS RRPDS in the snowplow/snowblower application. The benefit of this approach is that the CPDGPS aided INS RRPDS would require significantly less changes to the roadway infrastructure relative to the magnetometer only approach, thereby decreasing the installation and maintenance costs.

Therefore, the objective of the project discussed in this report is to evaluate, develop, and demonstrate an alternative roadway-relative vehicle position sensor. The project will utilize the same driver display as the existing system. The new roadway-relative vehicle position sensor utilizes differential carrier phase Global Positioning System (DCPGPS) and inertial measurements.

3 Prior status

UCR has previously demonstrated a DCPGPS aided INS that maintains cm accuracy position estimates at 150 Hz sample rate [4]. This system was used to control the lateral position of automobiles at low speeds at UCR and at high speeds during testing at the Crow's Landing test facility. Note that the DCPGPS aided INS does not require any alterations to the roadway.

UCR has also provided several demonstrations of a magnetometer and CPDGPS aided INS [1, 2, 5]. This system also maintained cm accuracy position estimates at 150 Hz. The navigation system is able to work with magnetometer measurements only, with DCPGPS measurements only, or with both measurements simultaneously. An advantage of this magnetometer and DCPGPS aided INS approach is that sensor redundancy makes it significantly more reliable to sensor failures than a single sensor approach could be. Also, in comparison to a magnetometer only approach, the combined system does not require magnets embedded in the roadway at a fixed 1.2 m spacing. Instead, magnets could be widely spaced on sections of roadway with an open view of the sky and more closely spaced only along those regions of the roadway where the sky is significantly obscured (e.g., tunnels).

4 Objectives of the Phase 1

The objectives stated for phase 1 of this project were:

Initial site analysis testing. The objective of the initial site test was to determine several specific characteristics of the test site and analyze whether any of these characteristics present unsurmountable barriers to the project's success. This initial test was performed using a standard automobile with the navigation system attached to the luggage rack. The characteristics to be tested include: (a) GPS signal availability, (b) differential correction availability, and (c) highway trajectory characteristics. The results of this task affect the results, order, and importance of the remaining Tasks. UCR borrowed a Trimble radio modem from AHMCT that was capable of receiving the Caltrans DGPS base station messages to evaluate characteristic (b).

Infrastructure development: Purchase equipment. This project required development of additional sets of GPS/INS hardware to be installed on test vehicles. Under this task we defined and purchased the necessary pieces of equipment. We have constructed additional DCPGPS prototypes that have been used for on-vehicle testing.

Infrastructure development: Vibration isolation and environment protection enclosure. The enclosure and vibration isolation system were purchased modified and tested.

Infrastructure development: Snowplow GPS/INS mounting development. This task will define, implement, and test the cabling, mounting, and power required to test the navigation hardware on a snow plow.

Infrastructure development: CPDGPS/INS software modifications and system test. The existing software was modified to accommodate the hardware changes that resulted during Task 2.

Infrastructure development: Software modifications for the HMI. The existing HMI software will be modified to accommodate the CPDGPS aided INS state information.

Test: Snow plow on-vehicle system test of CPDGPS aided INS. This task will test the navigation system basic operation on the snowplow. In addition, to checking the hardware, cabling, and power operation, an objective is to validate the navigation system performance with the mounting, vibration, and power stability characteristics of the snowplow. This will be performed at Crows Landing to facilitate any changes that might be required to the mounting design.

Trajectory Curve Fitting. The guidance information to be given to the driver will be determined based on the vehicle position determined by the navigation system and stored trajectory information. This task used the data from testing in the Donner Pass to develop an appropriate curve fit to the data describing the lane trajectory.

5 Experimental Results: I80 Donners Pass

On-site testing was performed on the I80 in Donners Pass during the week of August 25-29, 2003. The intent of this set of experiments was to acquire GPS data along the I80 so that we could perform an off-line analysis of the expected accuracy of estimated position using either DCPGPS or DCPGPS-aided-INS. Data was acquired in both the East-bound and West-bound lanes. In each lane, data was

Name	Direction	Date	Time
248959	WB	8/26/2003	14:10
251353	EB	8/26/2003	14:50
252370	EB	8/26/2003	15:10
254903	WB	8/26/2003	15:40
255417	EB	8/26/2003	15:58
256065	WB	8/26/2003	16:10
256666	WB	8/26/2003	16:19
257470	EB	8/26/2003	16:33
318969	WB	8/27/2003	
321932	EB	8/27/2003	
324509	WB	8/27/2003	

Table 1: Summary of data runs.

acquired at different times of the day on various days. This allows accuracy analysis for various satellite configurations. The time, date, direction, and filename for each dataset is shown in Table 1

This section contains analytic predictions of the position error expected to be achieved along the I80 in the vicinity of Donner Pass. The analytic predictions are made using covariance propagation methods as described in [1, 6]. The predictions are calculated off-line using only the satellites observable to the receiver during each run. Therefore, the predictions do not use satellites if there is not a direct and unblocked line of sight between the receiver and the satellite. The I80 through Donner Pass results in significant blockage of satellite signals due to the mountainous terrain and trees near the highway.

This analysis does not account for base station correction availability. The essential assumption is that base corrections are available for any satellite the rover needs to use. If base signals are not reliably available, then the performance of both the GPS-only and the CPDGPS-aided-INS would be worse than indicated. Availability of base correction information is discussed in a subsequent section.

Figures 1–6 show data for westbound runs. Figures 7–11 show data for eastbound runs. The top row of graphs in each figure predicts the size of the position error for calculations using only GPS carrier phase measurements. The size of the position error depends on the constellation of satellites for which the receiver can measure data. This constellation changes with time and location. If the satellite constellation is insufficient, then no solution is possible. In the figures, σ_T indicates the standard deviation of the position error tangent to the centerline and σ_N indicates the standard deviation of the position error perpendicular to the centerline. The bottom row of graphs in each figure predicts the size of the position error that would be obtained using a DCPGPS aided INS approach.

Several comments apply generally to the results.

1. The effect of the overpasses and agriculture inspection station is clearly evident in the DCPGPS error plots, but almost completely removed in the DCPGPS aided INS results.
2. The great majority of the time, the DCPGPS aided INS errors are predicted to be substantially less than 10 cm. The DCPGPS aided INS errors in a given direction only approach and then exceed 10 cm if the DCPGPS aiding signals from that direction are lost for a significant period of time.
3. The predicted error components are dependent on both the GPS satellite configuration (number of satellites in view and their locations in the sky) and the vehicle location along the roadway. The

areas where this is most obvious are near the agriculture inspection station and on the westbound lanes between Donner Summit and Kingvale. Such localized areas can be addressed through the augmentation methods suggested in the original proposal (i.e., altitude aiding, magnetometer aiding, or pseudolites). The next phase of this research project is to analyze the performance and feasibility of each type of aiding signal for this application.

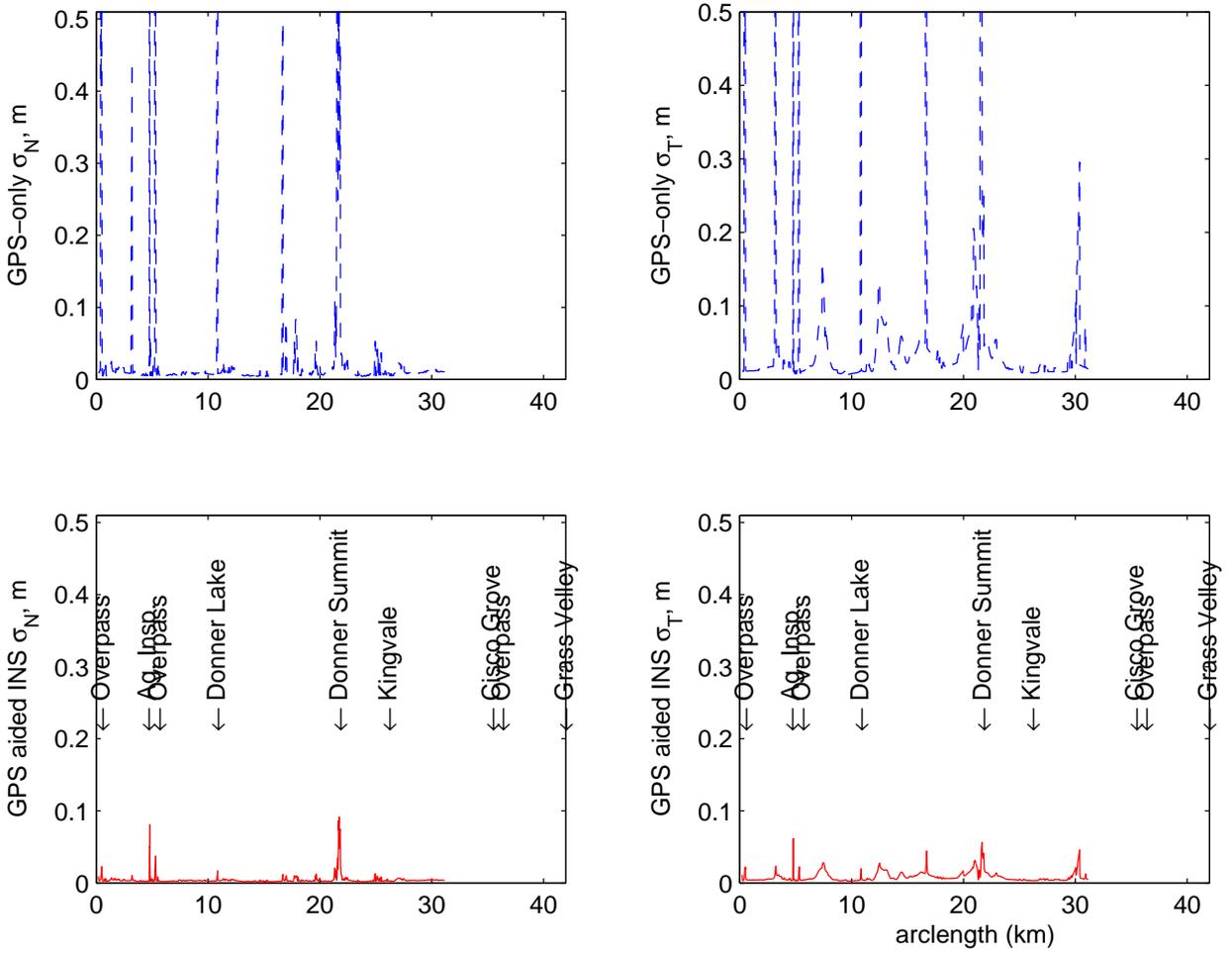


Figure 1: Predicted position error standard deviation for a westbound run. Error using only DCPGPS is shown on the top row. Error using DCPGPS aided INS is shown on the bottom row. The left column indicates the error normal to the lane centerline. The right column indicates the error parallel to the lane centerline. Note that the error axis is limited to a maximum of 0.5 m. Errors exceeding 0.5 m. are not shown.

The top row of graphs shows that for the satellite configuration available during this run, using GPS only, there are several sections of roadway where obstacles blocking satellite signals cause significant positioning errors. The bottom row of graphs shows that for the same satellite configuration, the DCPGPS aided INS would maintain less than 10 cm error for the entire run. This run starts at the Sierraville on-ramp and continues to the vicinity of Big Bend.

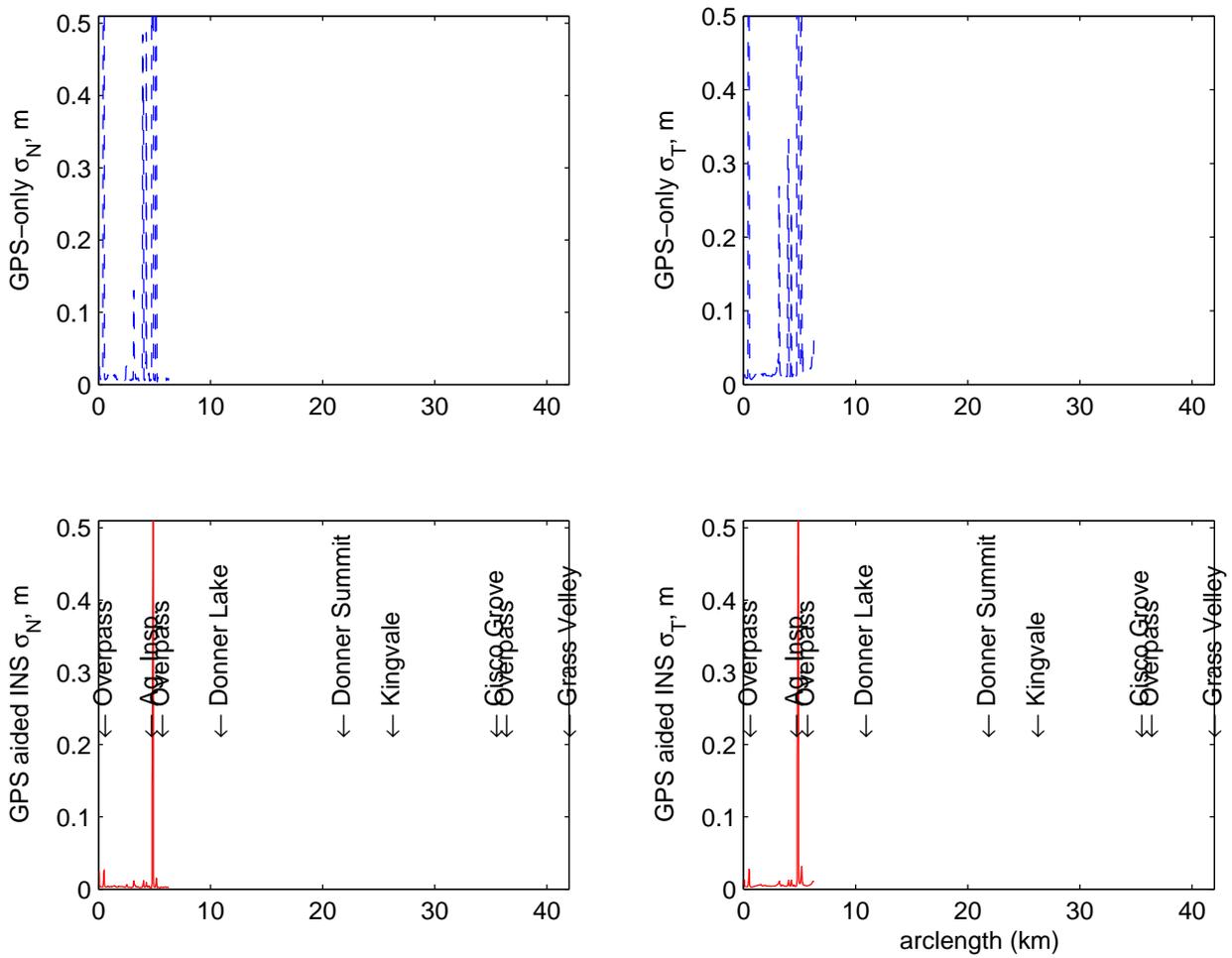


Figure 2: Predicted position error standard deviation for a westbound run. Error using only DCPGPS is shown on the top row. Error using DCPGPS aided INS is shown on the bottom row. The left column indicates the error normal to the lane centerline. The right column indicates the error parallel to the lane centerline. Note that the error axis is limited to a maximum of 0.5 m. Errors exceeding 0.5 m. are not shown.

Figure 2 contains four subfigures that indicate performance for a short run near Truckee. The top row of figures shows that for the satellite configuration available during this run, for the GPS only solution, there are several sections of roadway where obstacles blocking the satellite signals cause significant positioning errors. Locations where the signals are blocked by the overpasses and agriculture inspection station are clearly visible. The bottom row of graphs shows that for the same satellite configuration, the DCPGPS aided INS would maintain substantially less than 10 cm error for the entire run, except for the portion going through the agricultural inspection station where the accuracy parallel to the road centerline grows to more than 50 cm.

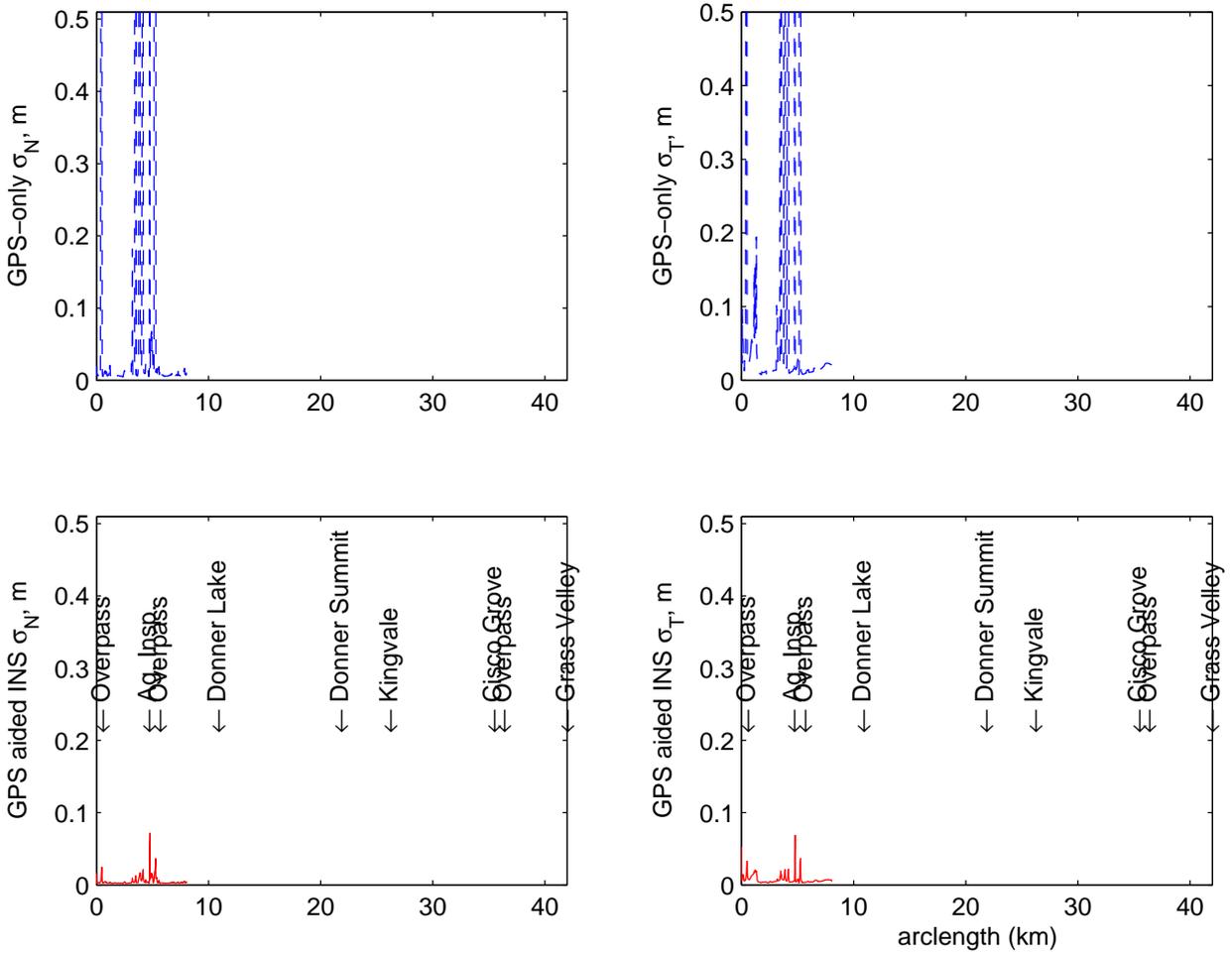


Figure 3: Predicted position error standard deviation for a westbound run. Error using only DCPGPS is shown on the top row. Error using DCPGPS aided INS is shown on the bottom row. The left column indicates the error normal to the lane centerline. The right column indicates the error parallel to the lane centerline. Note that the error axis is limited to a maximum of 0.5 m. Errors exceeding 0.5 m. are not shown.

