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University of California at Davis
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**IN-SITU REFERENCING FOR DIFFERENTIAL
GPS CORRECTIONS IN IVHS***
(Intelligent Vehicle Highway System)

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ABSTRACT

This report discusses a method for generating differential GPS corrections in IVHS (Intelligent Vehicle Highway System) applications using reference markers inserted in the roadway pavement. The method will provide automated lateral control of the Automated Highway System (AHS) vehicles. In the past, application of DGPS for lane keeping in AHS has not been practical due to the lack of existence of enough differential base stations that provide the differential correction data. In this paper, we propose providing the differential corrections from carefully surveyed roadway discrete reference markers instead of ground base stations. The proposed method, IS-DGPS (In-Situ-DGPS), uses magnetic nails, as reference markers, planted along the centerline of the highway lanes, one every 50 to 100 meters. IS-DGPS requires less roadway infrastructure than the other AHS methods, resulting in lower implementation cost. In comparison with DGPS, IS-DGPS eliminates the problematic base-rover communication link and its associated latency and line of sight requirements. Furthermore, it eliminates or greatly reduces errors due to spatial decorrelation, such as the tropospheric effect. IS-DGPS can also be used with road maintenance vehicles in rural and mountainous areas where a DGPS correction signal can not be adequately provided.

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DISCLAIMER / DISCLOSURE

The content of this report reflect the views of the authors. The contents do not necessarily reflect the official views or policies of the STATE OF CALIFORNIA or the FEDERAL HIGHWAY ADMINISTRATION and the UNIVERSITY OF CALIFORNIA. This report does not constitute a standard, specification or regulation.

CHAPTER 1

INTRODUCTION

One of the goals of IVHS, or Intelligent Transportation System (ITS), is the implementation of an Automated Highway System (AHS). AHS can be envisioned as a system of instrumented vehicles and roadways in order to achieve hands-off and feet-off driving, where vehicles are fully automatically controlled. In order to achieve this fully automated operation, precise lateral control of the vehicle is required. Several methods have been proposed and demonstrated to perform highway lane sensing/lane following for use in vehicle lateral control. The most promising methods are the use of roadway discrete magnetic markers, a vision based system, and GPS. The success of the chosen method will depend on its reliability and the cost involved.

The California PATH group at UC Berkeley developed a vehicle lateral control system using discrete magnetic markers [4,5] (Figure 1). This approach requires the insertion of closely spaced magnets, 1.2 meter apart, for the entire length of each lane of the highways. The approach has been implemented and demonstrated on a strip of highway I-15 near San Diego. The demonstration showed a robust lateral control of the vehicle. The problem with this approach is that it requires major changes in the highway infrastructure at a high cost.

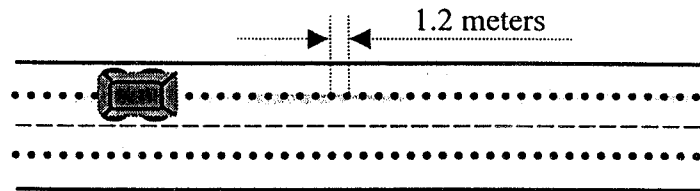


Figure 1: PATH approach

At Carnegie Mellon University [6] and other institutions a different approach was adopted using an image-based vision system. Roadway features such as high quality paint stripes, road edges and oil slicks are used in lane sensing. This approach also requires extensive vehicle and road infrastructure and maintenance. It also gives poor performance in poor weather and in poor lighting conditions.

SRI International presented a concept of AHS based on DGPS [7]. They proposed placing differential ground base stations along the highway in order to provide the differential corrections. In their paper, they demonstrated the method using a 1/4 scale model car going in a

circular trajectory, with a 200 m baseline. Their results showed a maximum error of 2 cm and an RMS deviation of 0.5 cm.

Bodor, et al. [8] used a DGPS system coupled with an IMU (Inertial Measurement Unit) to do highway lane sensing to prevent road departure in case the driver becomes incapable of handling the vehicle (for instance, the driver falls asleep). They used DGPS to sense the position of the vehicle and steer the vehicle to safety if it begins to run off the road. They used a single frequency carrier phase receiver in their experiments. The dynamic error perpendicular to the direction of motion was 4.57cm with a standard deviation of 39.6cm. The use of more accurate dual frequency GPS receivers would provide better numbers.

