Evaluation of In-Vehicle GPS-Based Lane Position Sensing for Preventing Road Departure

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Abstract

Determining a vehicle's lateral position in a highway lane is important for many applications - preventing run-off-the-road accidents, determining erratic driving behavior based on vehicle motion, providing feedback to the driver under low visibility conditions, etc. We present a systematic method for quantifying the dynamic performance of Differential GPS, in particular, the Novatel RT-20 DGPS unit. This is achieved by using an image processing approach.

Novatel's RT-20 Double Differencing Carrier Phase Measurement System is specified to achieve real-time positioning performance of better then 20 cm nominal accuracy. This paper documents the results from a series of dynamic tests carried out on the RT-20 to verify its actual accuracy while on a moving vehicle. The approach adopted here incorporates synchronized data acquisition using two separate computer systems, and experimental verification of the computational latency of the RT-20. The image processing scheme used for this analysis achieved high accuracy by taking advantage of subpixel resolution in the image processing algorithm.

Our results indicate that the RT-20 system exhibited a mean error of 2.03 cm in the lateral direction, and 3.16 cm in the longitudinal direction (note that both lateral and longitudinal are with respect to the moving truck) while moving at speeds ranging from 15 mph through 40 mph. The corresponding error standard deviations were 1.98 cm and 34.87 cm respectively. Our main interest is in the lateral positioning performance of the RT-20, which turns out to be very good. Furthermore, we believe that the longitudinal error standard deviation exhibited by the RT-20 can be reduced further by using an algorithm that eliminates the outlier data points.

1 Background

The University of Minnesota, in conjunction with the Minnesota Department of Transportation, is investigating means for reducing roadway departure incidents typically associated with driver fatigue. As part of this program, we are working on highway lane sensing strategies that can robustly operate under road and weather conditions typical of northern climates, and guidance systems that are capable of aggressive intervention, i.e. take over vehicle control in case the driver of the vehicle becomes incapacitated for whatever reason.

The methodology and experiments described here, represent the second phase of our efforts towards characterizing the NovAtel RT-20 differential GPS (DGPS) receiver for real-time dynamic positioning. Furthermore, we intend to use this or other DGPS in conjunction with inertial measurement for evaluating the ability of radar to detect obstacles under regular and adverse weather conditions. Recently, we also demonstrated the feasibility of using DGPS position information for projecting lane boundaries to the driver using a Heads-Up Display (projected on the front wind-shield) as an approach towards aiding driver perception of road edges and helping the driver make "informed" maneuvering decisions under poor visibility conditions.

The measurement methods for evaluating the dynamic accuracy of this or other DGPS are equally applicable towards characterizing many other lateral position sensing systems (eg. magnetic tape, vision based systems etc.). We begin with a description of our experiment design, and then give a detailed account of the evaluation results for the NovAtel RT-20 Differential GPS.

In the first phase of DGPS evaluation [2], we found that the Novatel RT-20 exhibited reasonably low error levels despite the fact that our experimental design at that time did not feature absolute synchronous data acquisition. However, even in a non-synchronous data acquisition mode, we are able to use the RT-20 as a principal lane-keeping sensor [4]. We re-designed our experimental setup to allow for time-stamped synchronous data collection. The results obtained in this second phase of DGPS evaluation show that the DGPS performs better than previously reported [1]. We are now working on modifying our controller to use the more efficient mode of data collection described further in this paper. This paper also features a discussion on the internal latency of the RT-20, and presents our approach used for experimental measurement of the RT-20's internal latency.