Figure 3 contains four subfigures that indicate performance for a short run near Truckee. The top row of figures shows that for the satellite configuration available during this run, for the GPS only solution there are several sections of roadway where obstacles blocking satellites cause significant positioning errors. The effect of signals being blocked by the overpasses and agriculture inspection station are clearly visible. The bottom row of figures shows that for the same satellite configuration, the DCPGPS aided INS would maintain substantially less than 10 cm error for the entire run.

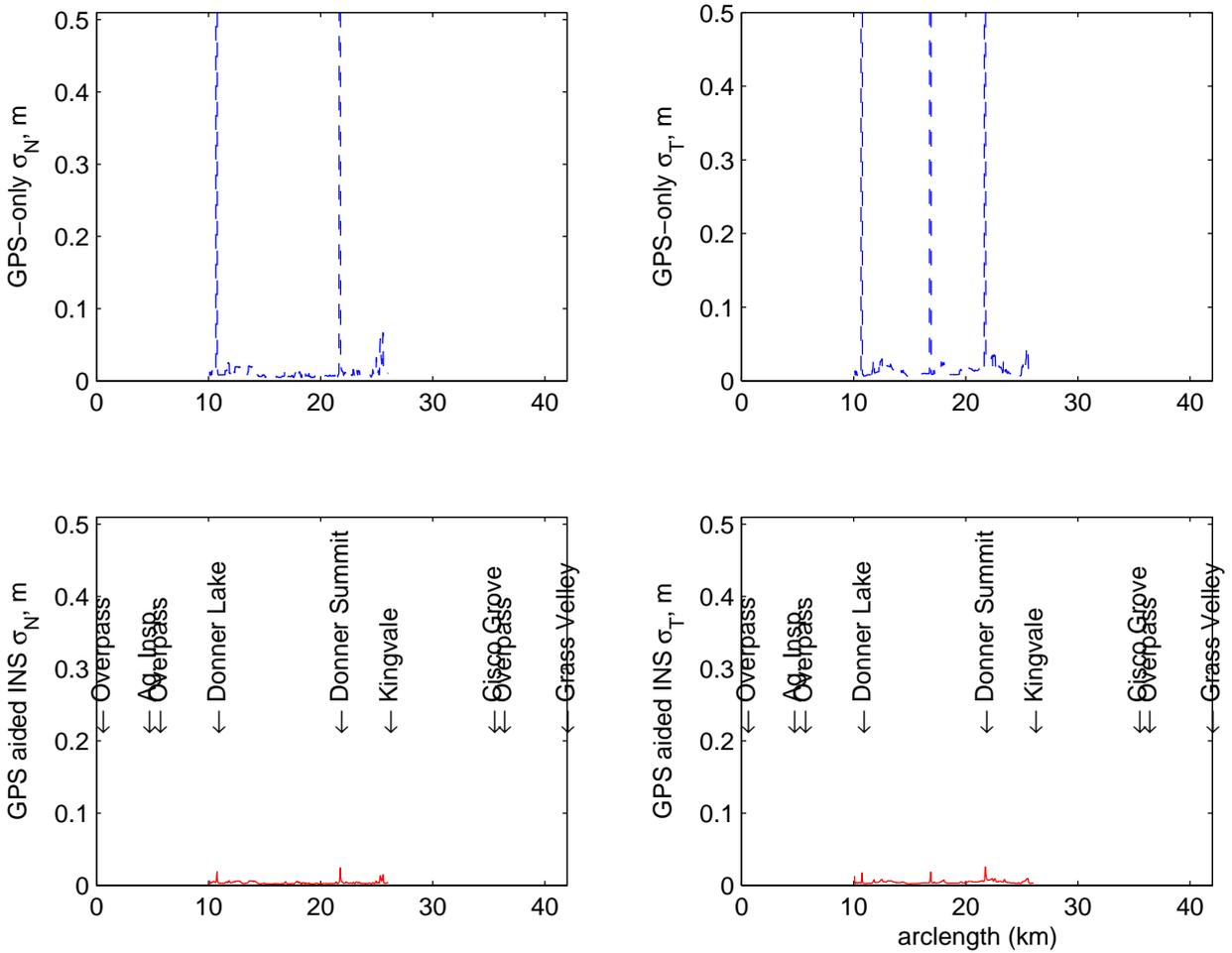


Figure 4: Predicted position error standard deviation for a westbound run. Error using only DCPGPS is shown on the top row. Error using DCPGPS aided INS is shown on the bottom row. The left column indicates the error normal to the lane centerline. The right column indicates the error parallel to the lane centerline. Note that the error axis is limited to a maximum of 0.5 m. Errors exceeding 0.5 m. are not shown.

Figure 4 contains four subfigures that indicate performance for a run between Donner Lake and Kingvale. The top row of figures shows that for the satellite configuration available during this run, there are a few sections of roadway where obstacles blocking satellite signals cause significant positioning errors for the GPS only solution. The bottom row of Figures shows that for the same section of road and same satellite configuration, the DCPGPS aided INS would maintain substantially less than 10 cm error for the entire run.

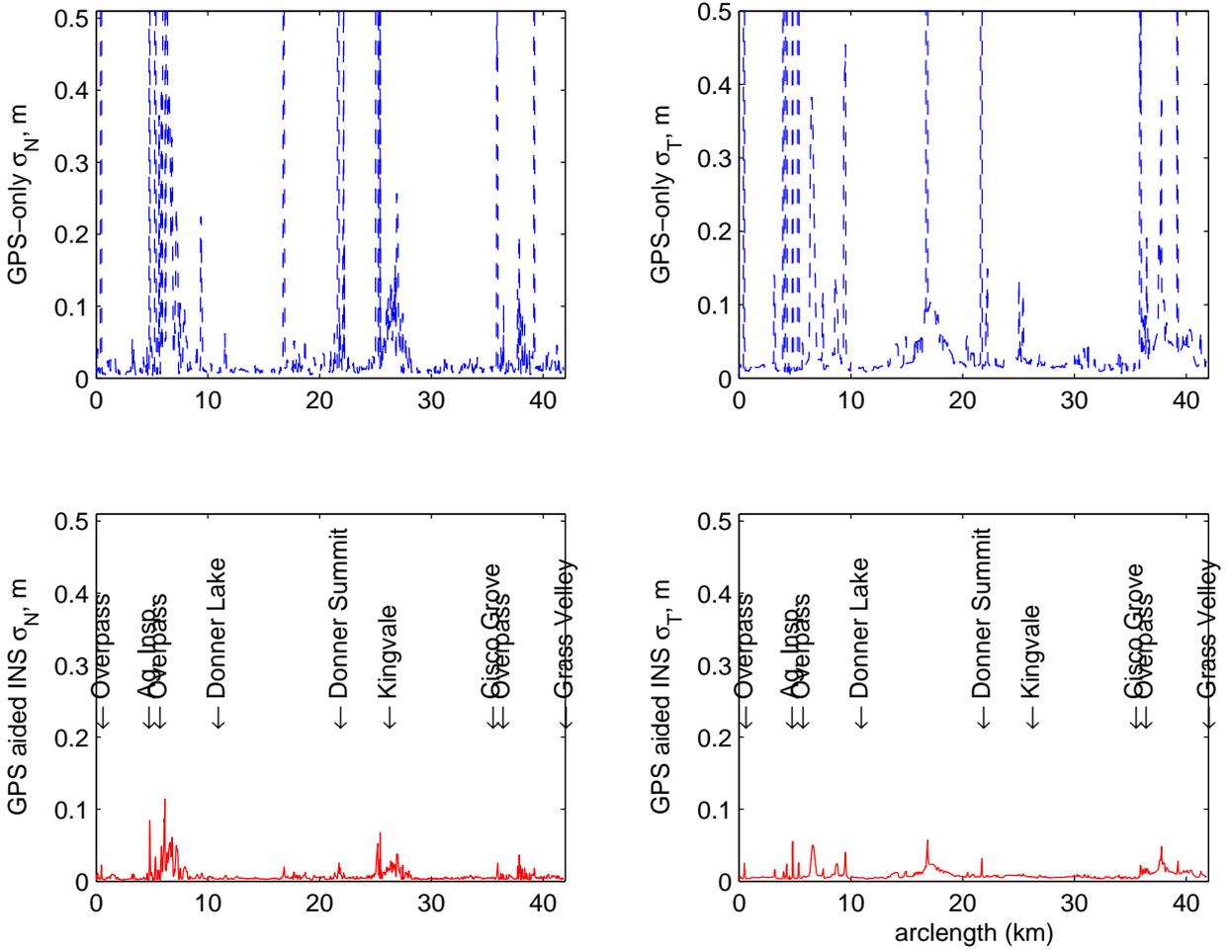


Figure 5: Predicted position error standard deviation for a westbound run. Error using only DCPGPS is shown on the top row. Error using DCPGPS aided INS is shown on the bottom row. The left column indicates the error normal to the lane centerline. The right column indicates the error parallel to the lane centerline. Note that the error axis is limited to a maximum of 0.5 m. Errors exceeding 0.5 m. are not shown.

Figure 5 contains four subfigures that indicate performance for a run between Seirraville and Grass Valley. The top row of graphs shows that for the satellite configuration available during this run, there are many sections of roadway where obstacles blocking satellite signals cause significant positioning errors for the GPS only solution. The bottom row of graphs shows that for the same section of road and same satellite configuration, the DCPGPS aided INS would maintain substantially less than 10 cm error for almost the entire run. The only location where the DCPGPS aided INS solution exceeds 10 cm error is between the agriculture inspection station and the subsequent overpass.

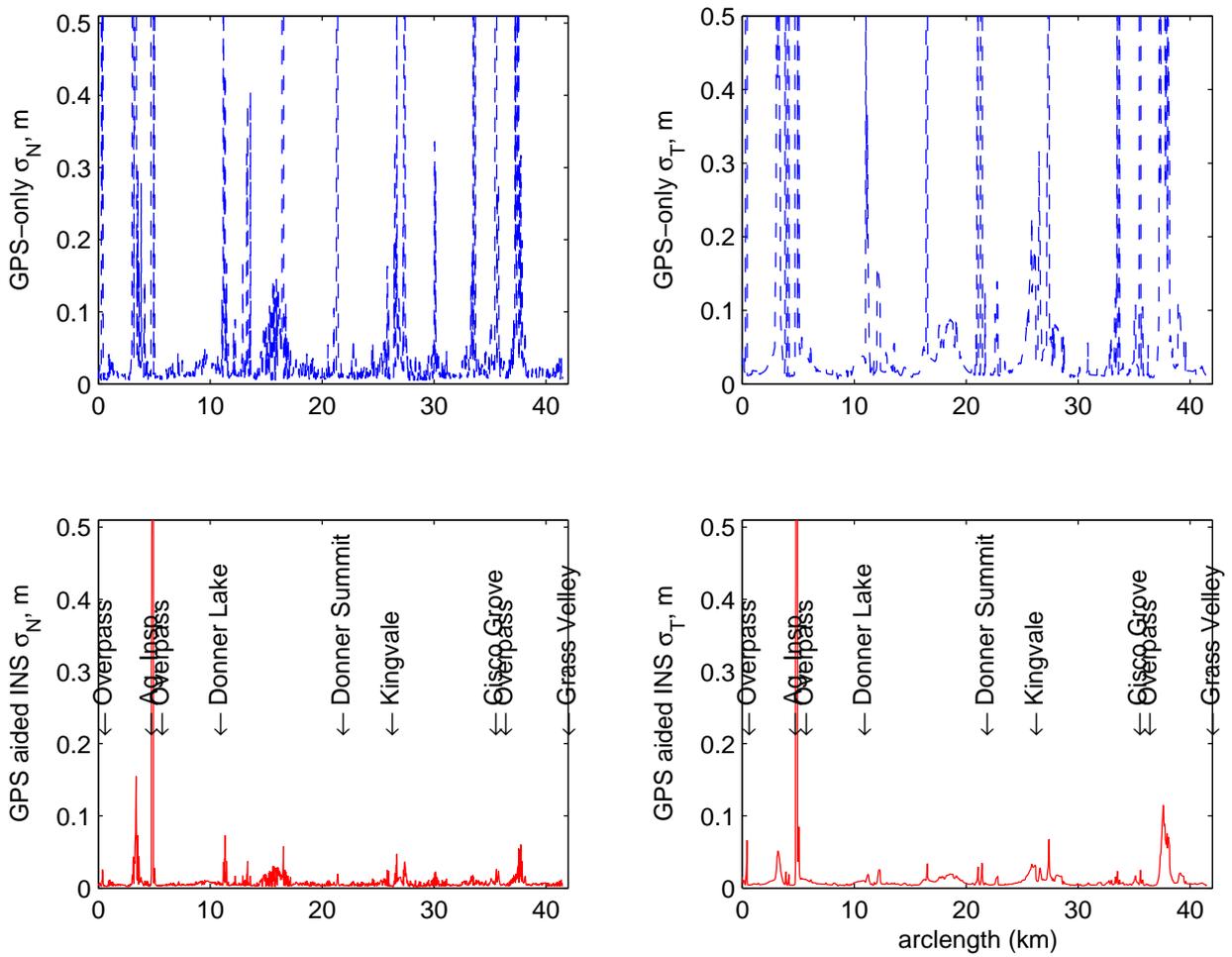


Figure 6: Predicted position error standard deviation for a westbound run. Error using only DCPGPS is shown on the top row. Error using DCPGPS aided INS is shown on the bottom row. The left column indicates the error normal to the lane centerline. The right column indicates the error parallel to the lane centerline. Note that the error axis is limited to a maximum of 0.5 m. Errors exceeding 0.5 m. are not shown.

Figure 6 contains four subfigures that indicate performance for a run between Seirraville and Grass Valley. The top row of graphs shows that for the satellite configuration available during this run, there are many sections of roadway where obstacles blocking satellite signals cause significant positioning errors for the GPS only solution. The bottom row of graphs shows that for the same section of road and same satellite configuration, the DCPGPS aided INS would maintain substantially less than 10 cm error for almost the entire run. The only locations where the DCPGPS aided INS solution exceeds 10 cm of error is near the agriculture inspection station and near the Cisco Grove overpass.

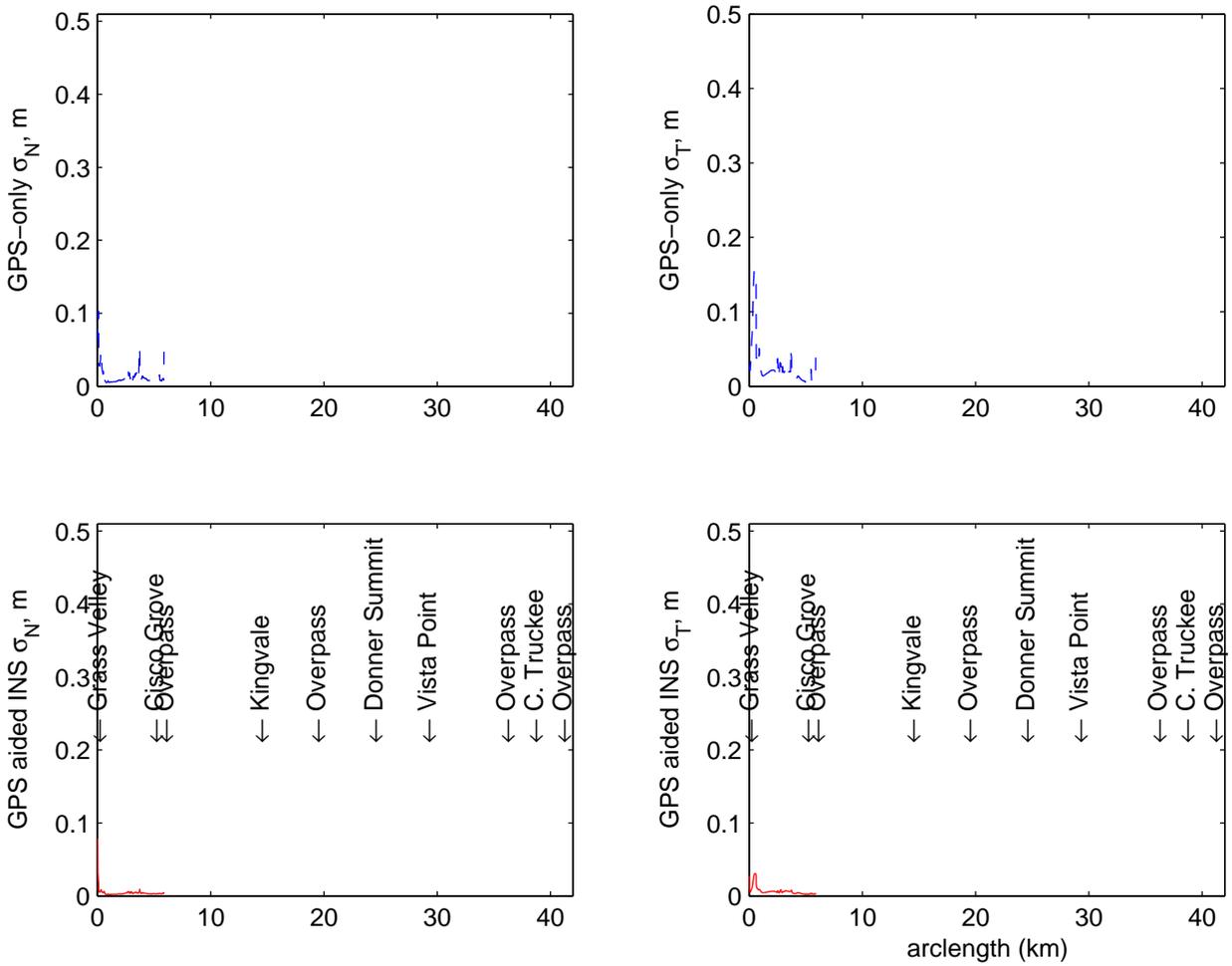


Figure 7: Predicted position error standard deviation for an eastbound run. Error using only DCPGPS is shown on the top row. Error using DCPGPS aided INS is shown on the bottom row. The left column indicates the error normal to the lane centerline. The right column indicates the error parallel to the lane centerline. Note that the error axis is limited to a maximum of 0.5 m. Errors exceeding 0.5 m. are not shown.

