Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Carrier Phase GPS for AHS Vehicle Control

U.S. Department of Transportation
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FOREWORD

This report was a product of the Federal Highway Administration's Automated Highway System (AHS) Precursor Systems Analyses (PSA) studies. The AHS Program is part of the larger Department of Transportation (DOT) Intelligent Transportation Systems (ITS) Program and is a multi-year, multi-phase effort to develop the next major upgrade of our nation's vehicle-highway system.

The PSA studies were part of an initial Analysis Phase of the AHS Program and were initiated to identify the high level issues and risks associated with automated highway systems. Fifteen interdisciplinary contractor teams were selected to conduct these studies. The studies were structured around the following 16 activity areas:

> (A) Urban and Rural AHS Comparison, (B) Automated Check-In, (C) Automated Check-Out, (D) Lateral and Longitudinal Control Analysis, (E) Malfunction Management and Analysis, (F) Commercial and Transit AHS Analysis, (G) Comparable Systems Analysis, (H) AHS Roadway Deployment Analysis, (I) Impact of AHS on Surrounding Non-AHS Roadways, (J) AHS Entry/Exit Implementation, (K) AHS Roadway Operational Analysis, (L) Vehicle Operational Analysis, (M) Alternative Propulsion Systems Impact, (N) AHS Safety Issues, (O) Institutional and Societal Aspects, and (P) Preliminary Cost/Benefit Factors Analysis.

To provide diverse perspectives, each of these 16 activity areas was studied by at least three of the contractor teams. Also, two of the contractor teams studied all 16 activity areas to provide a synergistic approach to their analyses. The combination of the individual activity studies and additional study topics resulted in a total of 69 studies. Individual reports, such as this one, have been prepared for each of these studies. In addition, each of the eight contractor teams that studied more than one activity area produced a report that summarized all their findings.

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Research
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ABBREVIATIONS

AHS	Automated Highway Systems
AICC	advanced interactive cruise control
Alvinn	Autonomous Land Vehicle in a Neural Network
A-S	anti-spoofing
AVCS	advanced vehicle control system(s)
bps	bits per second
C/A	coarse/acquisition (code)
CDMA	code division multiple access
DoD	U.S. Department of Defense
DOT	U.S. Department of Transportation
FDMA	frequency division multiple access
FHWA	Federal Highway Administration
FMCW	frequency-modulated continuous wave
GIC	GPS integrity channel
GLONASS	Global Navigation Satellite System (CIS)
GNSS	Global Navigation Satellite System (civilian)
GPS	Global Positioning System
IR	infrared
IRU	inertial reference unit
ISTEA	Intermodal Surface Transportation Efficiency Act
ITS	Intelligent Transportation Systems
LADGPS	Local Area Differential GPS
LIDAR	light detection and ranging
OTF	on-the-fly
P	precision (code)
PATH	Partners for Advanced Transit and Highways
pps	pulses per second
PRC	pseudorange correction
PSA	Precursor Systems Analysis
RAIM	receiver autonomous integrity monitoring
SA	selective availability
TDMA	time division multiple access
TEC	total electron content
USCG	U.S. Coast Guard

I INTRODUCTION

Throughout the United States it is becoming less feasible to build new highways or widen existing highways to relieve roadway congestion and meet the ever increasing demand of vehicle travel. The high costs of roadway construction and right-of-way, the environmental impacts of new roadways, and the demand for a safer transportation system are driving efforts to seek new solutions to America's surface transportation needs.

One such effort is the Automated Highway System (AHS) program within the Federal Highway Administration's (FHWA) Intelligent Vehicle Highway Systems (IVHS) initiative (recently renamed Intelligent Transportation Systems [ITS]), established by the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991. The long-term vision for an AHS is a system of automated vehicles and roadways that completely automates the driving tasks and guides vehicles under automated control. The benefits of such a system include: increased highway capacity through reduced vehicle separation, increased vehicle speeds, and possibly narrower lane widths; reduced frequency of accidents by reducing or eliminating driver errors from the system, and lessening the effects of adverse weather and other environmental factors; and reduced vehicle fuel consumption and emissions by alleviating stop-and-go operation. The AHS is envisioned to accommodate all vehicle types, including private automobiles, commercial trucks, and public transit vehicles.[1]

To speed the realization of AHS benefits, the ISTEA also mandates that automated vehicle and roadway prototypes be demonstrated by 1997. This "proof of technical feasibility" will demonstrate a prototype based on best available technologies. Actual deployment of AHS capabilities will be evolutionary, with such technologies as intelligent cruise control and collision avoidance systems leading the way. Deployment of a fully automated AHS is expected to occur in 10-15 years.