2 Experimental Design

The ground truth used for all these experiments was the set of pre-surveyed location coordinates in the State Plane system (referred to later as survey-nails), lining the Mn/Road research facility's low volume test road. Figure 1 illustrates the Mn/Road pavement test road and the survey-nails along the track. We ran several experimental runs using

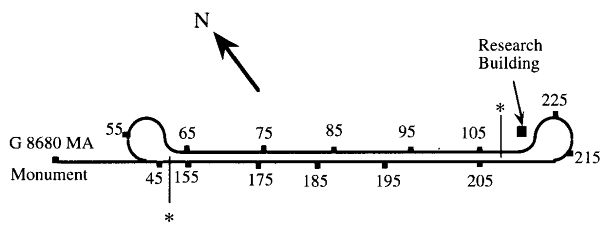

Figure 1: Mn/Road Test Facility (Wright County, MN) showing survey-nail locations (from Bodor et al [1]).

survey-nails numbered 194 through 179 (in that order while travelling in the North-West direction) for the experiments described here. White ceramic tiles measuring 12"x12" (accurate to within 0.1 mm) were placed at each survey-nail such that one corner of each tile was located exactly at the survey-nail. The tile corners that were placed exactly on the survey nails were marked for later reference during the image processing. The tiles were aligned with the South-North axis in order to verify the orientation angle made by the truck during the runs. The white tiles provided a good contrast against the color and texture of the road for image processing. Figure 2 depicts the principle of relative measurement used in our evaluation. DGPS specified positions were compared with those of the pre-surveyed survey-nails in image processing, and error offsets were generated. This is described in section 4. We aligned a CCD camera with high shutter speed (1/4000 sec) directly below the GPS receiver antenna and mounted them as a unit about a foot off the side of the truck (see Figure 3). A computer-controlled time-stamp VCR (JVC BR-S822 DXU) recorded the images of the tile from the camera and encoded each frame with a time-stamp.

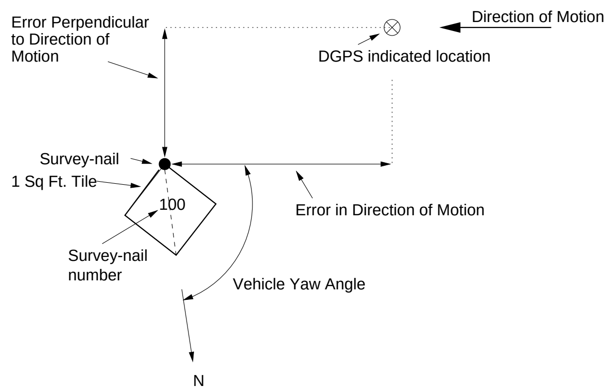

Figure 2: Calculation of Dynamic Errors based on Tile Images

The real-time accuracy of this VCR was specified to be no worse than 1.8 seconds per hour (about 1 part in 2000). We used two separate computer systems to accomplish the synchronized data collection, which was the most important feature of these experiments. A PC laptop (C1) running the Novatel WinSat software was used to record the data logs sent out by the RT-20 over the COM 1 serial port. While position data was logged regularly at a rate of 5 Hz, GPS time-stamp data was logged in response to triggers supplied by the second computing system, viz. a Motorola MVME 147 embedded processor running VxWorks (C2). During each run, C2 sent out "mark pulses" at regular intervals of 200 ms (frequency of 5Hz) to the "mark input" of the RT-20 system. For each pulse sent out, C2 recorded the corresponding time-stamp from the VCR and the rate gyro data, while C1 recorded the GPS time-stamp sent out by the RT-20, and also the other data logs specified at startup. Figure 4 shows the signal timing diagram that was used as a reference in the present experimental design. The first row illustrates the "mark pulse" (specified by Novatel Communications Ltd.). The second row shows the mark time log referenced as the "MKTA GPS time-stamp signal" corresponding to the instant of detection of the falling edge of the "mark pulse" by the RT-20, that is sent out to C1. Row 3 shows the P20A position data signals as bands of pulses packed together in sets regularly spaced at 200 ms. The next two rows show the VCR time stamp data (corresponding to the falling edge of the mark pulse), and the gyro data, that are recorded (by C2) after the "mark pulse" is sent out by C2. Figure 5 illustrates the interconnections between the different pieces of hardware used in the setup. Note that for the present set of survey nails, it was not necessary to use the rate gyro data for computing any geometrical compensations.