Figure 7 contains four subfigures that indicate performance for a run from Grass Valley to Cisco Grove. The top row of graphs shows that for the satellite configuration available during this run, the position errors predicted for the GPS only position solution are always less than 20 cm. The bottom row of graphs shows that for the same section of road and same satellite configuration, the DCPGPS aided INS would maintain substantially less than 10 cm error for the entire run.

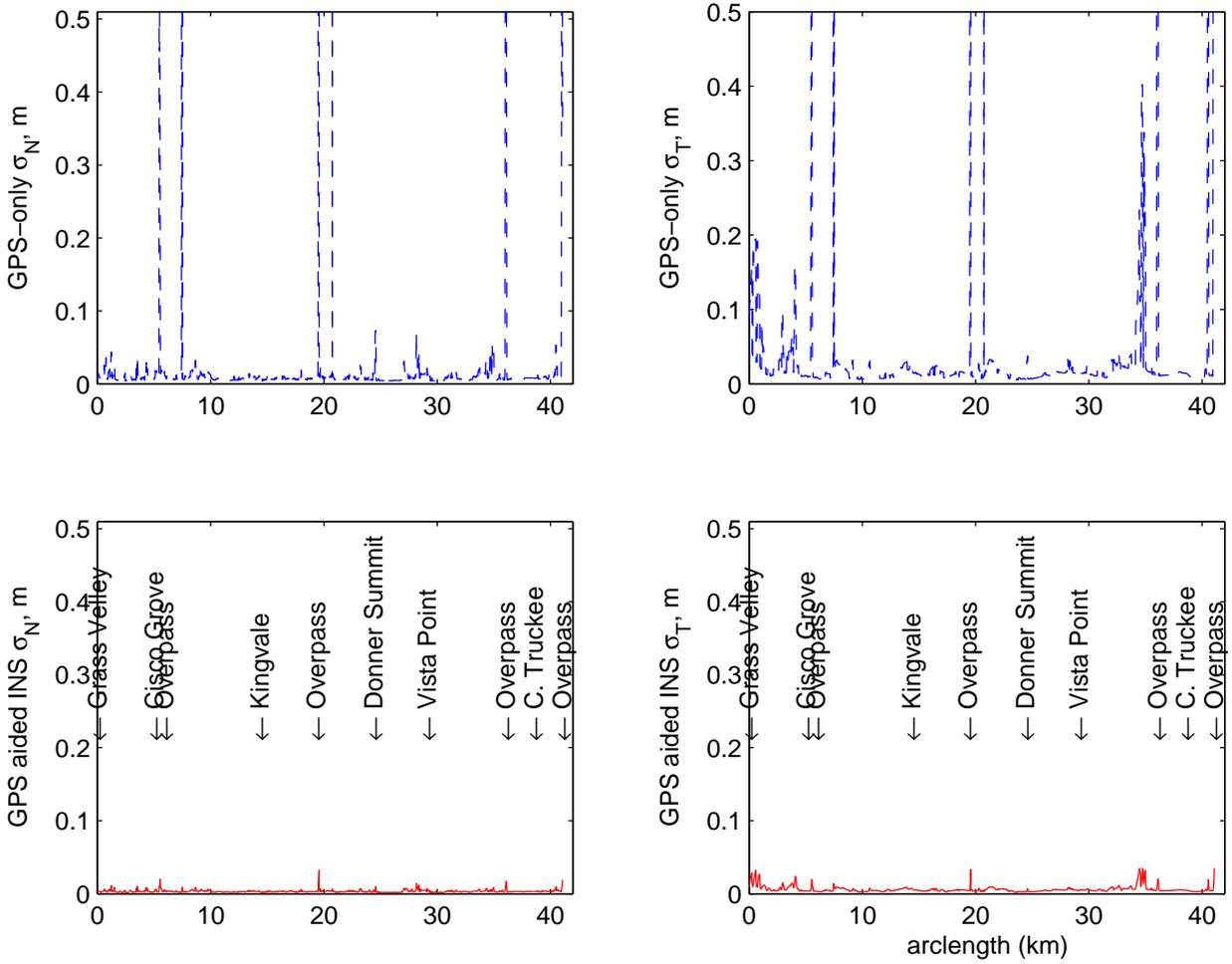


Figure 8: Predicted position error standard deviation for an eastbound run. Error using only DCPGPS is shown on the top row. Error using DCPGPS aided INS is shown on the bottom row. The left column indicates the error normal to the lane centerline. The right column indicates the error parallel to the lane centerline. Note that the error axis is limited to a maximum of 0.5 m. Errors exceeding 0.5 m. are not shown.

Figure 8 contains four subfigures that indicate performance for a run from Grass Valley to Sier-raville. The top row of graphs shows that for the satellite configuration available during this run, there are several sections of roadway where obstacles blocking satellite signals cause significant positioning errors for the GPS only solution. The bottom row of graphs shows that for the same section of road and same satellite configuration, the DCPGPS aided INS would maintain substantially less than 10 cm error for the entire run.

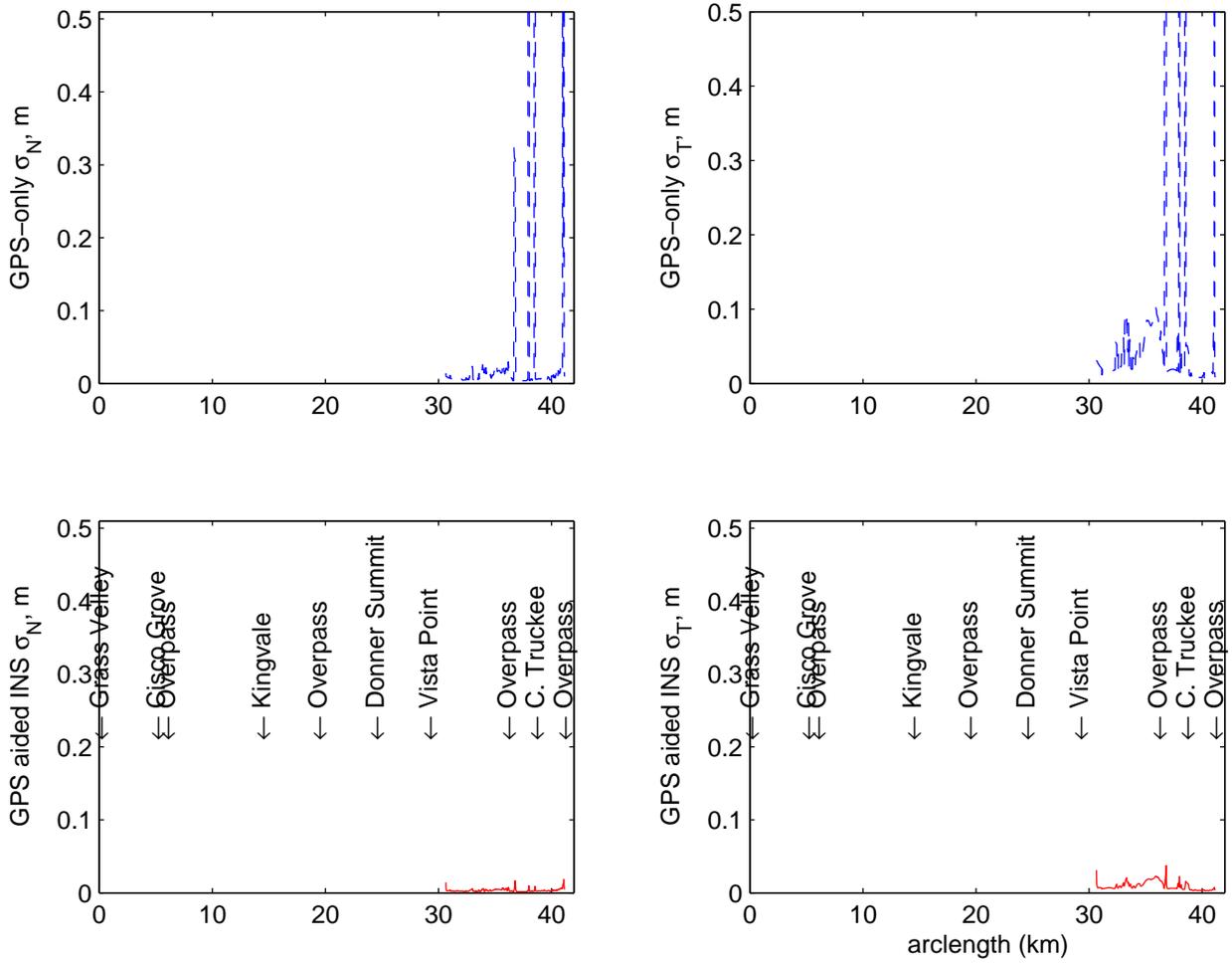


Figure 9: Predicted position error standard deviation for an eastbound run. Error using only DCPGPS is shown on the top row. Error using DCPGPS aided INS is shown on the bottom row. The left column indicates the error normal to the lane centerline. The right column indicates the error parallel to the lane centerline. Note that the error axis is limited to a maximum of 0.5 m. Errors exceeding 0.5 m. are not shown.

Figure 9 contains four subfigures that indicate performance for a run from Vista Point to Sier-raville (i.e., near Truckee). The top row of graphs shows that for the satellite configuration available during this run, there are two sections of roadway where obstacles blocking satellite signals cause significant positioning errors for the GPS only solution. The bottom row of graphs that for the same section of road and same satellite configuration, the DCPGPS aided INS would maintain substantially less than 10 cm error for the entire run.

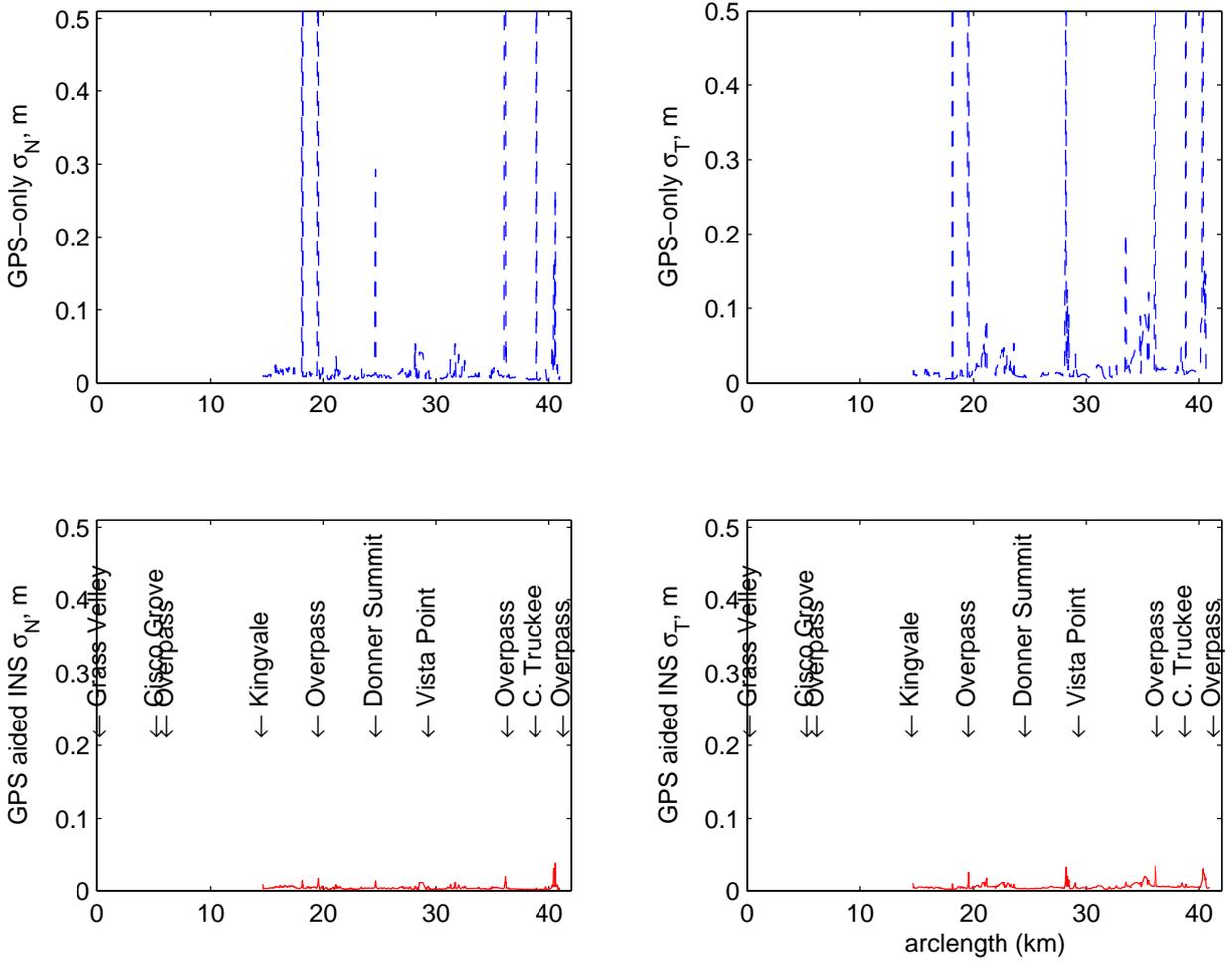


Figure 10: Predicted position error standard deviation for an eastbound run. Error using only DCPGPS is shown on the top row. Error using DCPGPS aided INS is shown on the bottom row. The left column indicates the error normal to the lane centerline. The right column indicates the error parallel to the lane centerline. Note that the error axis is limited to a maximum of 0.5 m. Errors exceeding 0.5 m. are not shown.

Figure 10 contains four subfigures that indicate performance for an eastbound run from Kingvale to Sierraville (i.e., near Truckee). The top row of graphs show that for the satellite configuration available during this run, there are several sections of roadway where obstacles blocking satellite signals cause significant positioning errors for the GPS only solution. The bottom row of graphs shows that for the same section of road and same satellite configuration, the DCPGPS aided INS would maintain substantially less than 10 cm error for the entire run.

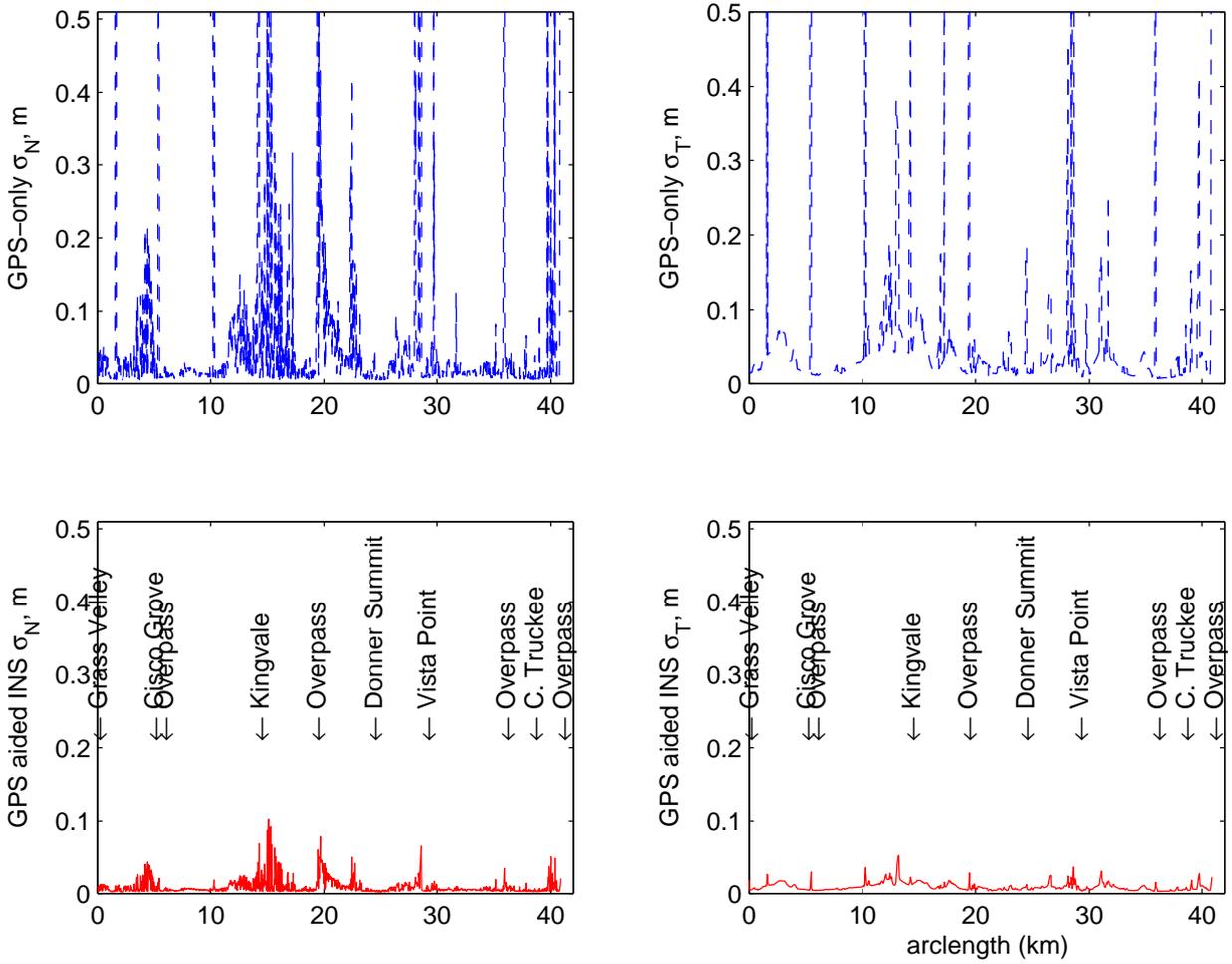


Figure 11: Predicted position error standard deviation for an eastbound run. Error using only DCPGPS is shown on the top row. Error using DCPGPS aided INS is shown on the bottom row. The left column indicates the error normal to the lane centerline. The right column indicates the error parallel to the lane centerline. Note that the error axis is limited to a maximum of 0.5 m. Errors exceeding 0.5 m. are not shown.