FHWA's AHS program is organized in three phases:

(1) *Analysis*--Provide the research foundation for defining an AHS. The cornerstone of this phase (nearing conclusion) is a set of 15 Precursor Systems Analyses (PSA) contracts awarded to study the technological and policy issues and risks associated with AHS design, development, and deployment.

(2) *System Definition*--Determine AHS performance and design requirements, conduct and evaluate a full-scale prototype demonstration (in 1997), select a preferred system approach, and develop system specifications. This phase, recently under way, is being conducted by the National Automated Highway System Consortium led by General Motors Corporation in partnership with FHWA.

(3) *Operational Evaluation*--Evaluate several deployed AHS implementations.

This report describes the results of a PSA contract awarded to SRI International to analyze applications of advanced Global Positioning System (GPS) measurement techniques to provide data for lateral and longitudinal control of AHS vehicles. The report includes: (1) a review of control sensor requirements suggested by other PSA contractors and AHS researchers; (2) an in-depth discussion of GPS principles of operation, advanced techniques for achieving extremely accurate GPS positioning and velocity data, and techniques for augmenting GPS to provide continuous high-accuracy data; (3) current and expected GPS capabilities and performance; (4) a review of other proposed sensor types for providing lateral and longitudinal control data; (5) a description of a notional architecture and operation of an AHS incorporating GPS; and (6) a preliminary evaluation by SRI of GPS operation in a typical AHS roadway environment.

II GPS POTEN4TIAL FOR AHS

The concept of an automated highway system, composed of automated vehicles that literally drive themselves on specially instrumented roadways, is in its early stages of development, with early deployment of fully automated systems not anticipated for at least 10-15 years. Technology shortfalls, legal issues, consumer acceptance, and infrastructure costs are some of the major barriers. Some advanced vehicle control systems (AVCS), such as advanced interactive cruise control (AICC) and collision avoidance systems, are commercially available now and will serve as evolutionary steps to a fully operational AHS. GPS technology could have a major impact on the feasibility of early deployment of more capable interim systems by providing highly accurate position and velocity data for the lateral and longitudinal control of vehicles. Indeed, GPS appears to be unique in its ability to provide both absolute and relative data to simultaneously keep vehicles on the road and separated from each other, night and day, under all weather conditions. In addition to supporting the operation of autonomous automated vehicles, specialized GPS techniques can support the operation of platoons in which the lead vehicle is manually driven and the following vehicles are automated to maintain safe separation distances while following the same path as the lead vehicle. Because GPS has already been developed and deployed, additional infrastructure costs required for GPS to support AHS are limited situations where GPS satellites are obscured, such as in a tunnel, or when unique data communications for GPS-specific techniques or databases containing roadway geometries and features are required.

The considerable amount of GPS research and development currently under way is increasing the potential utility of GPS for AHS applications. Advances being made in disciplines such as aviation and surveying are directly applicable to making GPS feasible for AHS. Automated landings of full-size jet aircraft have been demonstrated using GPS, and the considerable amount of research conducted to satisfy accuracy, availability, and integrity requirements for low-visibility landing conditions provide a framework for formulating similar AHS requirements.

A. AHS LATERAL AND LONGITUDINAL CONTROL SENSOR REQUIREMENTS

Because of the developing nature of AHS, there are currently no definitive requirements for the accuracies and rates at which parameters such as vehicle position, velocity, acceleration, and attitude must be measured in order to control AHS vehicles. Most of the research previously conducted concerning sensors for AHS has focused on sensors dedicated to either lateral or longitudinal control, with emphasis placed upon relative position between vehicles, and distance between visual or embedded lane markers. Two main reasons account for this research emphasis: (1) a decoupling or separation of the control algorithms required for lateral and longitudinal control, and (2) a paucity of sensors that are able to supply data for both lateral and longitudinal control.