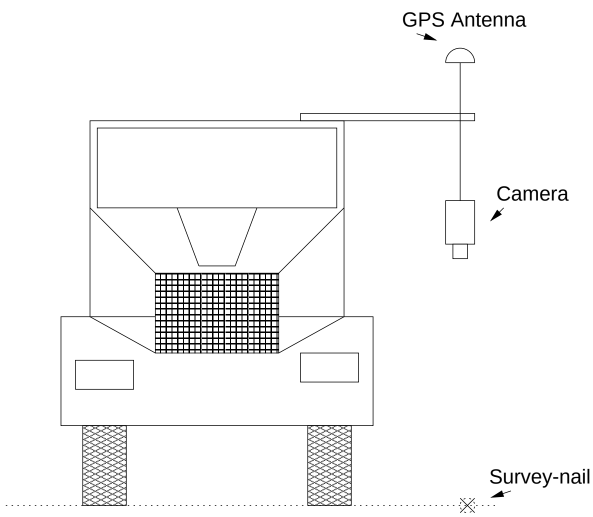

Figure 3: Measurement Setup for Evaluating the DGPS

Attempts were first made to extract the GPS computed data from the RT-20 using one of the available built-in transputer links, based on the idea that such an approach might possibly eliminate the delay involved in serial data acquisition. However we ran into complications with the availability of a necessary synchronizing clock signal accurate to within 40 ns, and developing a custom interface using a link adapter. Further research revealed that the primary cause for the quoted 70 ms nominal latency in the data log was the high processing overhead on the transputer, and as such, "faster" data acquisition would not change the basic latency.

3 Experimental Procedure

Two discrete sets of experiments were conducted. One for the actual GPS data collection with the RT-20 for accuracy testing, and the other set for examining the latency in the data log transmitted by the RT-20 over its serial port.

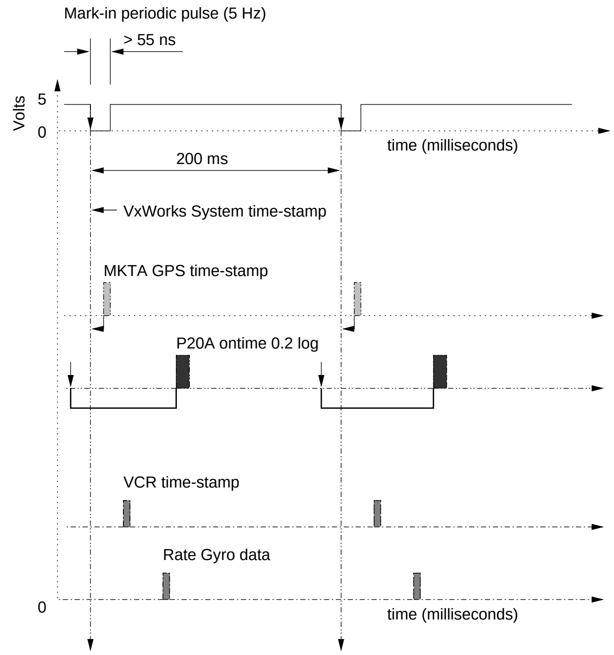

Figure 4: RT-20 signal timing diagram

3.1 GPS Data Collection

Eight runs were made along the portion of the MnRoad track identified earlier, at speeds ranging from 15 mph through 40 mph. These runs were done one after the other spanning over 2 hours. Before starting the first run, enough time (approximately 45 minutes) was allowed for the RT-20 to converge to an accurate solution. We used the P20A position data log along with the MKTA GPS time-stamp data log at 9600 baud and monitored the differential correction flag to ensure that differential correction signals were being received.

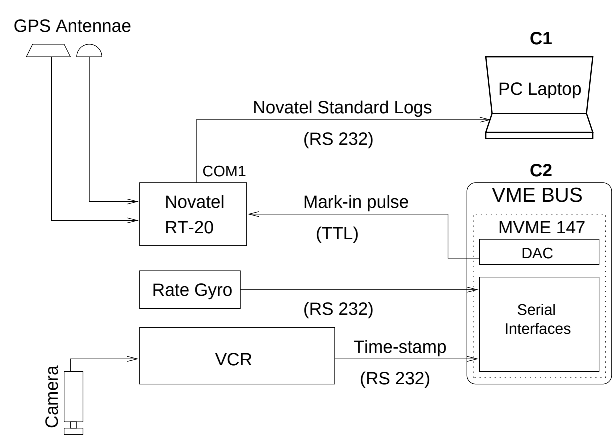

Figure 5: Data acquisition setup

3.2 Latency Measurement

We define the computational latency of a GPS position data log transmitted over either the COM1 or COM2 by the RT-20 unit as the time period between the instant at which a measurement in space corresponding to a transmission was made, and the the instant at which the serial transmission began. Note that the computational latency together with the data acquisition delay (time required for the data to travel on the serial line to the host data acquisition computer) comprises the total latency associated with a given data log.