Figure 11 contains four subfigures that indicate performance for an eastbound run from Kingvale to Sierraville (i.e., near Truckee). The top row of graphs shows that for the satellite configuration available during this run, there are many sections of roadway where obstacles blocking satellite signals cause significant positioning errors for the GPS only solution. The bottom row of graphs shows that for the same section of road and same satellite configuration, the DCPGPS aided INS would maintain less than 10 cm error for almost the entire run.

6 Base Station

6.1 Caltrans Base

Differential Carrier Phase GPS requires a base station. There is a Caltrans GPS base station in the vicinity of the I80 in Donners Pass. It is a Trimble 4700 WinCORS receiver located at

39 : 19 : 18.7s North Latitude and 120 : 20 : 11.7 West Longitude.

The receiver broadcasts CMR format differential corrections via a Trimble Trintalk 450s radio with a center frequency of 453.8875 MHz and a 12.5 kHz channel spacing. The baud rate is 1200-9600 bps. This base has an expected range of 10 km line-of-site at 0.5 W. It is repeater capable.

Figures 12–22 show data indicative of differential correction reception versus arclength. Each figure contains three graphs of data indicating the time delay between reception of consecutive base corrections. Ideally, one correction should be received per second. Delays of 2 or 3 seconds can be accommodated easily. Delays of more than 7 seconds are problematic. In each figure, the top two plots are the same data, just plotted with different scales. The top graph has a scale that includes all data points. The second graph has a vertical range between 0 and 6, to more clearly indicate the distribution of data in this range. The third plot is a histogram of the data. This data shows that each run contained at several instances of base corrections not being received for at least 10 s. Fortunately, the bad base station reception appears to occur at nearly the same arclength for the various runs. Therefore, this issue may be addressable by adding base station repeaters (off the highway) along the roadway.

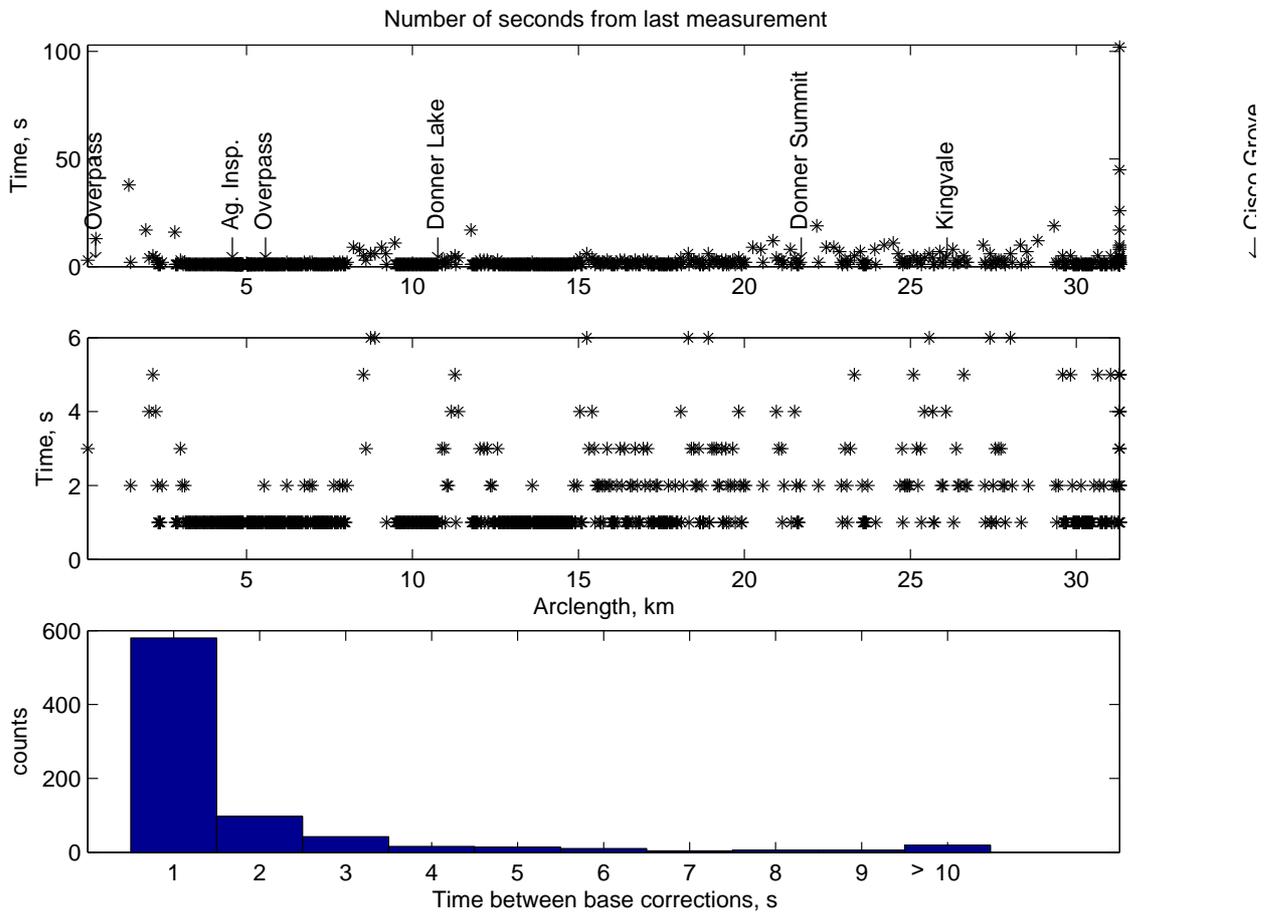


Figure 12: Time delay between subsequent DGPS correction using the Caltrans base station. This is a westbound run.

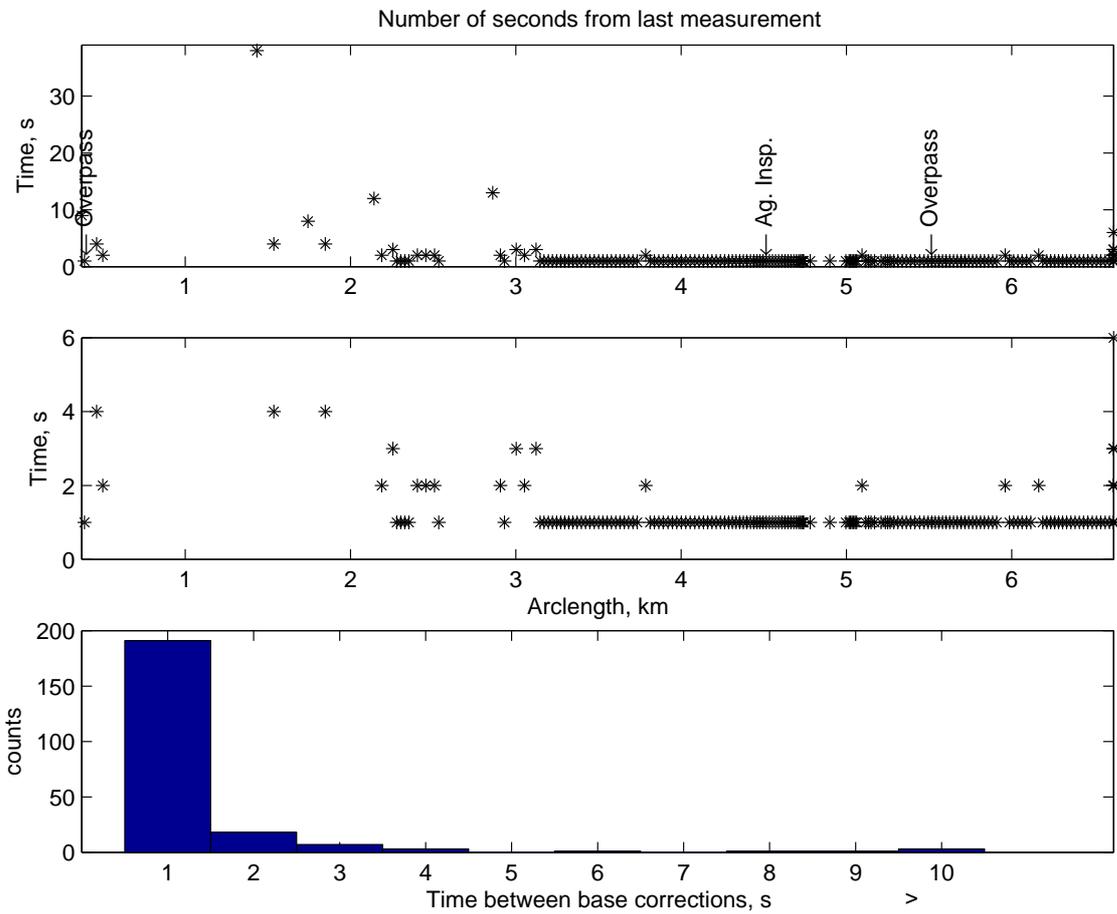


Figure 13: Time delay between subsequent DGPS correction using the Caltrans base station. This is a westbound run.

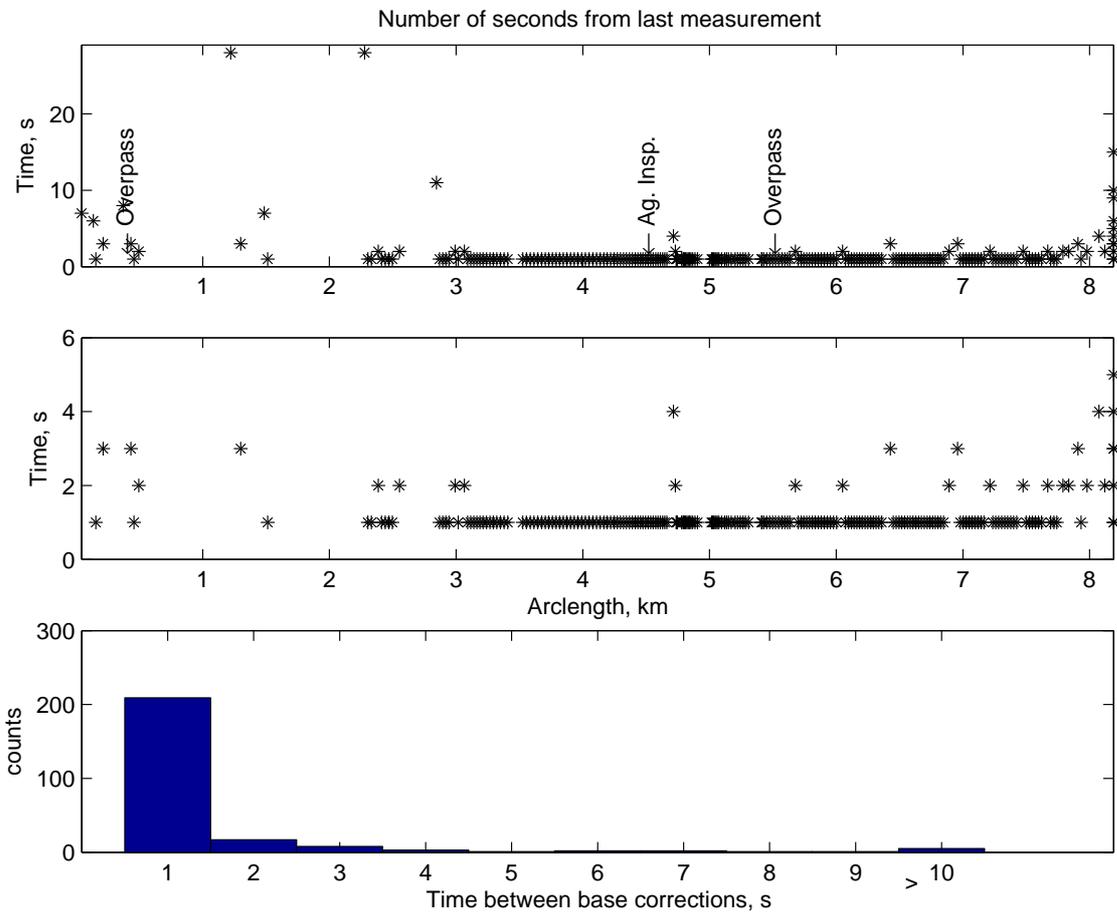


Figure 14: Time delay between subsequent DGPS correction using the Caltrans base station. This is a westbound run.

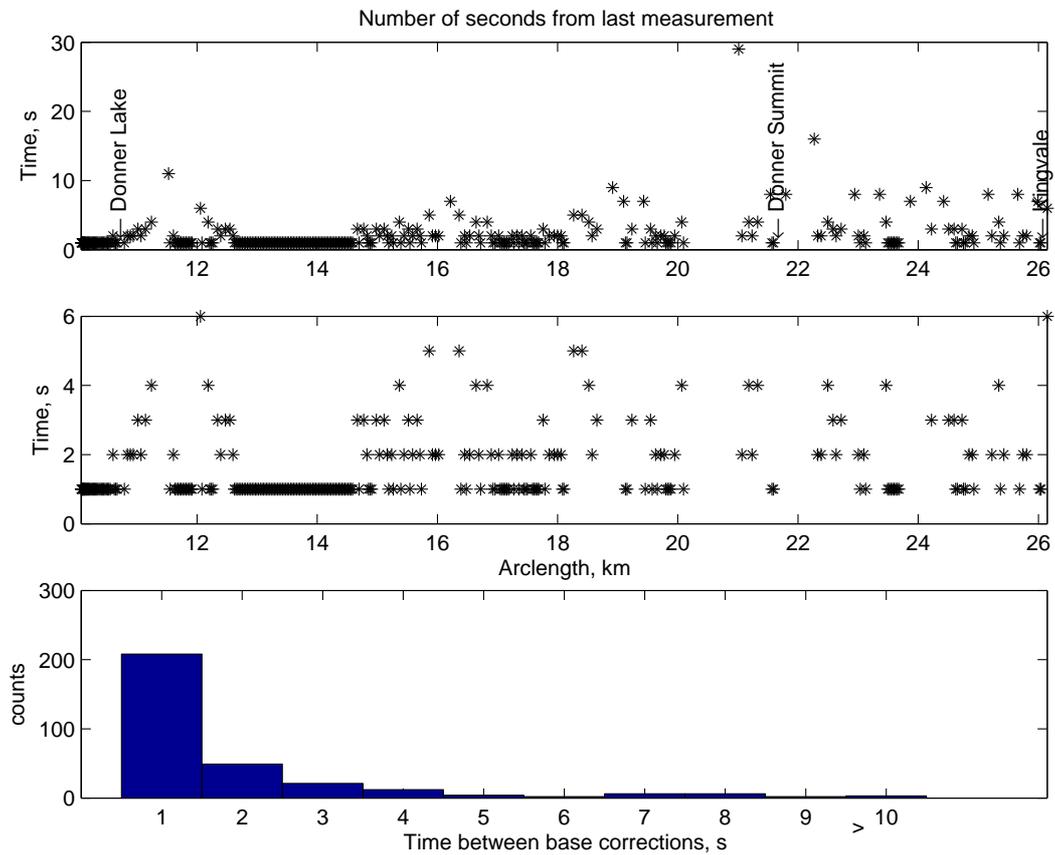


Figure 15: Time delay between subsequent DGPS correction using the Caltrans base station. This is a westbound run.

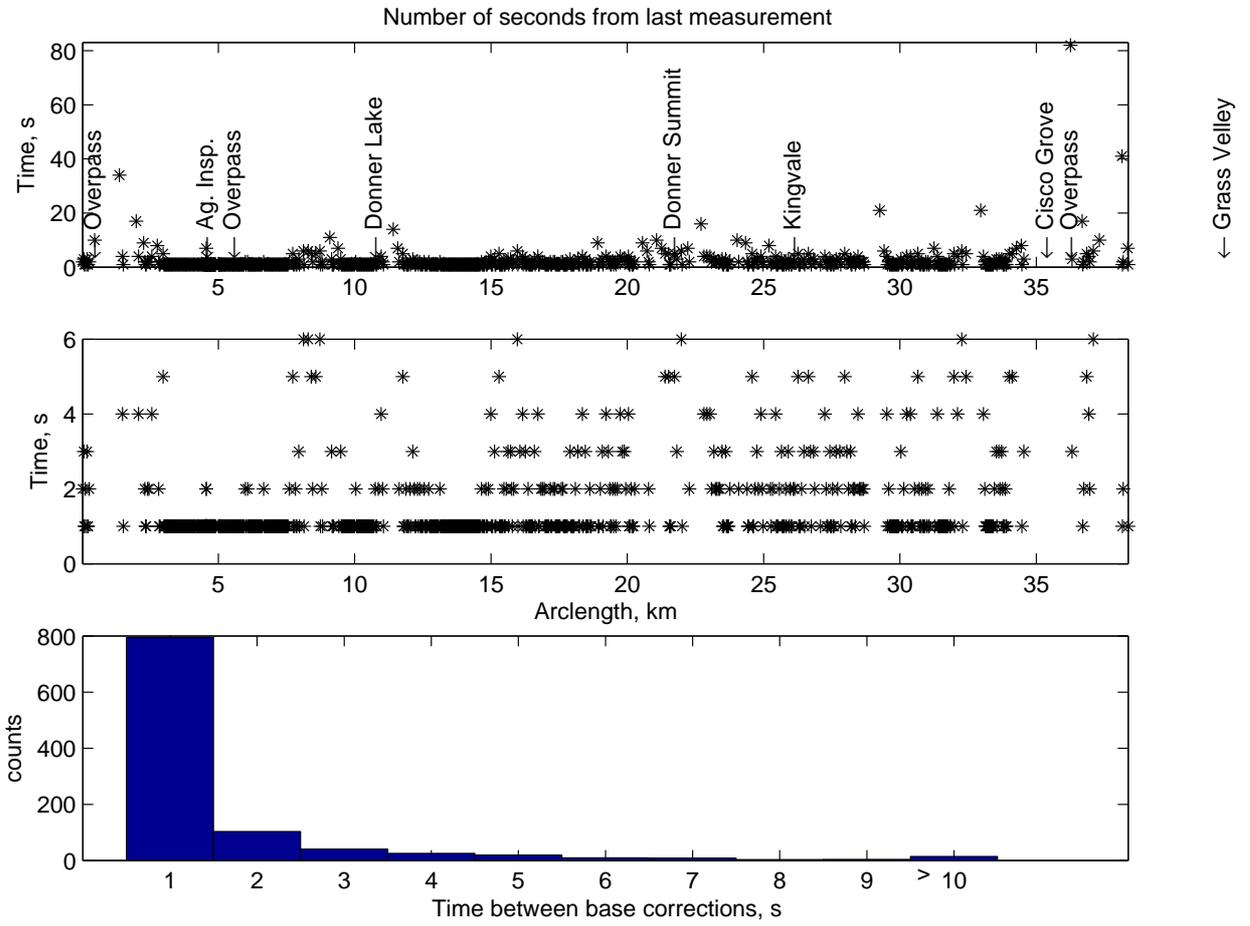


Figure 16: Time delay between subsequent DGPS correction using the Caltrans base station. This is a westbound run.