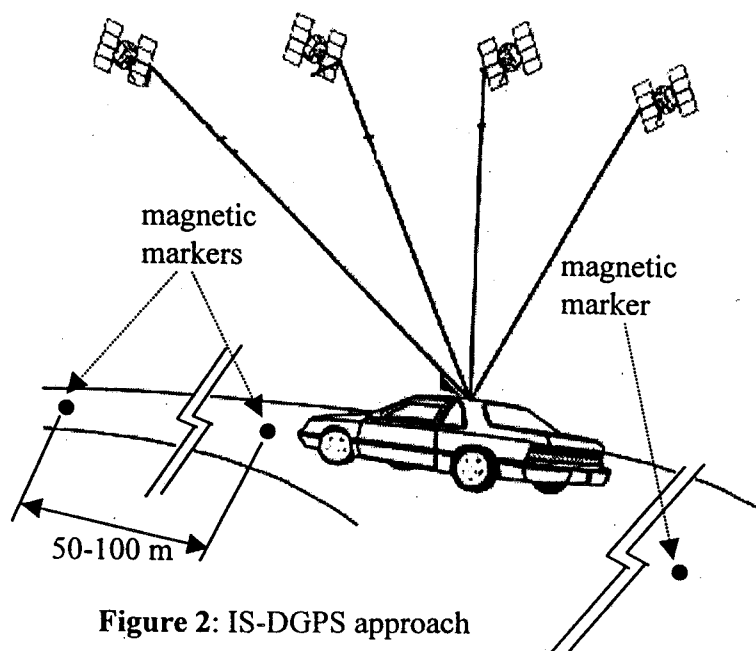
The need for differential ground base stations has limited the application of GPS technology for use in automatic guidance and control of vehicles on the nation's highways. There are two major problems with using the differential ground base stations on the highways. Firstly, establishing the base stations amounts to a major roadway infrastructure change at a high cost. One station is required every about 40 kilometers. Secondly, it has the inherent problem with the communication link between the base station reference receiver and the vehicle's receiver which prevents achieving accurate and continuous real-time kinematics RTK. Some of the problems with the communication link are:

- It requires a continuous line of sight.
- It requires no interruption in the data transmission.
- There is a rover-base distance restriction due to spatial decorrelation errors.
- There is a base to rover data transfer latency.
- There are delays in doing time matching between base and rover observations[2].

In this report, we propose using the GPS system for continuous positioning and sparse magnetic markers, similar to those used by PATH; to generate the differential corrections. This method is given the name: IS-DGPS (In Situ-DGPS) since the differential corrections are acquired using markers that are embedded in the infrastructure. The method requires only minor and low cost changes to the highway infrastructure. It does not require differential reference base stations and would only need sparse, rather than frequently placed roadway markers, (one every 50 – 100 m) (Figure 2). The marker locations would be accurately surveyed once with centimeter accuracy and then used to calculate the differential correction when the vehicle drives over them.

Lapucha et al'95 [2] stated the operational limitations of doing real-time kinematics (RTK) with differential GPS due to data link latency and time matching delays. Their argument strengthened the case of IS-DGPS to be a successful DGPS method with the carrier phase observable.

IS-DGPS can be applied with the C/A code observable as well as the carrier phase observable. In this report, the formulation is presented using both observables. Also, the formulation for using multi-antenna receivers is presented.



CHAPTER 2

IS-DGPS CORRECTIONS WITH CODE PSEUDORANGES

As the moving vehicle passes over a surveyed reference magnet A at epoch t_o (Figure 3), the code range model is written as:

$$P_A^j(t_o) = \rho_A^j(t_o) + \Delta\rho_A^j(t_o) - c \cdot dt_A^j(t_o) + c \cdot dT_A(t_o) + v_A^j(t_o)$$

where:

$P_A^j(t_o)$ & $\rho_A^j(t_o)$ are the pseudo- and the true ranges.

$\Delta\rho_A^j(t_o)$ is the orbital and atmospheric errors.

$dt_A^j(t_o)$ & $dT_A(t_o)$ are the satellite & receiver clock errors.