With technical guidance from NovAtel, we were able to measure the latency of the RT-20 using signals that are available at the output connectors of the unit. We used the following signals:

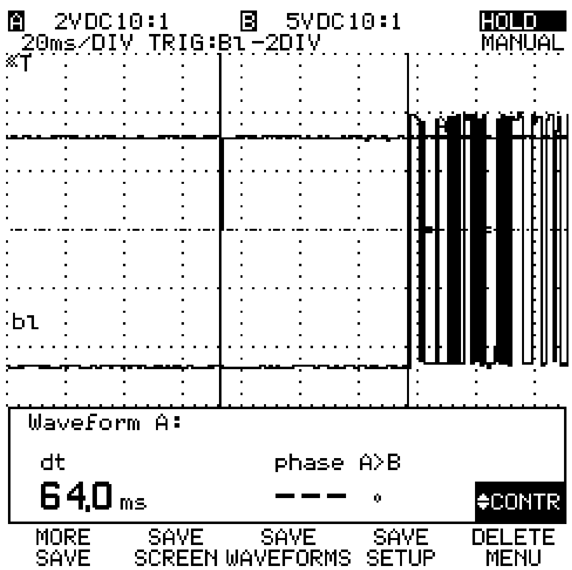

Figure 6: Image of scope meter screen used for Latency Measurement. 'dt' is the time measured between the two cursors = 64ms. The first vertical line represents the first cursor, it overlaps with the "Measurement made" signal which is a single falling spike. The second vertical line to the right of the first represents the second cursor, it is placed at the first rising edge of the data transmission signal from the RT-20.

- "Measurement made" signal = Pin 3 on the DB 9 connector marked as I/O on the RT-20 unit.
- Ground for "measurement made" signal = Pins 6,7,8 on the I/O DB 9 connector.
- Serial data was acquired over the COM1 line (DB 9: Pin 3).
- Ground for the serial data was provided on COM1 line (DB 9: Pin 5).

All measurements were made with a scopemeter (Fluke 105B Scopemeter Series II) which had provision for freezing the display of waveforms to be measured; this helped us make accurate measurements using the provided cursors. Figure 6 shows a sample latency measurement setup on the screen of the scope meter. The time-phase difference between the "measurement made" signal and the first appearance of the serial data is the computational latency (shown as 64 ms in Figure 6).

4 Data Processing

We processed only those GPS data that had a corresponding reference measurement (based on a tile image stored by the VCR at that time instant) against which to determine its absolute accuracy. Subsequent steps involved the conversion of position coordinates provided by GPS (in degrees latitude, longitude) to State Plane coordinates, the determination of the error offsets using the data from the images, and conversion of final errors back to the truck (i.e. the local travelling) coordinate system. Since this experimental design used GPS timestamps to achieve record matching in the time domain, the position estimates provided by the P20A RT-20 log were interpolated based on their timestamps, and the corresponding time stamps provided by the MKTA RT-20 log. Each P20A log captures the time at which satellite data was received and the position solution computation began. The MKTA time-stamp captures the GPS-time that is aligned with the VCR frame time-stamp. We use the MKTA time-stamp to interpolate the position stored in two consecutive P20A logs. Thus for every VCR frame, we have a corresponding GPS specified position. Image processing of the VCR frame results in the identification of the true position of the truck at that instant. This is then compared with the GPS specified position, and the error is determined.