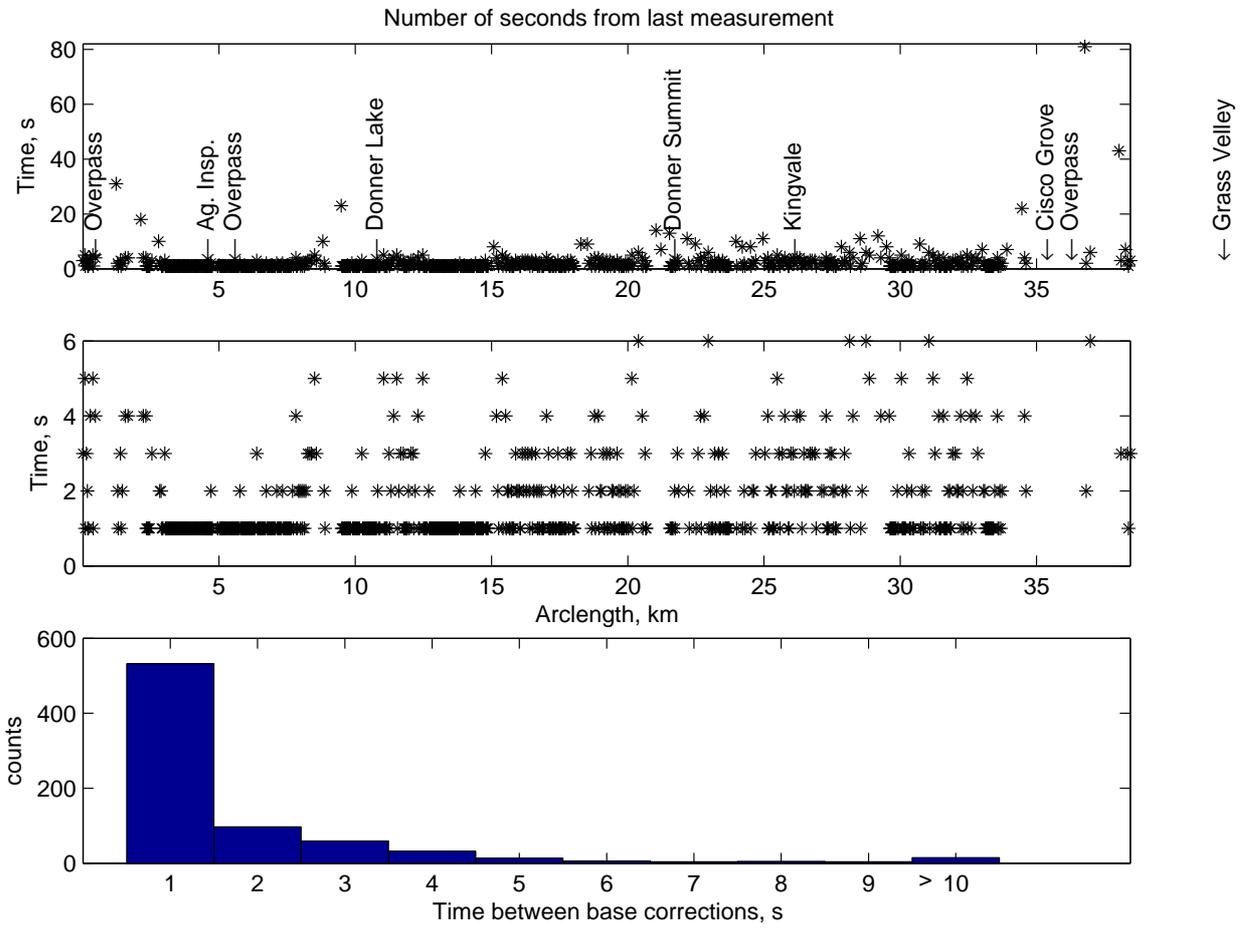


Figure 17: Time delay between subsequent DGPS correction using the Caltrans base station. This is a westbound run.

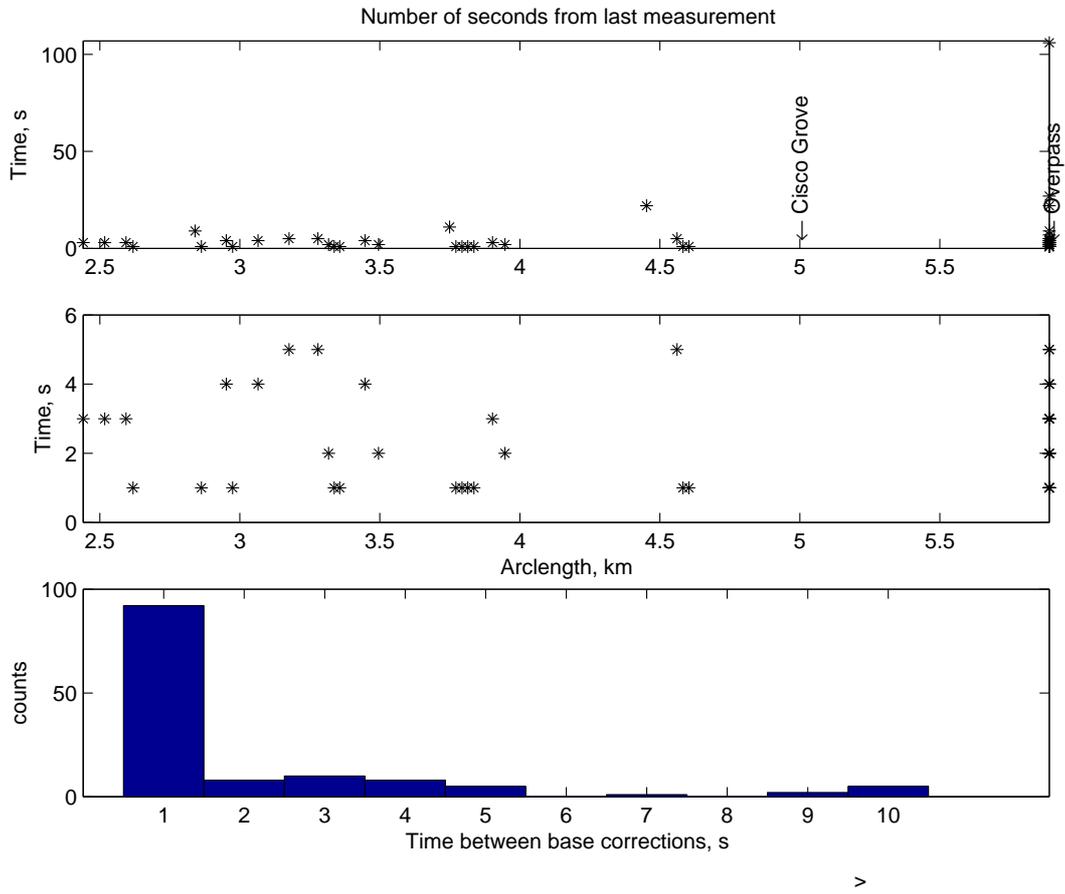


Figure 18: Time delay between subsequent DGPS correction using the Caltrans base station. This is a eastbound run.

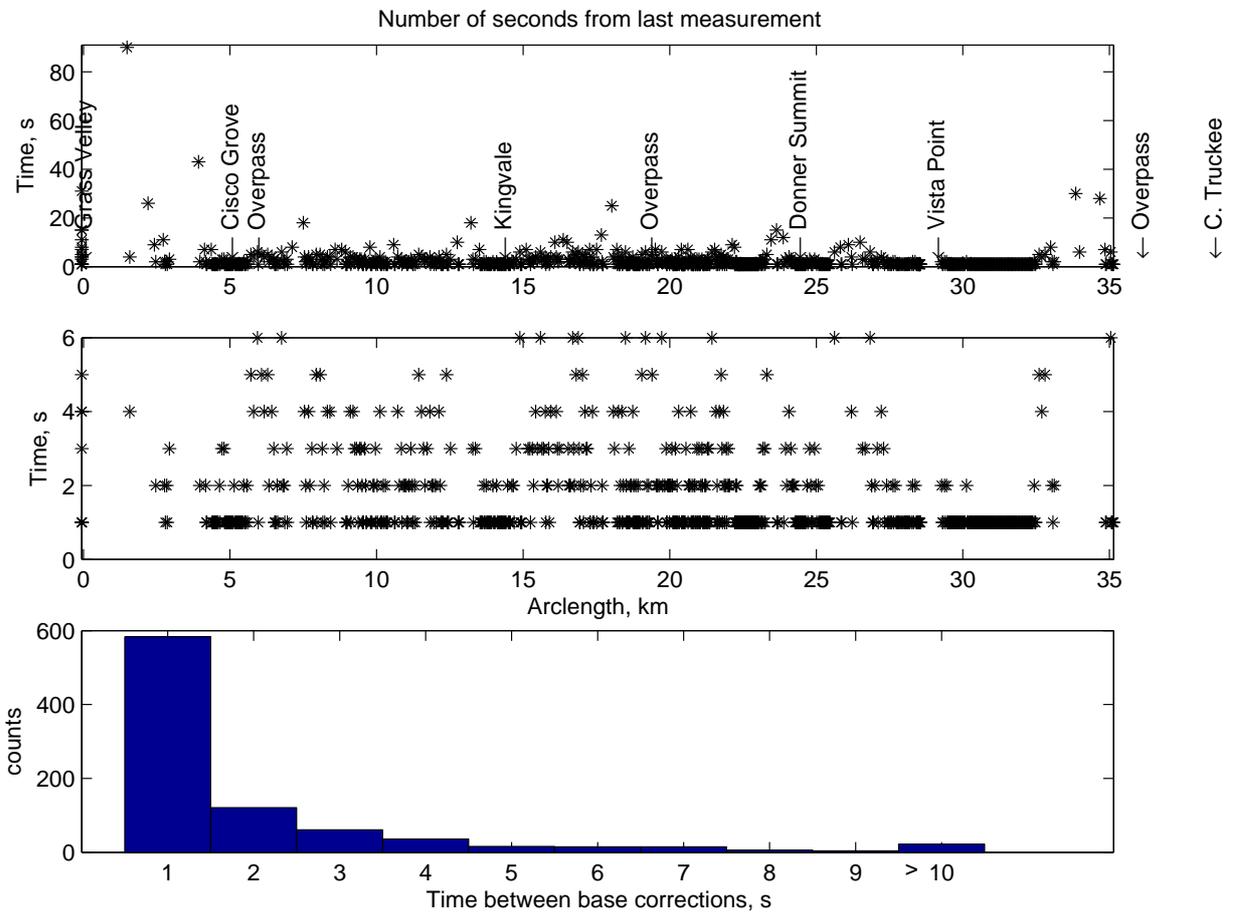


Figure 19: Time delay between subsequent DGPS correction using the Caltrans base station. This is a eastbound run.

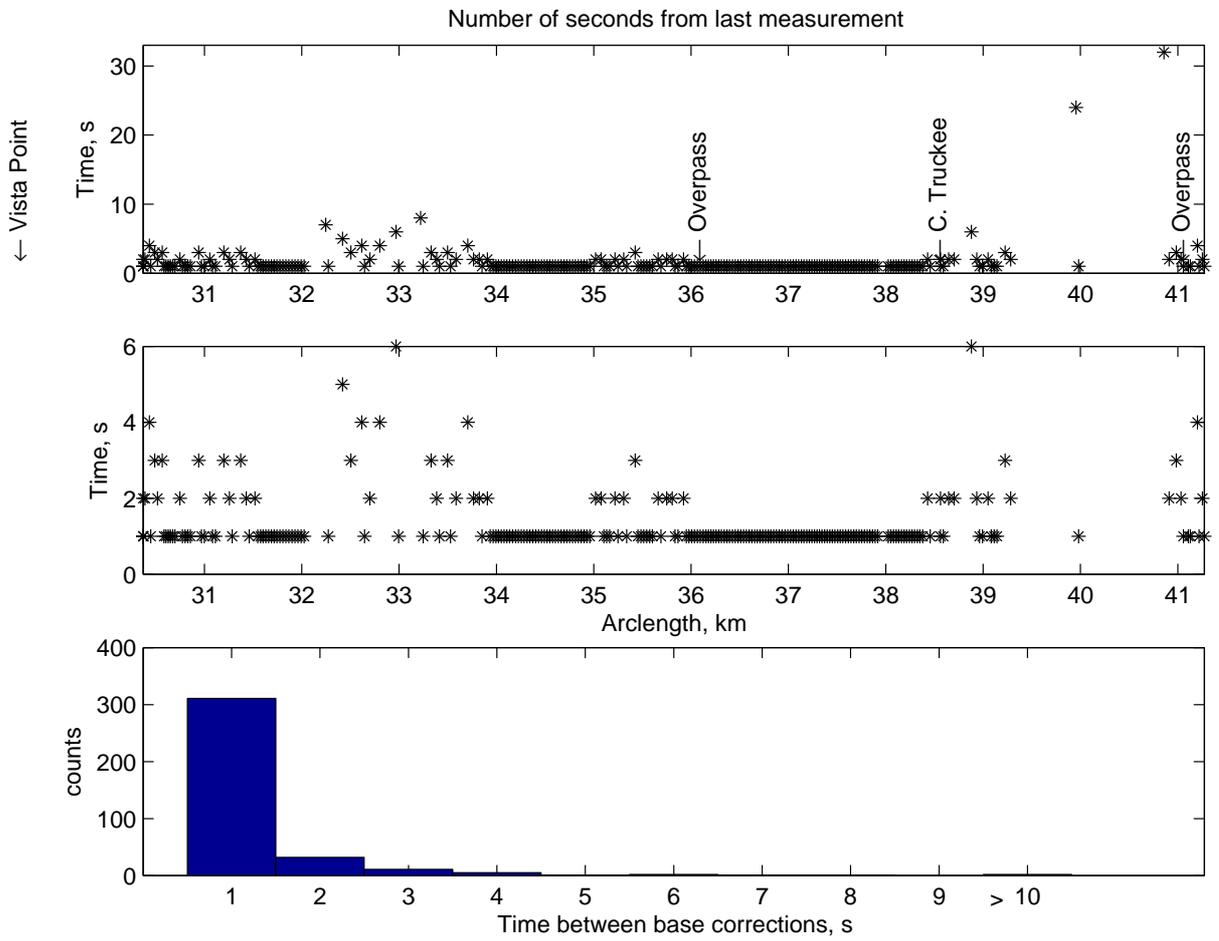


Figure 20: Time delay between subsequent DGPS correction using the Caltrans base station. This is a eastbound run.

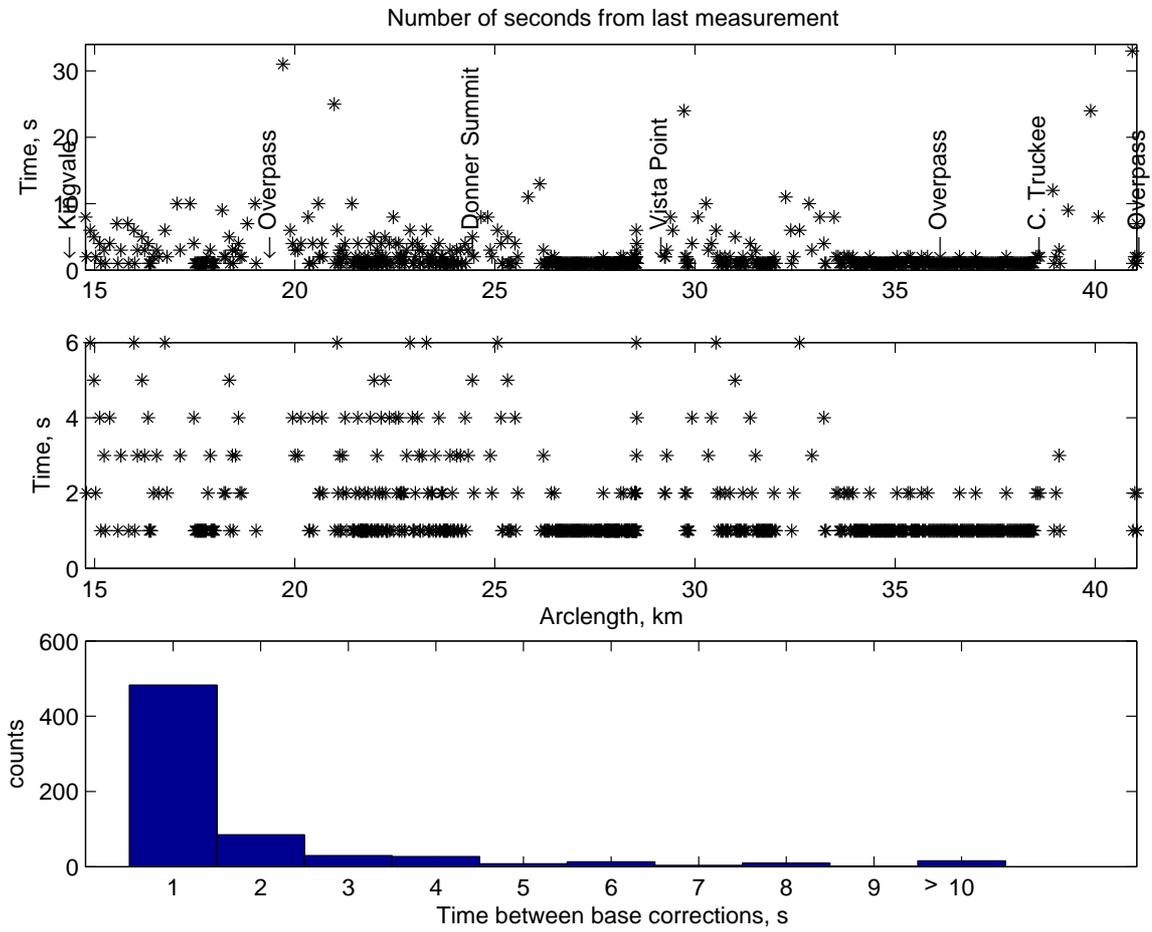


Figure 21: Time delay between subsequent DGPS correction using the Caltrans base station. This is a eastbound run.