$v_A^j(t_o)$ is multipath and noise errors.

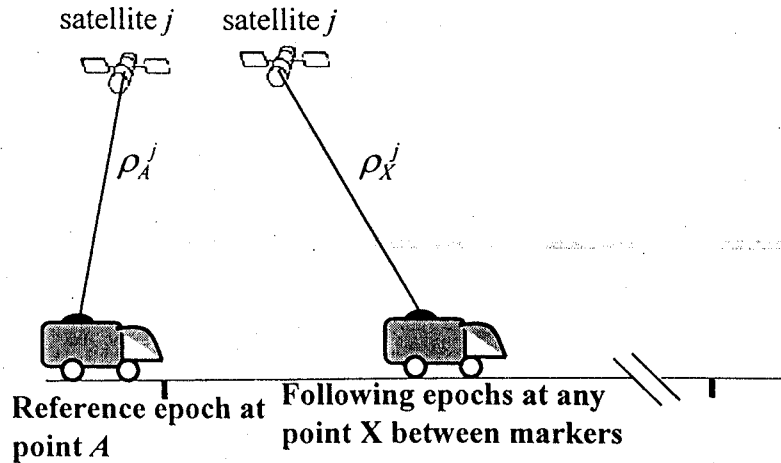


Figure 3: IS-DGPS concept

The coordinates of the magnet are known so the coordinates of the antenna can be quickly calculated. The code range correction for satellite j at reference epoch t_o is:

$$\begin{aligned} PRC^j(t_o) &= -P_A^j(t_o) + \rho_A^j(t_o) \\ &= -\Delta\rho_A^j(t_o) + c \cdot dt_A^j(t_o) - c \cdot dT_A(t_o) - v_A^j(t_o) \end{aligned}$$

The range rate correction RRC can be calculated from previous PRC 's [3]. Thus, the code range correction at an arbitrary epoch t is approximated by:

$$PRC^j(t) = PRC^j(t_o) + RRC^j(t_o) \cdot (t - t_o)$$

Where $t - t_o$ is the latency in applying the correction.

Now, the code ranges measured at an unknown point X is modeled as:

$$P_X^j(t) = \rho_X^j(t) + \Delta\rho_X^j(t) - c \cdot dt_X^j(t) + c \cdot dT_X(t) + v_X^j(t)$$

Applying the range correction to the measured pseudorange yields:

$$P_X^j(t)_{Corr.} = P_X^j(t) + PRC^j(t)$$

$$P_X^j(t)_{Corr.} = \rho_X^j(t) + (\Delta\rho_X^j(t) - \Delta\rho_X^j(t_o)) + c(dt_X^j(t) - dt_X^j(t_o)) - c(dT_X(t) - dT_X(t_o)) + (v_X^j(t) - v_X^j(t_o))$$

The combined error $\Delta\rho_X^j(t)$ and $\Delta\rho_X^j(t_o)$ are virtually equal. The error of the satellite clock is a slowly varying error, so it will cancel out. Ignoring $v_X - v_A$ the corrected range would be:

$$\begin{aligned} P_X^j(t)_{Corr.} &= \rho_X^j(t) - c(dT_X(t) - dT_X(t_o)) \\ &= \rho_X^j(t) - c\Delta dT_{AX}(t) \end{aligned}$$

Where $\Delta dT_{AX}(t) = dT_X(t) - dT_X(t_o)$ is the combined error of the receiver clock at times t_o and t .

The effect due to SA, ionospheric and tropospheric refractions have been diminished or eliminated. At least four satellites are needed to solve for the coordinates of point X and the combined receiver clock error.

In deciding about the frequency of the reference markers, the concern is about the selective availability effect and the generation of the RRC from the previous PRC 's. With IS-DGPS, the frequency of the reference magnets has to be such that an adequately accurate RRC is generated. Using 60 mph as a nominal speed, the reference magnets can be three seconds (75 meters) apart, so, after six seconds, three PRC 's can be used to calculate an RRC (Figure 4) that will be used in the next three seconds. PRC and RRC are updated every three seconds.