Experimental results using a Doppler radar that have been presented by the California Partners for Advanced Transit and Highways (PATH)[2] indicate that for longitudinal control, the along-track distance between vehicles must be known to better than ±2 m. It was also reported that both range and range/closing rate data are required even when the closing rate is zero or near zero; these data are necessary because it is desired to maintain a constant separation between each of 15-20 closely spaced vehicles operating in a platoon. For lateral control, good test track results were obtained using a magnetic reference system in which lateral sensing system errors of ~5 mm were achieved, with resulting tracking errors of less than 15 cm even under adverse conditions.[3]

For the purposes of this study, other PSA researchers were queried about combined lateral and longitudinal control sensor data requirements. Position location accuracies of 0.5-0.01 m, velocity accuracies of 0.5-0.01 m/s, and update rates of 10-100 Hz reflect the range of possible data requirements. These data are required in the x and y directions only. The data must (1) be supplied continuously and (2) provide the capability to determine vehicle geometric relationships, including separations and closing rates between vehicles, and along-track position along the roadway and cross-track position between lanes and road shoulders.

AHS data requirements and sensor characteristics will ultimately depend on the control algorithms and vehicle system architectures that are implemented. Multiple sensors will be required both for redundancy and because no single sensor has been identified that can reliably and cost-effectively satisfy all of the requirements under all conditions. Of special concern is the ability of the sensor suite to operate under the complete range of expected environmental conditions--e.g., night and day, dusk and dawn, rain, snow, fog, dust storms, and ice.

In addition to vehicle data requirements, it is widely acknowledged that preview or "look-ahead" data are required to adequately negotiate curves in the roadway.[4] Look-ahead data have been collected autonomously while driving[5] with vision-based systems, or they can be collected "off-line" by road surveys. The roadway data are stored in a database, which is accessed in real-time by the vehicle controller as it senses its absolute location along the roadway. The required accuracy of look-ahead data varies with the geometry of the roadway and vehicle speed.

B. UTILITY AND LIMITATIONS OF GPS FOR AHS

Using advanced equipment, techniques, and augmentations described later in this report, GPS has the potential to supply data with sufficient accuracy and the proper characteristics to satisfy the lateral and longitudinal control sensor requirements previously discussed. Three-dimensional absolute position and velocity data provided by GPS can be used, in conjunction with a database of roadway parameters, for lateral control inputs. For longitudinal control, this absolute position data can also be used to calculate relative distances and closing velocities between vehicles utilizing an inter-vehicle datalink. Manuevers can be controlled (by individual vehicles or by a central controller) to provide collision avoidance, platooning, and negotiated dynamic manuevers. GPS is very reliable with minimal or no degradation by seasonal and daily environmental changes and effects. GPS can also provide two- or three-dimensional attitude data and highly accurate time.

1. Current and Expected GPS Capabilities and Performance

Table 1 summarizes the present capabilities, sizes, and costs of GPS receivers, and indicates improvements in these features that are probable within the next several years. Because fully automated highways are not expected to be deployed for 10-15 years, GPS technology advances and research and development efforts now under way in other areas will increase the utility of GPS for AHS. Current areas of very intense GPS research and development efforts include automated aircraft landing systems, surveying, navigation, and robotics.

Table 1: CURRENT AND ANTICIPATED CAPABILITIES OF GPS RECEIVERS

	Current	**Anticipated**
Position Accuracy (horizontal with differential corrections) Code Carrier	 1 m 1-10 cm	 0.5 m 1-5 cm
Velocity Accuracy (with differential corrections)	0.02 m/s	0.01 m/s
Attitude Accuracy (1-m antenna spacing)	0.1 deg	0.1 deg
Update Rate	1-10 Hz	50-100 Hz (with IRU)*
Size (without antenna)	2.5-300 in.^{3}	1-10 in.^{3}
Cost	$150-$35,000	$75-$1,000

*Inertial Reference Unit.