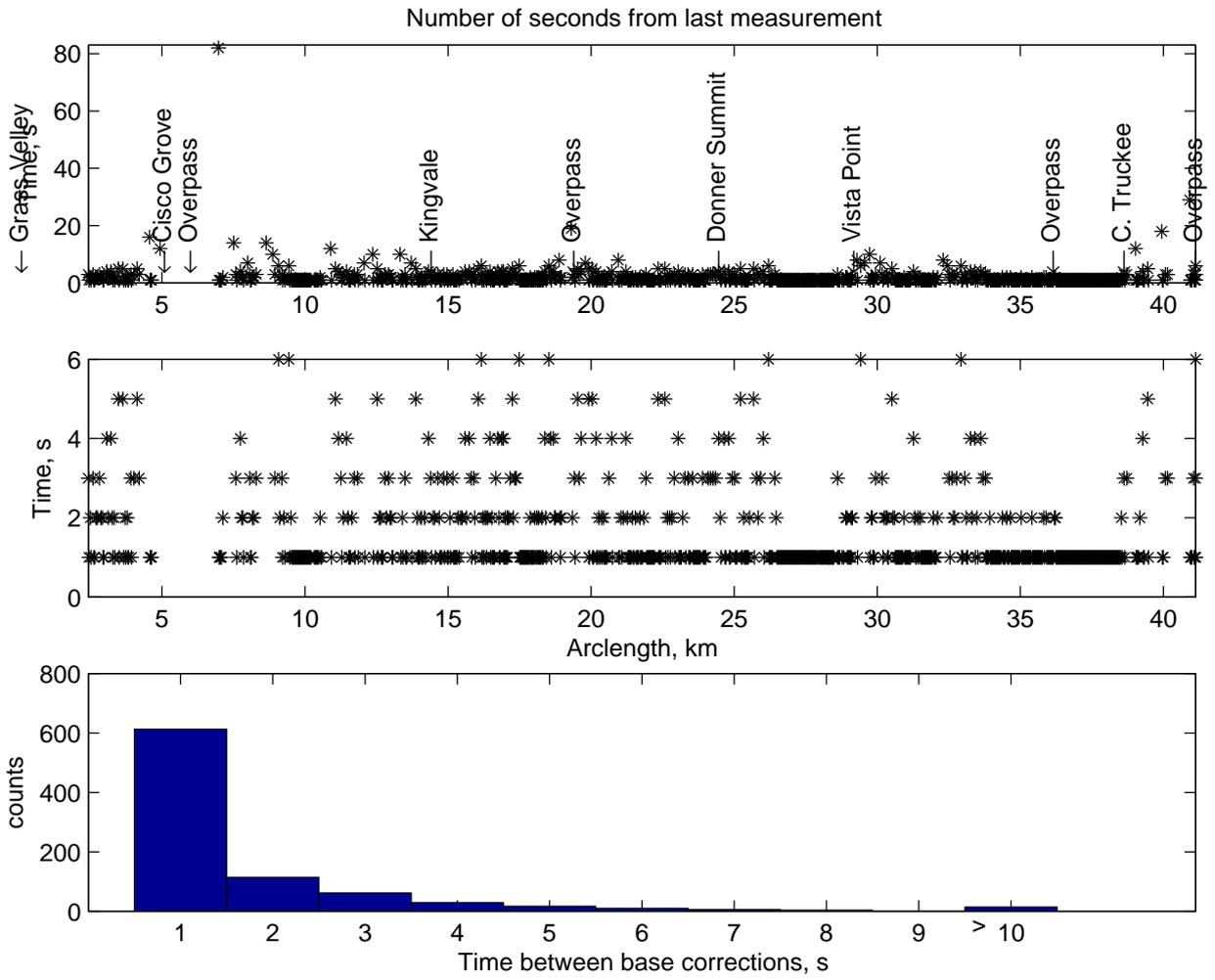


Figure 22: Time delay between subsequent DGPS correction using the Caltrans base station. This is a eastbound run.

6.2 Base and Rover Satellite Reception Data

Figures 23–33 show the show analytic predictions of accuracy, previously shown in Figures 1–11 along with graphs showing the number of satellites available to the rover and the number of satellite corrections received from the base by the rover, each as a function of arclength.

Note that the analytic predictions of accuracy assume that base station corrections are continuously available, even though they are not. However, the base signal availability issue should be fixable with radio modem repeaters.

These figures indicate that the GPS signal drop outs occur at repeatable locations. Therefore, either magnetometer or pseudolite aiding would only be required near those locations and would be expected to fix the issues related GPS signal dropouts.

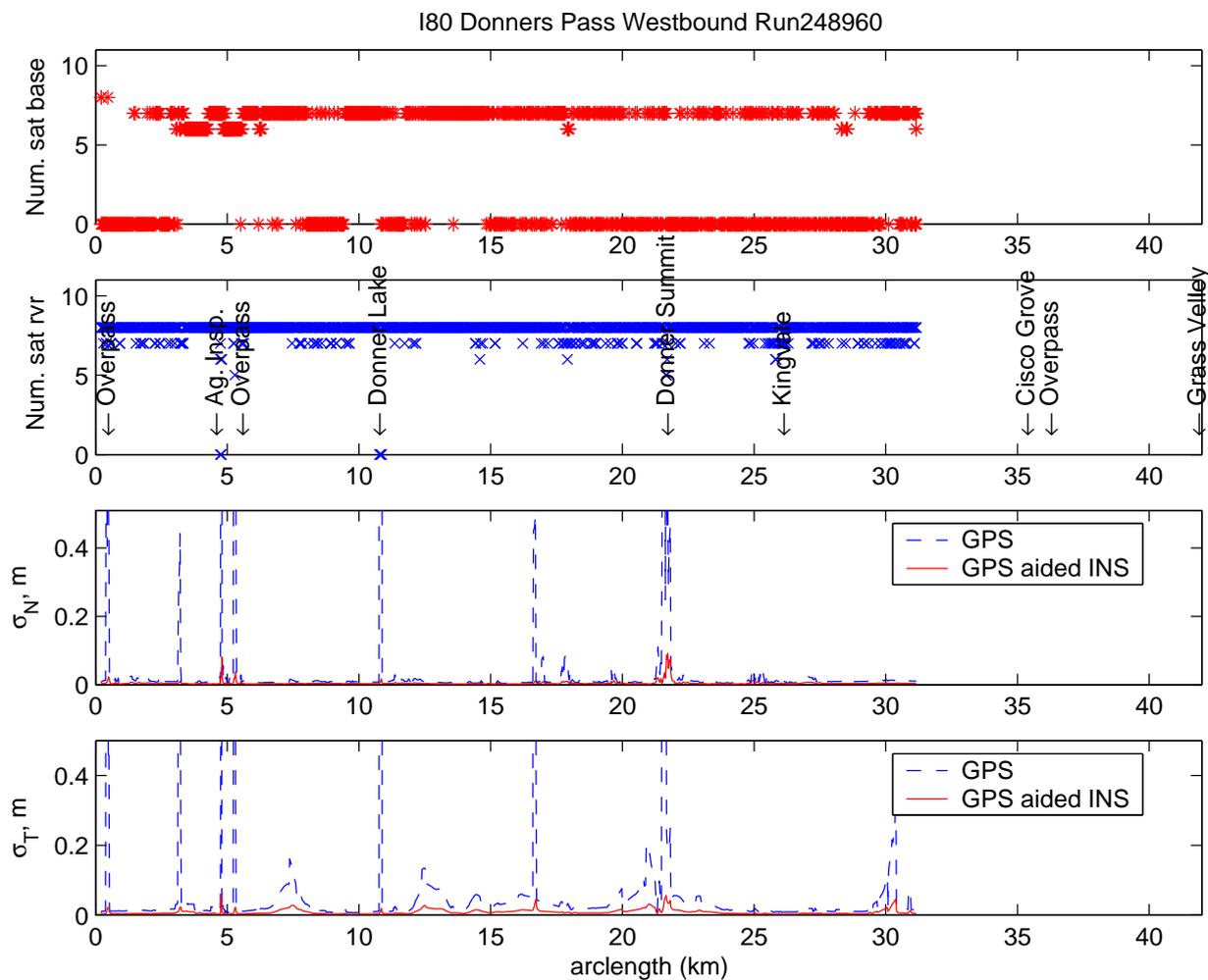


Figure 23: Top – Number of satellite DGPS corrections received from the base as a function of arclength. Second from top – Number of satellite measurements received at the rover versus arclength. Second from bottom – Position inaccuracy expected in direction perpendicular to the lane center as a function of arclength. Bottom – Position inaccuracy expected in direction parallel to the lane center as a function of arclength. Note that the scale of the bottom two graphs is artificially limited to 0.5m. Curves that exceed the axis limits may have position inaccuracy significantly greater than 0.5 m.

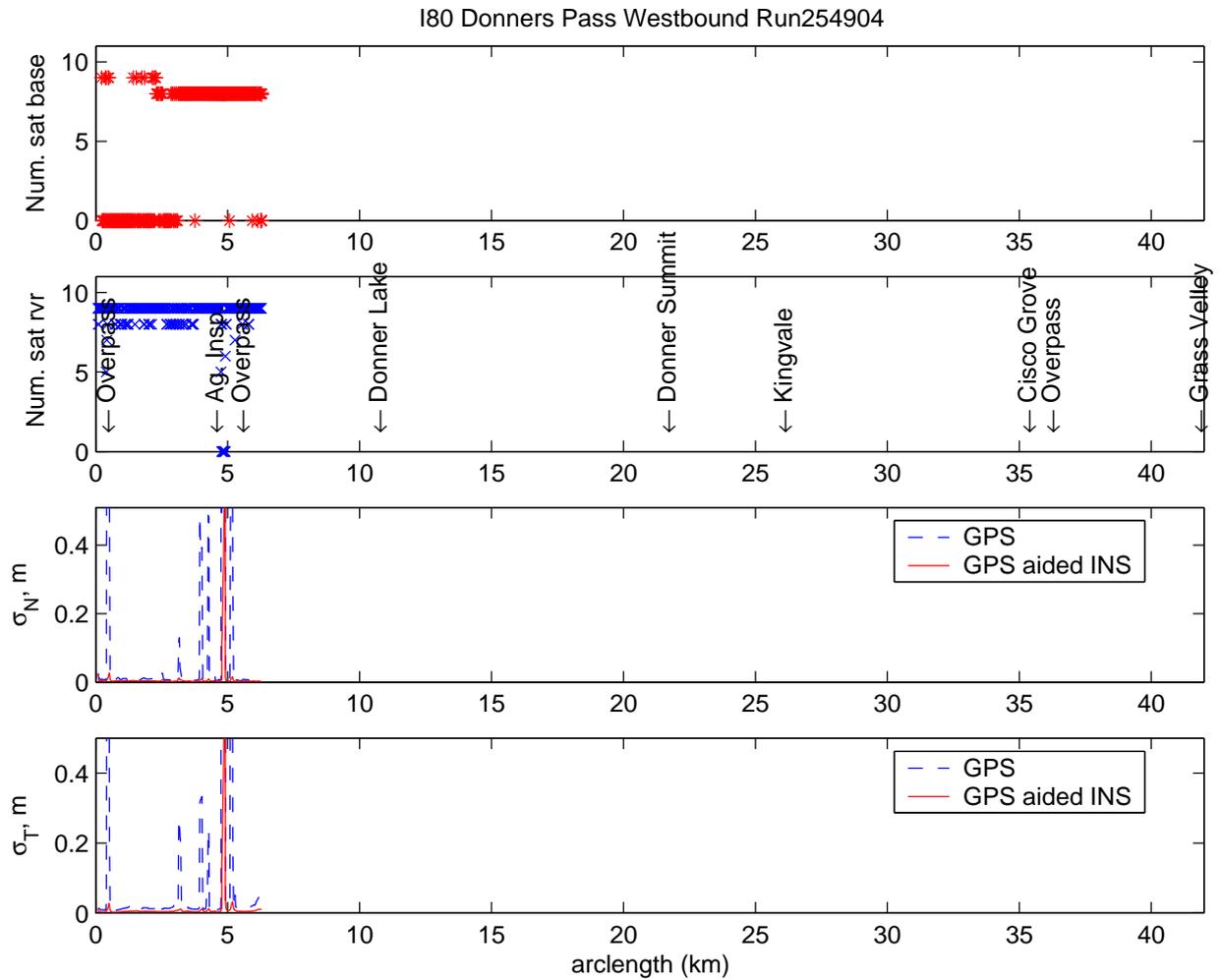


Figure 24: Top – Number of satellite DGPS corrections received from the base as a function of arclength. Second from top – Number of satellite measurements received at the rover versus arclength. Second from bottom – Position inaccuracy expected in direction perpendicular to the lane center as a function of arclength. Bottom – Position inaccuracy expected in direction parallel to the lane center as a function of arclength. Note that the scale of the bottom two graphs is artificially limited to 0.5m. Curves that exceed the axis limits may have position inaccuracy significantly greater than 0.5 m.

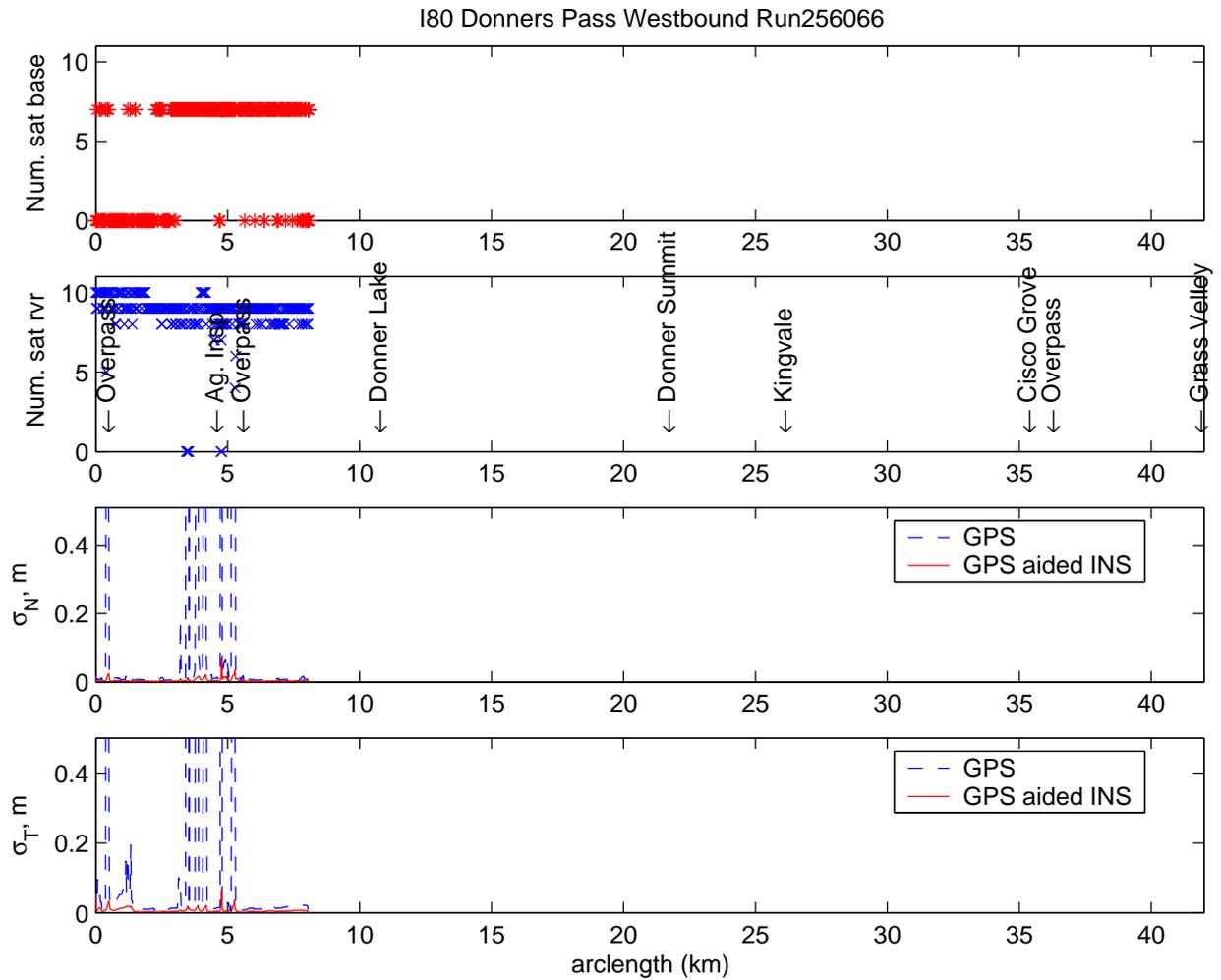


Figure 25: Top – Number of satellite DGPS corrections received from the base as a function of arclength. Second from top – Number of satellite measurements received at the rover versus arclength. Second from bottom – Position inaccuracy expected in direction perpendicular to the lane center as a function of arclength. Bottom – Position inaccuracy expected in direction parallel to the lane center as a function of arclength. Note that the scale of the bottom two graphs is artificially limited to 0.5m. Curves that exceed the axis limits may have position inaccuracy significantly greater than 0.5 m.