4.1 Image Processing

The Image Processing Subsystem (IPS) consisting of a group of appropriate algorithms, was developed in order to extract the error "offsets" from the images of tiles. The images were first digitized from the video cassette taped on the JVC VCR, using a Silicon Graphics workstation. Each image (Figure 7 shows a sample video image) was then processed using the IPS. The IPS is briefly described below.

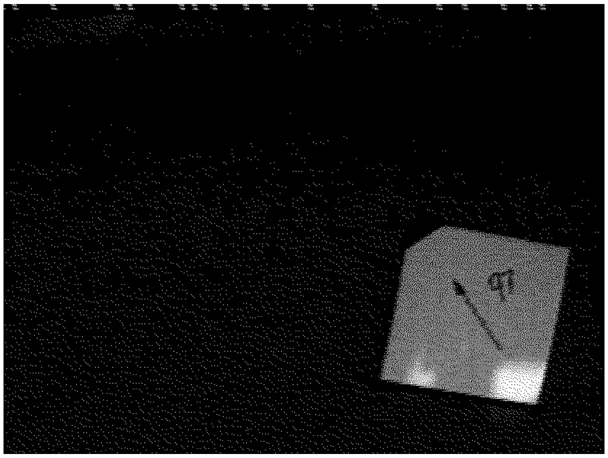

Figure 7: Sample Video Image of a Tile (located at Survey Nail number 97). Arrow points to the Survey Nail, and is aligned along North-South i.e. arrow points in the North direction.

General Description of the IPS : After the image file name is specified, the IPS loads up the image. This is followed by specifying the location of the "mask" window (of pre-determined size dependent on the true size of the tile) such that the mask surrounds the tile in the image. Separate routines then perform the edge detection (using a Laplacian of Gaussian Kernel), and line fitting (using the Hough Transform) operations on the tile. Next the program prompts for an identification of the tile corner 'C' at which the survey-nail was located. This is done manually based on visual recognition of a marking on the corner of the tile. This could have been automated but the time for developing the code was limited. The IPS proceeds to compute the error offsets (which from the IPS point of view are the coordinates of the corner 'C' w.r.t the center of the image) and the orientation angle of the truck (which is the angle made by the marked diagonal of the tile with the horizontal image axis in the clockwise direction). The IPS then creates a new record in the data file "info.asc" for the processed image and writes all the relevant computation results described in the previous section. Other items are briefly described below:-

• Input parameters to the IPS include the true tile size (e.g. 12"), and the name of the image file containing that tile.
• The Image file name and the position of the mask (approximately centered over the tile in the image) are manually entered.
• The processing time per image is about 15 seconds.
• The Resolution of all the images processed was based on NTSC (640 x 480 pixels).
• The IPS generates results with sub-pixel level accuracy.
• A dynamic calibration is performed based on the true tile size for every image. Dimensionless scale factors ScX and ScY (in the X and the Y directions respectively) are returned in the record for that image in the output data file. The offsets (in the X and the Y directions) reported by the IPS in the output file are divided by ScX and ScY respectively to get the values of the offsets in actual units (inches).

5 Results and Discussion

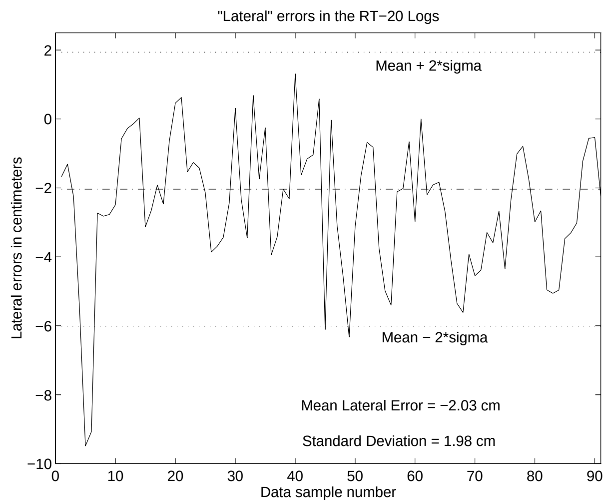

Figure 8: "Lateral" Errors in the RT-20 Position Solution (for eight runs from Survey Nail number 194 to Survey Nail number 179 at speeds ranging from 15 mph to 40 mph

Figures 8 and 9 show the lateral and longitudinal errors that we determined in the RT-20 position solution. The mean lateral error was found to be -2.03 cm, while the mean longitudinal error was -3.16 cm. The corresponding error standard deviations were 1.98 cm, and 34.87 cm respectively. We collected 91 data samples from 8 runs over the portion of the track indicated earlier. This represents a statistical level of confidence of 99 percent.