Figure 4: Frequency of reference magnetic markers

CHAPTER 3

IS-DGPS CORRECTIONS WITH SINGLE FREQUENCY CARRIER PHASES

The pseudorange derived from single frequency carrier phases measured at the surveyed magnet A is:

$$\Phi_A^j(t_o) = \rho_A^j(t_o) + \Delta\rho_A^j(t_o) - c \cdot dt_A^j(t_o) + c \cdot dT_A(t_o) + \lambda \cdot N_A^j + \varepsilon_A^j(t_o)$$

where $\lambda \cdot N_A^j$ is the unknown phase ambiguity and $\varepsilon_A^j(t_o)$ is the multipath and noise error. The phase range correction at reference epoch t_o is given by:

$$\begin{aligned} PRC^j(t_o) &= -\Phi_A^j(t_o) + \rho_A^j(t_o) \\ &= -\Delta\rho_A^j(t_o) - c \cdot dt_A^j(t_o) + c \cdot dT_A(t_o) - \lambda \cdot N_A^j - \varepsilon_A^j(t_o) \end{aligned}$$

The phase pseudorange correction PRC at an arbitrary epoch t is approximated by:

$$PRC^j(t) = PRC^j(t_o) + RRC^j(t_o) \cdot (t - t_o)$$

Now, the phase ranges measured after the surveyed magnet A at epoch t can be modeled as:

$$\Phi_X^j(t) = \rho_X^j(t) + \Delta\rho_X^j(t) - c \cdot dt_X^j(t) + c \cdot dT_X(t) + \lambda \cdot N_X^j + \varepsilon_X^j(t)$$

Notice that the ambiguity stays the same: $N_A^j = N_X^j$. Applying the range correction to the measured phase range yields:

$$\begin{aligned} \Phi_X^j(t)_{Corr.} &= \Phi_X^j(t) + PRC^j(t) \\ \Phi_X^j(t)_{Corr.} &= \rho_X^j(t) + (\Delta\rho_X^j(t) - \Delta\rho_A^j(t_o)) + \lambda(N_X^j - N_A^j) + c(dt_X^j(t) - dt_A^j(t_o)) - c(dT_X(t) - dT_A(t_o)) + (\varepsilon_X^j(t) - \varepsilon_A^j(t_o)) \end{aligned}$$

The combined errors $\Delta\rho_A^j(t)$ and $\Delta\rho_X^j(t)$ are virtually equal, the satellite clock error is a slowly varying error, so, it cancels out and the ambiguities cancel out as long as a cycle slip or a loss of lock does not occur. The multipath and noise are ignored. The corrected range becomes:

$$\begin{aligned} \Phi_X^j(t)_{Corr.} &= \rho_X^j(t) - c \cdot (dT_X(t) - dT_A(t_o)) \\ \Phi_X^j(t)_{Corr.} &= \rho_X^j(t) - c \cdot \Delta dT_{AX}(t) \end{aligned}$$

CHAPTER 4

IS-DGPS IMPLEMENTATION

One of the requirements is to be able to identify a reference marker and its particular coordinates among many markers, especially in case of initialization while the vehicle is moving. We must not confuse the detected magnet with neighboring ones since regular GPS accuracy before a differential fix could be more than 40 meters.