Figure 1 presents a history of GPS receiver size; Figure 2 presents a history of the cost of GPS receivers. These two figures indicate the rapid advances in GPS technology and support the premise that more advances can be expected in the near future. A more detailed discussion of techniques and accuracies is presented later in this report.

In addition to the types and quality of data provided by GPS, a major advantage for AHS is that the great majority of GPS infrastructure components are already in place with a proven track record. Moreover, GPS receivers are likely to become optional or even standard equipment on future vehicles, and therefore would be available to support AHS functions. If GPS equipment manufacturers perceive that there will be a large market in the future for receivers optimized for

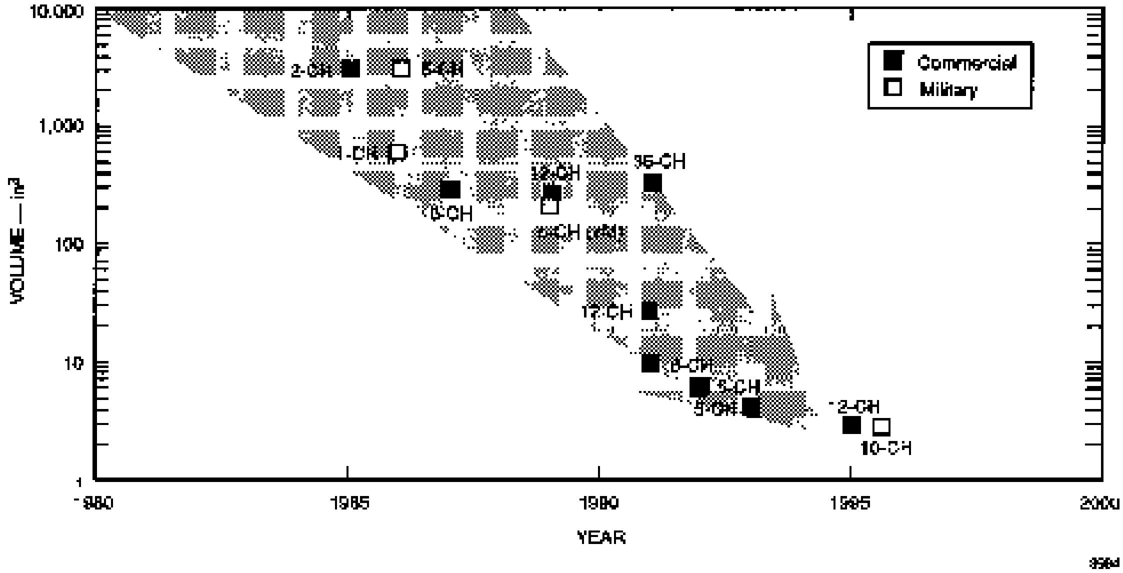

Figure 1. History of GPS receiver size.