Note that the longitudinal errors in this case do not need to be compensated for latency. Synchronization and record matching for data processing are both done on the basis of GPS time-stamps, which indicate the exact time at which the signals were captured from the GPS satellite, to which the finally computed GPS data correspond. It is not

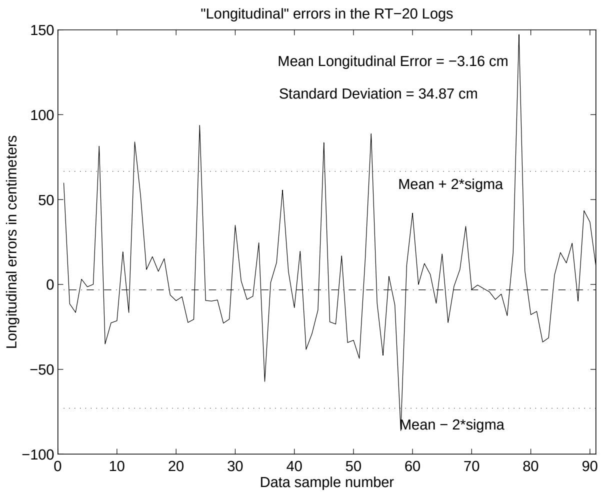

Figure 9: "Latency Compensated" Longitudinal Errors in the RT-20 Position Solution (for ten runs from Survey Nail number 87 to Survey Nail number 105 at three different speeds)

necessary to know when the computations were actually completed (start-time + latency) inside the RT-20; because in this experimental design, we do not "synchronize" based on the data acquisition, but rather on the initial capture trigger data and its time-stamp.

Several groups have evaluated DGPS for applications requiring significant dynamic accuracy requirements. Studies such as that at SRI [3] categorize GPS performance based upon the convergence algorithms used. According to the information presented in that study, GPS receivers using the narrow correlator technology equipped with robust floating point ambiguity resolution techniques should exhibit dynamic accuracies at the 10 cm level. It seems that the Novatel RT-20 does much better than 10 cm if appropriately used.

The method presented here can be applied to the accuracy measurement of a variety of other sensors also. For example, if a rate gyro is to be tested, we can use the angle information derived from image processing to compute the rate of angle change, and compare with the measurement provided by the rate gyro.

In closing, it is important to note that the methods and the analysis of the Novatel RT-20 was motivated by the following two concerns:
1. The need to evaluate the performance of high accuracy, high bandwidth lateral position sensing technologies (DGPS, magnetic striping/magnetometer methods etc.) for a variety of applications including driver-assistive vehicle control systems [4].
2. The need for sensors that can provide instantaneous realtime position information used for an augmented display (such as a Heads-Up-Display) that would project the future course of the road on the windshield for navigational assistance under poor visibility conditions.

Our interest is clearly in the **lateral** positioning performance of the RT-20, which turns out to be very good. However, we think it is important to also investigate the causes for the large residual error standard deviations in the **longitudinal** direction, so that we can directly use the RT-20 or other similar systems, for evaluating other types of sensors, such as radar.

One of the issues that will ultimately limit the RT-20's use is a loss in satellite lock. If it takes a long time to re-converge every time that we go under an overpass, then other sensors will have to be used and evaluated, e.g., a dual frequency GPS receiver such as the Novatel RT-2 which recovers within a minute after a complete loss of lock. Gurthermore, we have found that going under overpasses does not always lead to a loss of lock. Reasonable performance can often be maintained. One solution to the satelite loss of lock problem is to put a receiver at the front and back of the truck, and synchronize the two of them. This study has also not evaluated the multipath rejection capabilities of the unit, a subject for further study.

6 Acknowledgements

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