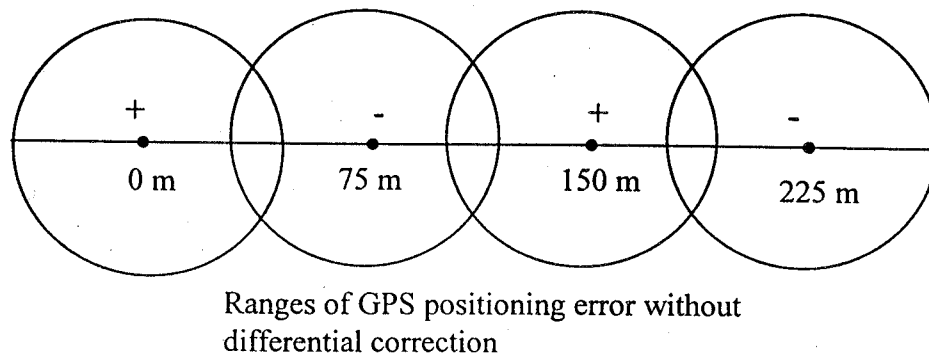


Figure 5: Reference magnet identification

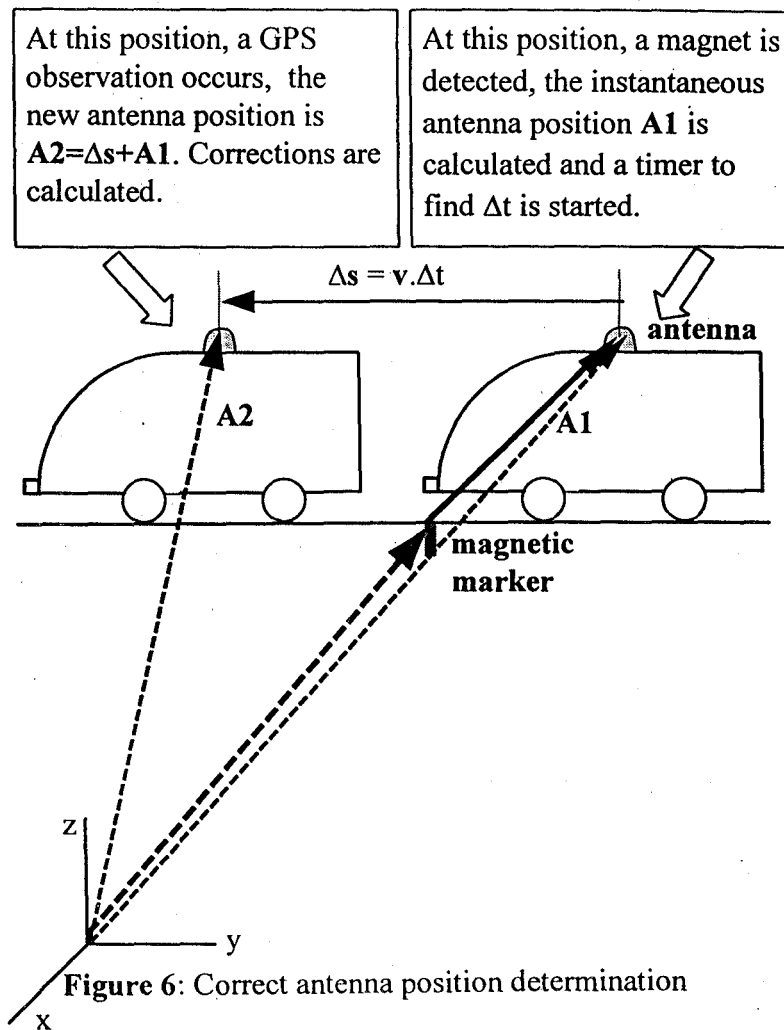
We propose to use the polarity in an alternating fashion (Figure 5). The detected magnetic marker would have an opposite polarity to the two neighboring magnets. Since a good GPS receiver positioning error is below 75m radius, we can quickly identify the detected marker and get its (x,y,z) position from the reference marker database.

The marker detection system (3 fluxgate magnetometers) is capable of locating a marker to within ± 1 centimeter laterally and ± 3 centimeters longitudinally [4,5].

One assumption we made is that the direction of traveling of the vehicle is parallel to the centerline of the lane or the tangent that passes through the surveyed marker.

When a marker is detected, the GPS antenna's position is calculated. Since there is latency Δt involved between detecting the marker and taking a GPS observation, the position of the antenna is interpolated at exactly the instant when a GPS observation is taken. This way, we

account for the traveled distance during Δt (Figure 6). Then, the calculation of the correction value PRC and its rate RRC takes place.



CHAPTER 5

ADVANTAGES AND WEAKNESSES OF SINGLE RECEIVER IS-DGPS METHOD

Advantages:

- No data communication link.
- Since with IS-DGPS the baselines are short (tens of meters), the spatial decorrelation effect on the radial orbital error and atmospheric errors [1] is eliminated.
- There is less implementation cost, in comparison with DGPS, by the elimination of the network of ground base stations.

Weaknesses:

As presented so far IS-DGPS has these weaknesses:

- Positioning accuracy is limited.
- It only works while the vehicle is moving.
- Going at low speeds increase the time between corrections so that the time dependent errors, such as SA, show some decorrelation which reduces the measurement accuracy.
- Since only a few *PRC*'s are used to calculate the range rate correction *RRC*, it might not be as accurately predicted as in the case of DGPS.
- Cm accuracy in determining the exact location of the receiver's antenna when a marker is detected might be a challenge.