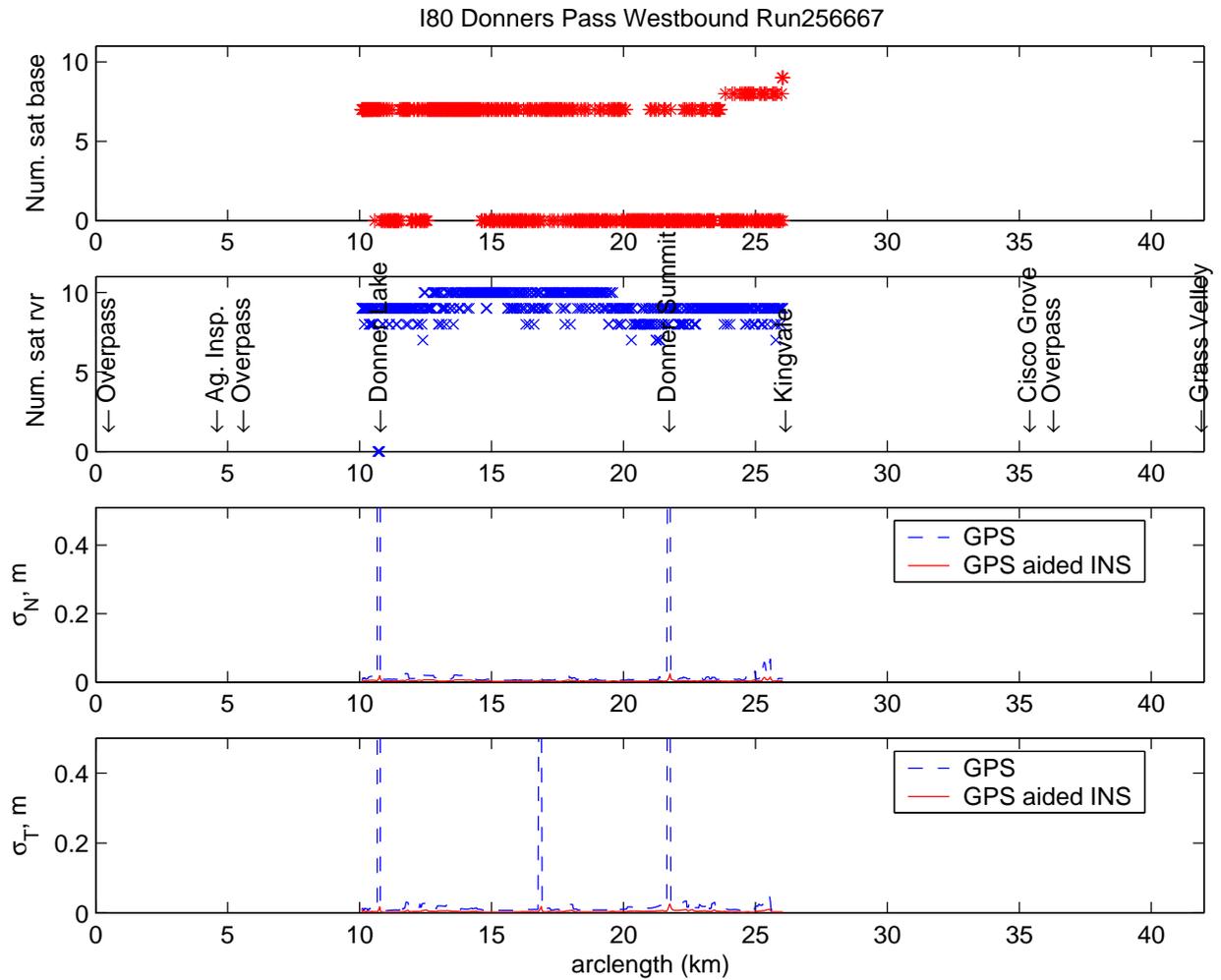


Figure 26: Top – Number of satellite DGPS corrections received from the base as a function of arclength. Second from top – Number of satellite measurements received at the rover versus arclength. Second from bottom – Position inaccuracy expected in direction perpendicular to the lane center as a function of arclength. Bottom – Position inaccuracy expected in direction parallel to the lane center as a function of arclength. Note that the scale of the bottom two graphs is artificially limited to 0.5m. Curves that exceed the axis limits may have position inaccuracy significantly greater than 0.5 m.

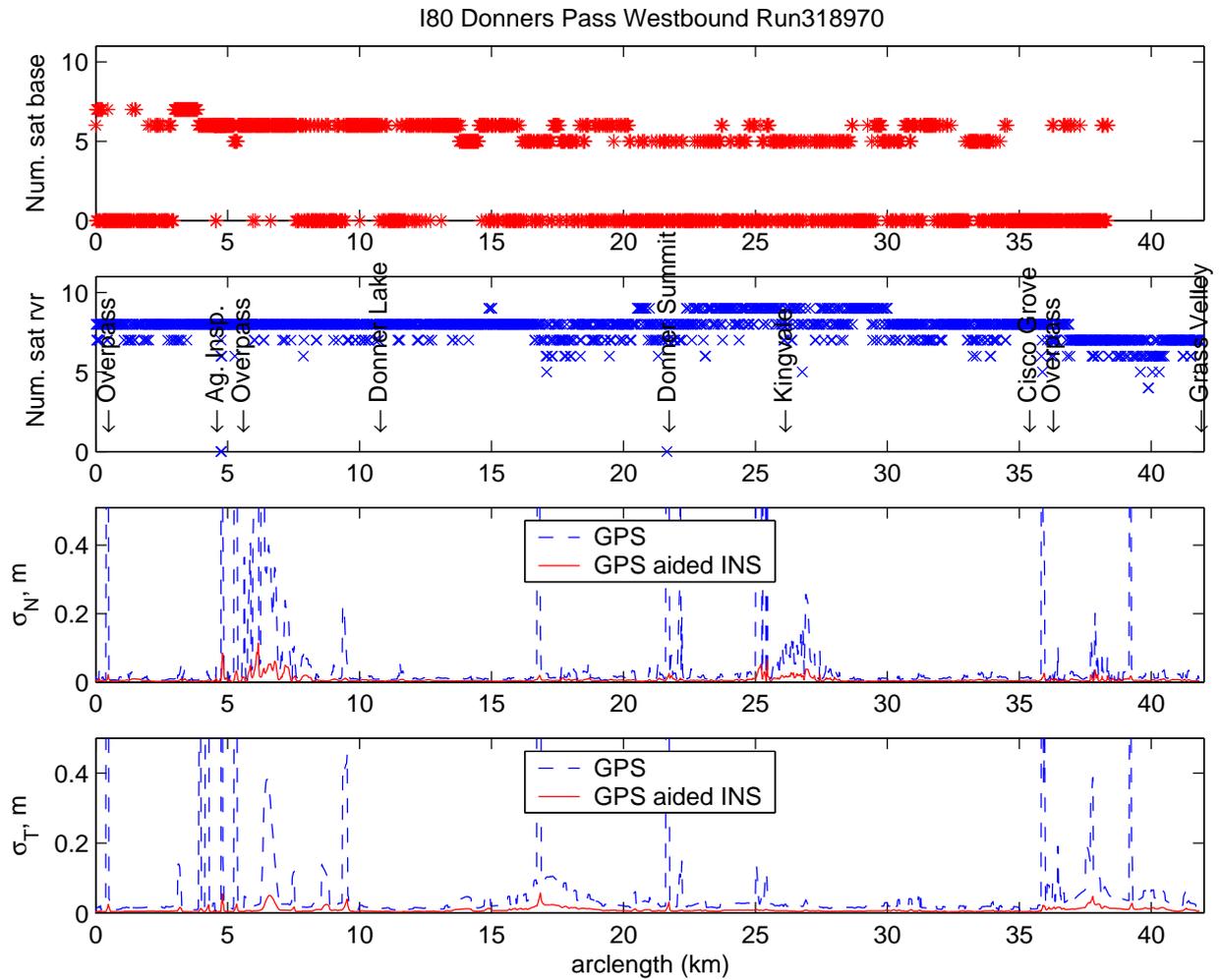


Figure 27: Top – Number of satellite DGPS corrections received from the base as a function of arclength. Second from top – Number of satellite measurements received at the rover versus arclength. Second from bottom – Position inaccuracy expected in direction perpendicular to the lane center as a function of arclength. Bottom – Position inaccuracy expected in direction parallel to the lane center as a function of arclength. Note that the scale of the bottom two graphs is artificially limited to 0.5m. Curves that exceed the axis limits may have position inaccuracy significantly greater than 0.5 m.

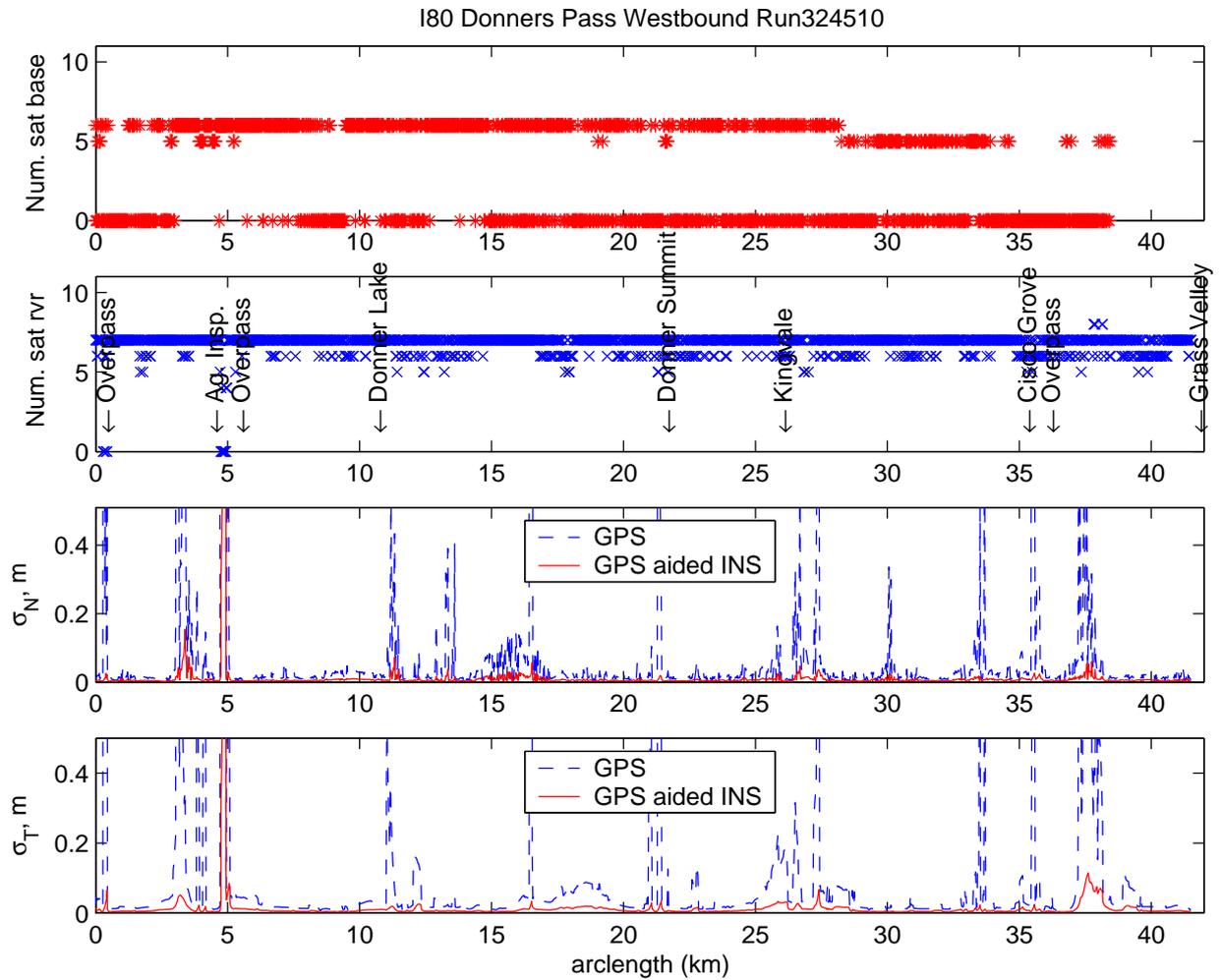


Figure 28: Top – Number of satellite DGPS corrections received from the base as a function of arclength. Second from top – Number of satellite measurements received at the rover versus arclength. Second from bottom – Position inaccuracy expected in direction perpendicular to the lane center as a function of arclength. Bottom – Position inaccuracy expected in direction parallel to the lane center as a function of arclength. Note that the scale of the bottom two graphs is artificially limited to 0.5m. Curves that exceed the axis limits may have position inaccuracy significantly greater than 0.5 m.

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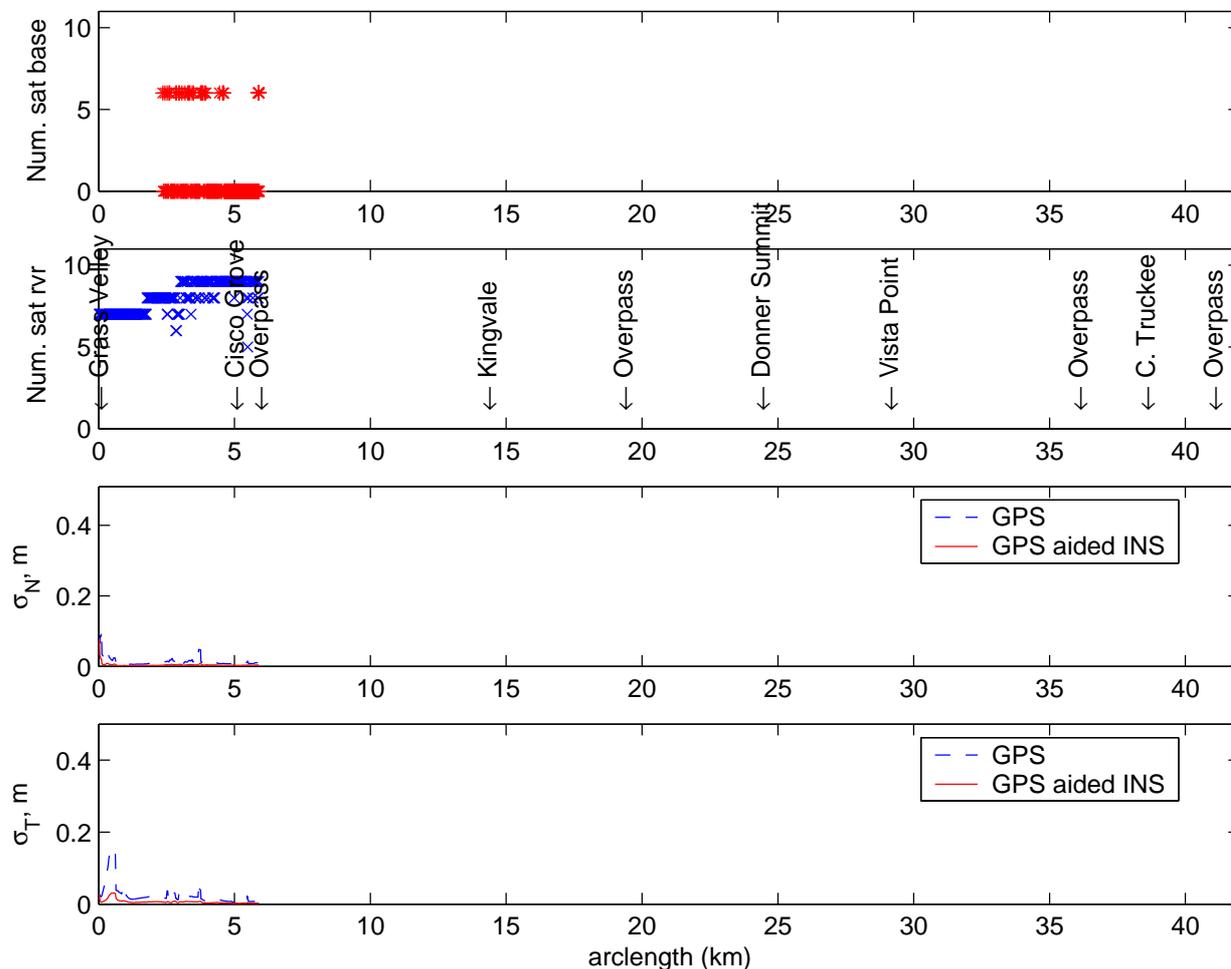


Figure 29: Top – Number of satellite DGPS corrections received from the base as a function of arclength. Second from top – Number of satellite measurements received at the rover versus arclength. Second from bottom – Position inaccuracy expected in direction perpendicular to the lane center as a function of arclength. Bottom – Position inaccuracy expected in direction parallel to the lane center as a function of arclength. Note that the scale of the bottom two graphs is artificially limited to 0.5m. Curves that exceed the axis limits may have position inaccuracy significantly greater than 0.5 m.

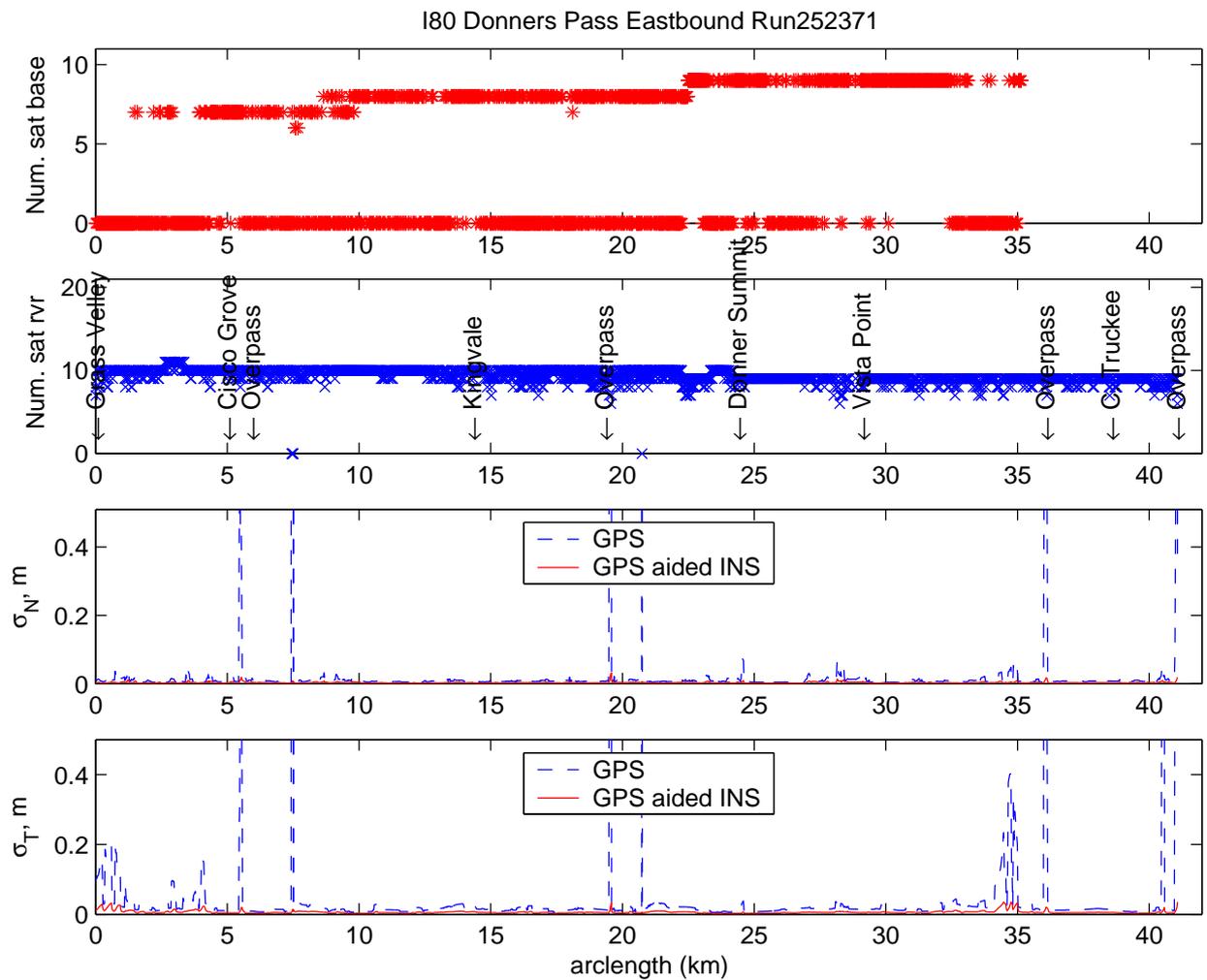


Figure 30: Top – Number of satellite DGPS corrections received from the base as a function of arclength. Second from top – Number of satellite measurements received at the rover versus arclength. Second from bottom – Position inaccuracy expected in direction perpendicular to the lane center as a function of arclength. Bottom – Position inaccuracy expected in direction parallel to the lane center as a function of arclength. Note that the scale of the bottom two graphs is artificially limited to 0.5m. Curves that exceed the axis limits may have position inaccuracy significantly greater than 0.5 m.