CHAPTER 6

GPS RELATIVE POSITIONING APPROACH

Relative positioning (direct differencing) is when we have zero latency in applying the differential corrections. Cm accuracy becomes feasible, since SA is totally eliminated, and the ambiguities can be quickly resolved. Using the relative positioning approach with IS-DGPS would eliminate most of the above weaknesses and provide cm accuracy positioning due to the cancellation of the latency. We propose using a dual antenna receiver, which is basically two receivers in one, in order to perform relative positioning. Dual antenna receivers are usually used for attitude determination [10]. This receiver is usually a single frequency carrier phase receiver with a master antenna and a slave antenna. It usually has two antennas with 8 channels for each one. The two sets share the same processor and receiver clock. It will produce the azimuth angle as well as the position of the master antenna. Both antennas would

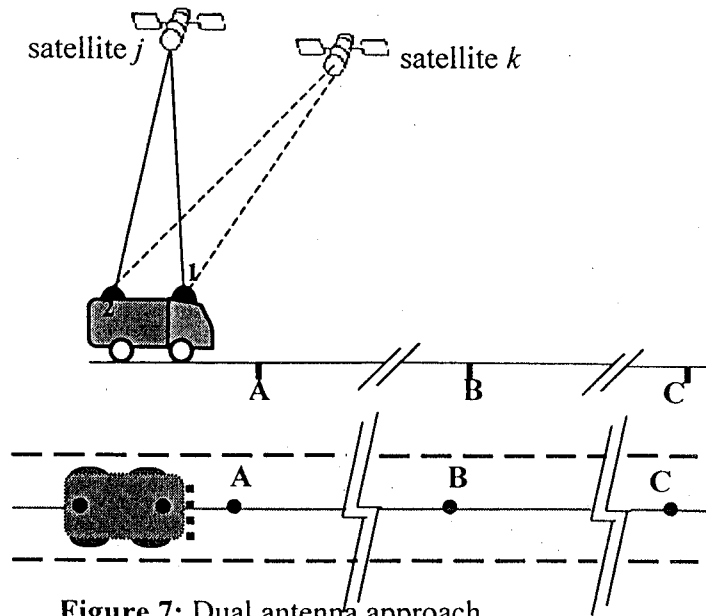


Figure 7: Dual antenna approach

be mounted on the top of the vehicle (Figure 7). With IS-DGPS, when front antenna is at a reference marker A, the rear antenna is at A'. The carrier phase equations are:

$$\Phi_A^j = \rho_A^j + \Delta\rho_A^j - c \cdot dt_A^j + c \cdot dT + \lambda \cdot N_A^j + \varepsilon_A^j$$

$$\Phi_{A'}^j = \rho_{A'}^j + \Delta\rho_{A'}^j - c \cdot dt_{A'}^j + c \cdot dT + \lambda \cdot N_{A'}^j + \varepsilon_{A'}^j$$

where ρ_A^j and $\rho_{A'}^j$ are known.

Since the two antennas and channels share the same receiver clock then its bias will be differenced out. Differencing these two equations and ignoring the noise and multipath effects ε_A^j :

$$\Phi_{AA'}^j = \rho_{AA'}^j + \lambda \cdot N_{AA'}^j$$

Using double differencing in order to get rid of the clock line bias, we get:

$$\Phi_{AA'}^{jk} = \rho_{AA'}^{jk} + \lambda \cdot N_{AA'}^{jk}$$

and at the following reference markers B and C similar equations are derived.

$$\Phi_{BB'}^{jk} = \rho_{BB'}^{jk} + \lambda \cdot N_{BB'}^{jk}$$

$$\Phi_{CC'}^{jk} = \rho_{CC'}^{jk} + \lambda \cdot N_{CC'}^{jk}$$

Notice that: $N_{AA'}^{jk} = N_{BB'}^{jk} = N_{CC'}^{jk}$ if no loss of signal or cycle slip occurs.

Then the equations can be solved for the ambiguities $N_{AA'}^{jk}$. An On-The-Fly technique can then be used to fix the ambiguities to their integer values [9].

Once the ambiguities are resolved, accurate position and attitude of the vehicle, at any point X on the road, can be found, using:

$$\Phi_{XX'}^{jk} = \rho_{XX'}^{jk} + \lambda \cdot N_{XX'}^{jk} + \varepsilon_{XX'}^{jk}$$

and the constraint equation, since the distance d between the two antennas is known:

$$d = \sqrt{(x_X - x_{X'})^2 + (y_X - y_{X'})^2 + (z_X - z_{X'})^2}$$

The unknowns are the six coordinates of X and X'.

The elevation constraint can also be used to reduce the number of unknowns, so less satellites would be needed to solve for the positions.

Using three antennas or more (Figure 8) would compensate for the situations where single differenced equations completely cancel out due to the same number of cycles between a satellite and the two antennas. Using three antennas more double difference equations will be generated. Then, the weak equations can be eliminated. For instance, using four satellites and three antennas nine double difference equations can be generated:

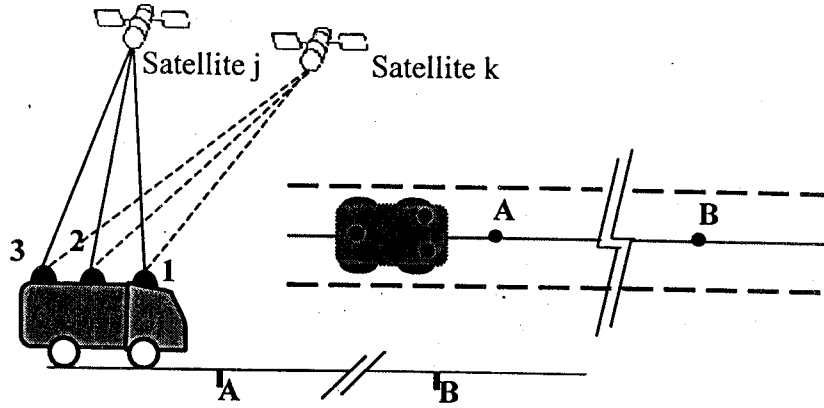


Figure 8: Multiple antenna approach

$$\Phi_{AA'}^{jk} = \rho_{AA'}^{jk} + \lambda \cdot N_{AA'}^{jk}$$

$$\Phi_{AA''}^{jk} = \rho_{AA''}^{jk} + \lambda \cdot N_{AA''}^{jk}$$

$$\Phi_{AA'}^{jl} = \rho_{AA'}^{jl} + \lambda \cdot N_{AA'}^{jl}$$

$$\Phi_{AA''}^{jl} = \rho_{AA''}^{jl} + \lambda \cdot N_{AA''}^{jl}$$

$$\Phi_{AA'}^{jm} = \rho_{AA'}^{jm} + \lambda \cdot N_{AA'}^{jm}$$

$$\Phi_{AA''}^{jm} = \rho_{AA''}^{jm} + \lambda \cdot N_{AA''}^{jm}$$

$$\Phi_{A'A''}^{jk} = \rho_{A'A''}^{jk} + \lambda \cdot N_{A'A''}^{jk}$$

$$\Phi_{A'A''}^{jl} = \rho_{A'A''}^{jl} + \lambda \cdot N_{A'A''}^{jl}$$

$$\Phi_{A'A''}^{jm} = \rho_{A'A''}^{jm} + \lambda \cdot N_{A'A''}^{jm}$$

After solving for the ambiguities of the selected equations, the corresponding equations, at any point X, along with the constraint equations and the elevation constraints can be used to solve for the location of the antennas.

CHAPTER 7

CONCLUSIONS

Although, the majority of accurate GPS applications involve the use of two or more receivers, the reason GPS was developed in the first place is to determine an instantaneous location of an object with only one GPS receiver. Detecting magnetic markers was proven to be done easily and fairly accurately, which makes the concept of IS-DGPS feasible and attractive. IS-DGPS has less possibility for failure since no signals are transmitted and received over long distances, except for the GPS satellite signal. IS-DGPS will be a more robust method when selective availability SA is lifted, since SA injects a time varying error that forces the use of short time interval between differential corrections (short distance between markers). A coupled inertial navigation system (INS) with GPS can benefit from the magnetic markers, since the accuracy degrading drift in the INS is reset at every marker. Hence, a less expensive INS can be used instead of an elaborate and expensive one. INS would provide a consistent and sufficient navigation accuracy indefinitely during satellite signal outage periods. Also, a combination of an INS, GPS and magnetic markers (IS-GPS- INS) using Kalman filtering techniques would provide a more robust positioning system without relying on any differential base stations.