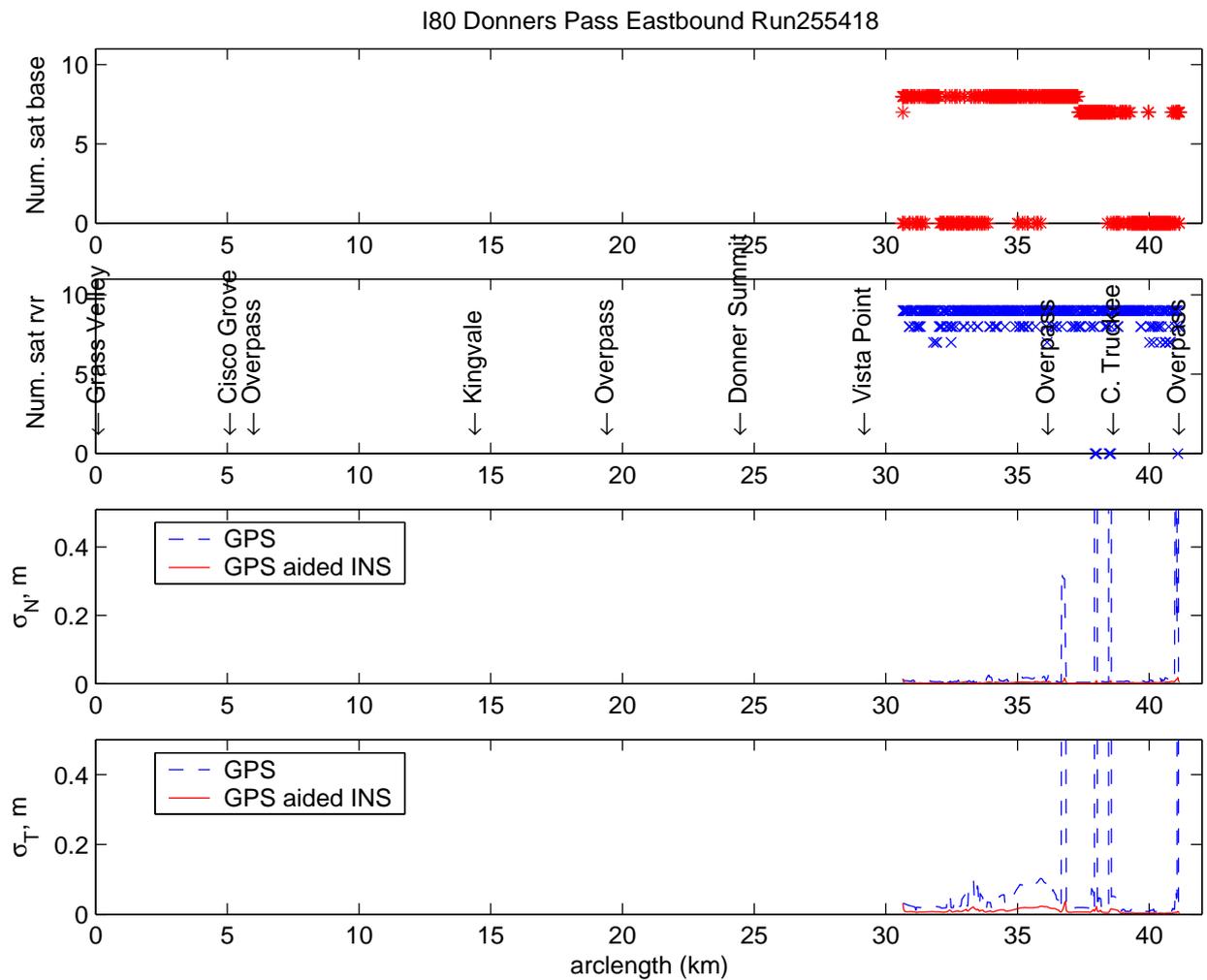


Figure 31: Top – Number of satellite DGPS corrections received from the base as a function of arclength. Second from top – Number of satellite measurements received at the rover versus arclength. Second from bottom – Position inaccuracy expected in direction perpendicular to the lane center as a function of arclength. Bottom – Position inaccuracy expected in direction parallel to the lane center as a function of arclength. Note that the scale of the bottom two graphs is artificially limited to 0.5m. Curves that exceed the axis limits may have position inaccuracy significantly greater than 0.5 m.

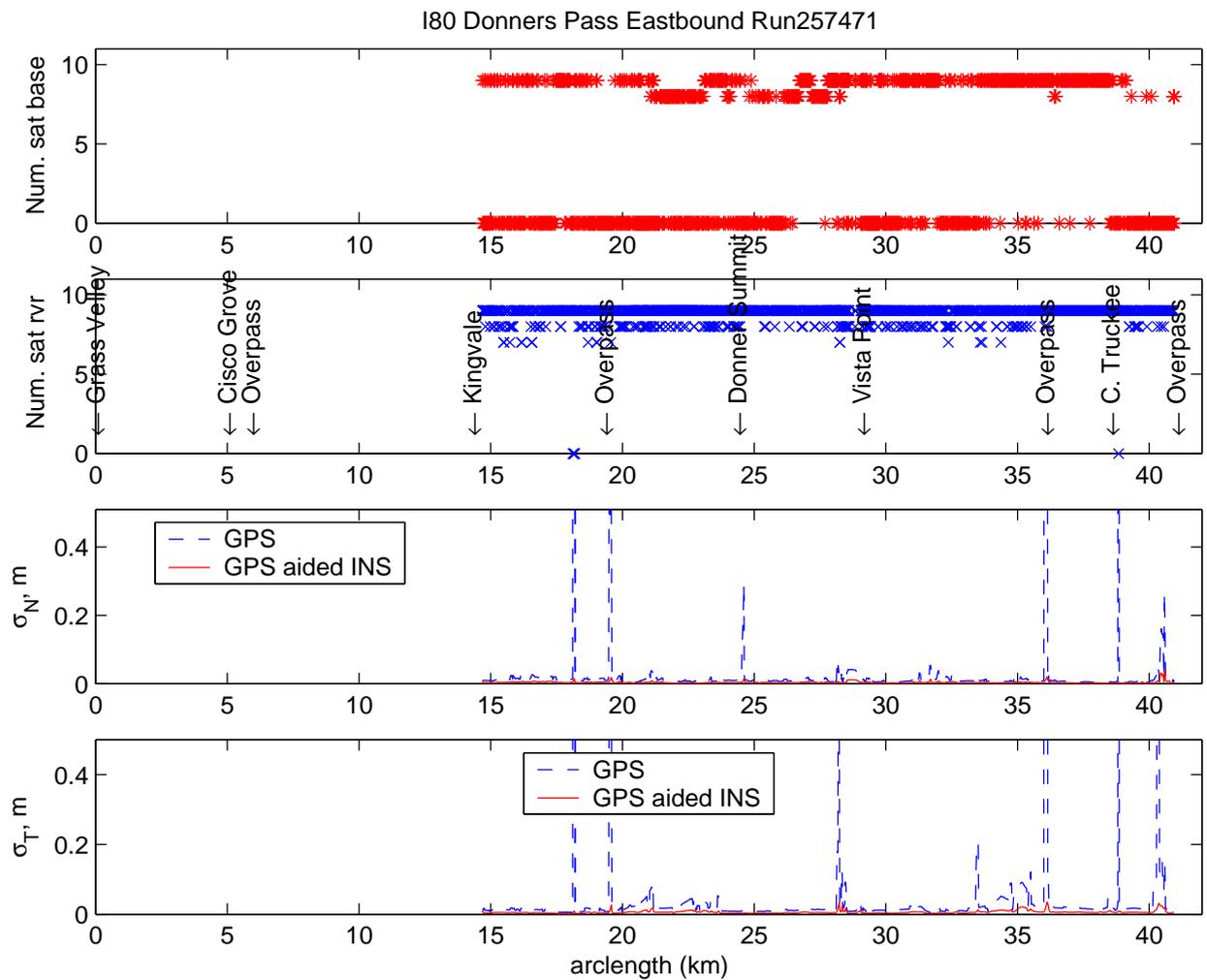


Figure 32: Top – Number of satellite DGPS corrections received from the base as a function of arclength. Second from top – Number of satellite measurements received at the rover versus arclength. Second from bottom – Position inaccuracy expected in direction perpendicular to the lane center as a function of arclength. Bottom – Position inaccuracy expected in direction parallel to the lane center as a function of arclength. Note that the scale of the bottom two graphs is artificially limited to 0.5m. Curves that exceed the axis limits may have position inaccuracy significantly greater than 0.5 m.

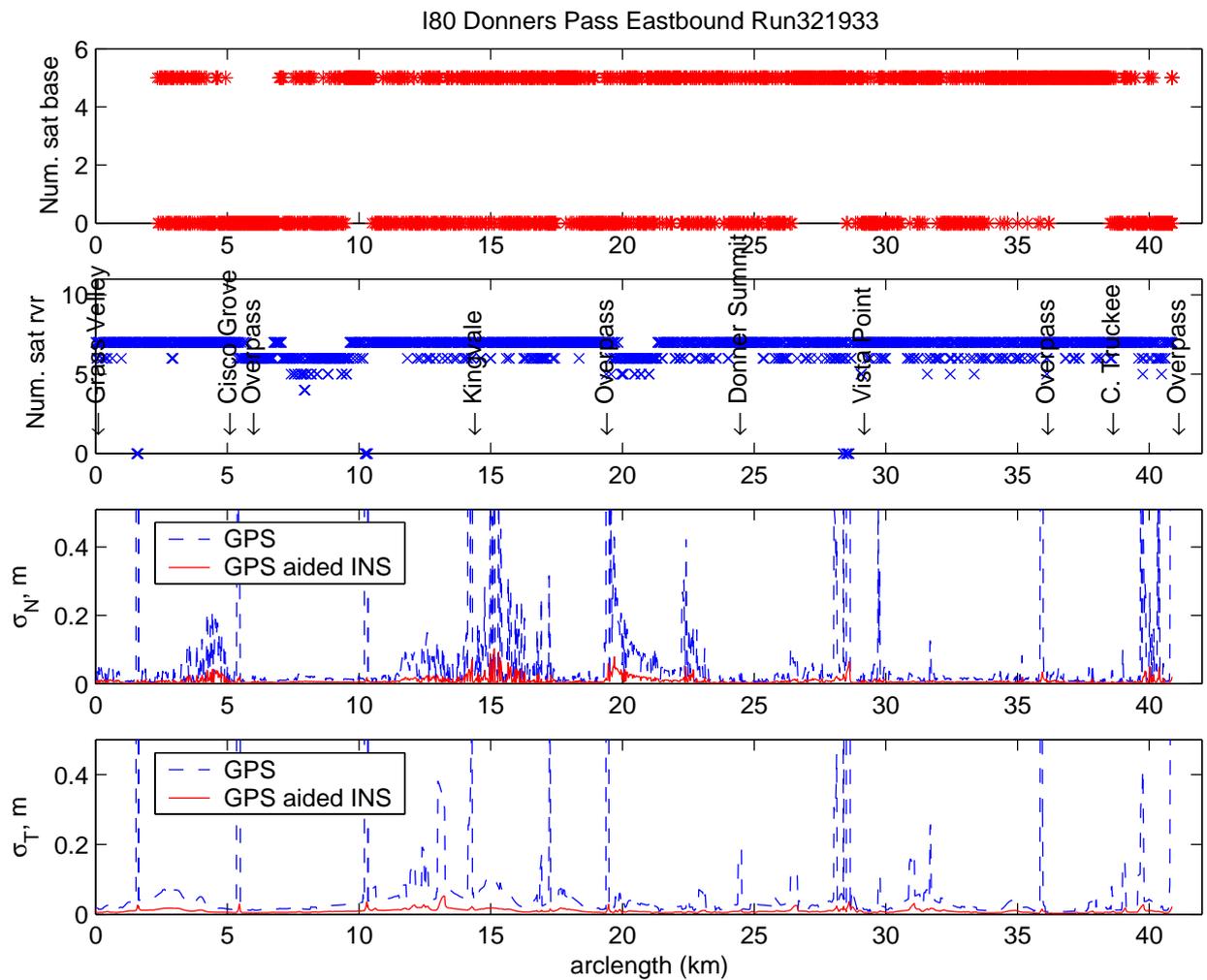


Figure 33: Top – Number of satellite DGPS corrections received from the base as a function of arclength. Second from top – Number of satellite measurements received at the rover versus arclength. Second from bottom – Position inaccuracy expected in direction perpendicular to the lane center as a function of arclength. Bottom – Position inaccuracy expected in direction parallel to the lane center as a function of arclength. Note that the scale of the bottom two graphs is artificially limited to 0.5m. Curves that exceed the axis limits may have position inaccuracy significantly greater than 0.5 m.

6.3 UCR Base

For setting up a temporary DGPS base station, if necessary in the future, there is National Geodetic Survey marker located along the frontage road above Donner Lake. It is implanted in a large stone about 10 m south of the road along the curve below the overlook. It is well marked. There is space adjacent to it to park a car, if required for power. The NAD83 coordinates and marker information are

Latitude	39:19:2.06651 N
Longitude	120:19:3.60282 W
Ellipse height	2046.24 m
Geod. height	-23.19 m
PID	KS0107
Destination	V1201
ECEF X	-2,495,029.505 m
ECEF Y	-4,266,710.430 m
ECEF Z	4,020,922.809 m

The marker was located on the afternoon and evening of August 27, 2003. The UCR base station was set up on the marker. It broadcast corrections using a Freewave spread spectrum modem. The DCPGPS aided INS worked very well in the vicinity of the base station. Several runs of the DCPGPS aided INS were attempted on the I80 in the vicinity of Truckee; however, the modem signal was too weak to be reliably received. Future on-site test will attempt to use the Caltrans base station with the UCR DCPGPS aided INS.

7 Phase 1 Results

The objectives stated for phase 1 of this project were:

Initial site analysis testing. Our assessment is that there are no insurmountable barriers to successful demonstration of carrier phase GPS aided INS along the I80 in the vicinity of Donners Pass. The data contained herein demonstrate that the number of available GPS satellites is sufficient to maintain the INS accuracy assuming that certain technical challenges can be overcome:

- GPS signals may be blocked by terrain or man-made features. These locations can be addressed by local augmentation or enhanced receiver technology.
- The base signal is not currently reliably received. This can be addressed either by use of modem repeaters, cell phone modems, or correction prediction methods.

Infrastructure development: Purchase equipment. Leica GPS receivers, freewave modems, and YH-Tek IMU's were purchased and the integrated system was constructed to support the project.

Infrastructure development: Vibration isolation and environment protection enclosure. The enclosure and vibration isolation system were purchased modified and tested.

Infrastructure development: Snowplow GPS/INS mounting development. PATH and UCR collaborated to mount the hardware on a Snowplow that was on loan to PATH.

Infrastructure development: CPDGPS/INS software modifications and system test. The existing software was modified to accommodate the hardware changes that resulted during Task 2.

Infrastructure development: Software modifications for the HMI. PATH's HMI software was modified by PATH to accommodate the CPDGPS aided INS state information.

Test: Snow plow on-vehicle system test of CPDGPS aided INS. Due to PATH's involvement in various demonstrations in 2003, the work and funding for this task were delayed to 2004. In early September 2004, testing was performed on a snowplow at the PATH facility. The test required surveying of a base location at PATH on September 7, 2004. Testing was performed on September 8-9, 2004. Testing showed the need for power stabilization hardware within the GPS/INS system due to poor power quality on the snowplow. Otherwise, the GPS/INS performed at the same performance levels on the snowplow as it had in previous vehicle demonstrations.

Trajectory Curve Fitting. Matlab software was developed to perform the curve fitting task. The software receives as input the latitude, longitude, and height data from a prior run when the vehicle was driven along the desired trajectory. The software performs a curve fit which smooths the data and outputs the parameters of the curve fit. These parameters are used by the GPS/INS software on future runs to compute the state of the vehicle relative to the stored trajectory.

8 Conclusions

This report discusses results of Phase I of the project 65A0148 and includes detailed analysis of data collected on the I80 in the vicinity of Donner Pass (i.e., between Sierraville and Grass Valley. The raw data, as expected, shows that there are local stretches of the I80 where the Caltrans base station signal is not reliably received at a near 1 Hz rate and that there are stretches of the I80 where a sufficient constellation of GPS signals are not reliably received. These stretches appear to be localized and repeatable. Therefore, the base station reception issue should be fixable using radio modem repeaters. The GPS signal reception should be addressable by the augmentation methods originally proposed (e.g., magnetometer, roadway altitude, pseudolite, or ultratight aiding) or by advances in GPS receiver technology that are currently either proposed or already in progress. Use of these methods will be investigated in the Phase II of the project.

9 Contact Information

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