CHAPTER 8

CURRENT RESEARCH

The experimental work is being done in two stages. In the first stage, a radio controlled $\frac{1}{4}$ scale model car is used (Figure 9) in order to determine the accuracy of both, single antenna and dual antennas, IS-DGPS approaches. The car carries a GPS receiver along with a laptop PC and a power source. For the single antenna approach, a Novatel RT-20 single carrier phase receiver antenna is mounted on the car. The car, which travels at about 2.5 m/s, is attached to a pole by a rope so that it travels in a perfect circular trajectory of 25 m radius. Close to 20 reflective markers are placed on the trajectory, evenly spaced. The marker locations were accurately surveyed using cm accuracy differential GPS. The car carries a photoelectric cell under the GPS antenna and looking down to the pavement. For the dual antenna approach, the antennas of a Novatel Beeline dual antenna receiver will be mounted one meter apart. The Beeline software algorithm has to be modified to accommodate the IS-DGPS formulation.

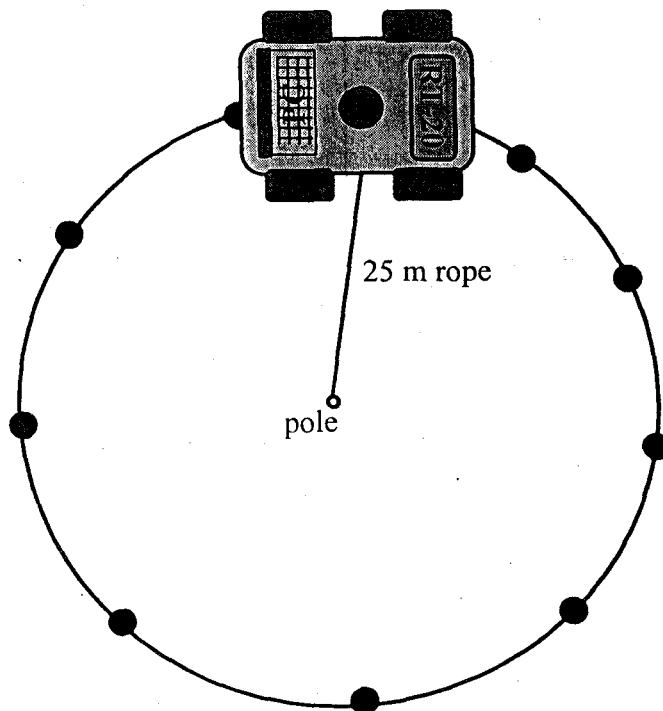


Fig. 9: experimental IS-DGPS set up

In the second stage, the method will be tested on an actual autonomous vehicle on the road in order to see how accurate the positioning process is. The vehicle has a set of three magnetometers under the front bumper and an automatic steering and speed control system.

In applications such as vehicle automatic control, redundancy of data is critical to guarantee a fault free system. Also, GPS signals are vulnerable to outages and blockages. Combining an INS with GPS is a necessity to achieve accurate vehicle real-time kinematics. Research is being undertaken to implement an IS-DGPS-INS combination for accurate positioning for the purpose of vehicle automatic lateral control.

CHAPTER 9

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APPENDIX A

ACRONYMS & ABBREVIATIONS

AHMCT:	Advanced Highway Maintenance and Construction Technology
AHS:	Automated Highway System
C/A:	Coarse/Acquisition
GPS:	Global Positioning System
DGPS:	Differential GPS
IMU:	Inertial Measurement Unit
INS:	Inertial Navigation System
IS-DGPS:	In Situ-DGPS
ITS:	Intelligent Transportation System
IVHS:	Intelligent Vehicle & Highway System
PATH:	Program on Advanced Technology for the Highway
RTK:	Real-Time Kinematics