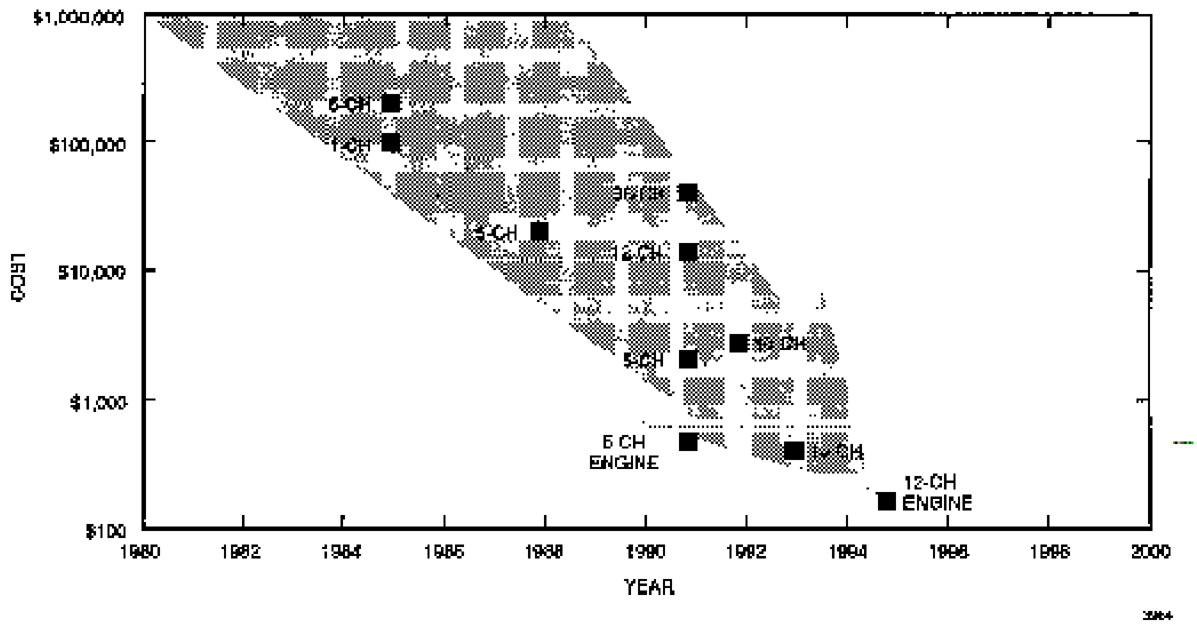

Figure 2. History of GPS receiver cost.

AHS use, receivers with the accuracies, outputs, and characteristics appropriate for AHS will be forthcoming.

2. Limitations of GPS for AHS

The primary limitation of GPS is its requirement for line-of-sight visibility to GPS satellites. Tunnels, tall buildings, hills, foliage, bridges, and even large vehicles are all capable of occluding satellite signals needed by a GPS receiver to operate. Unless GPS is augmented with other instrumentation to replace the occasionally inaccessible satellite transmissions, vehicles employing GPS will be unable to operate consistently in the AHS environment. Candidate augmentations discussed later in this report are expected to provide accurate GPS data even when direct satellite signals are occluded.

C. GPS PRINCIPLES OF OPERATION

1. Multilateration Using Satellite Signals

GPS is a navigation system that uses a constellation of 24 satellites whose orbits are arranged in such a way that in practically all areas of the Earth, six or more satellites are almost always visible above the local horizon. The satellites continuously transmit coded signals that, when tracked and decoded by a GPS receiver, can be used to accurately determine the location and velocity of the receiver. The receiver is "passive" in the sense that it does not transmit any signals back to the satellite. Therefore, any number of receivers may operate in a given area without interfering with one another.

Multilateration is based on the principle that, if the distance from three or more known points is known, the location relative to those points can be determined by triangulation. In GPS, the satellites serve as the known points, because, at any given time, the position of each satellite in its orbit can be calculated by the GPS receiver, using orbital information (called "ephemeris data"). These parameters are updated hourly in order to provide the receiver with very accurate estimates of each satellite's position. Ephemeris data are broadcast from the satellites to the receiver by means of a 50 bit per second (bps) data message encoded on each satellite's signal. The receiver measures the distance to the satellites by a signal containing information that indicates the time the signal left the satellite; the receiver also contains a clock that allows it to know the time when the signal arrives. In practice, the GPS receiver must be tracking four (or more) GPS satellites to arrive at a three-dimensional location because the receiver must calculate, in addition to latitude, longitude, and elevation, any errors in the time registered by its own clock.

2. C/A Code

As discussed earlier, the distance from a GPS satellite to a GPS receiver is determined indirectly by measuring the time elapsed between the transmission of signals from GPS satellites and reception of the signals by a receiver. The satellite signal is modulated in such a way that its arrival time at the receiver can be measured to an accuracy of a few nanoseconds. The time of transmission can be deduced from information contained in the satellite data messages, which are also modulated onto the transmitted signal. For commercial receivers, the timing modulation is referred to as coarse/acquisition (C/A) code, which is transmitted at the rate of 1 MHz.

The satellites are equipped with expensive atomic clocks; hence, the transmission time is accurate to within ~10 ns (neglecting selective availability).

The GPS receiver, however, to minimize size and cost, is equipped with an inexpensive crystal oscillator, thus making the estimate of receive time somewhat erroneous. The satellite-to-receiver distance, as measured by the receiver, is therefore referred to as a "pseudorange," indicating the uncertainty resulting from the local clock error.

3. P-Code

Because GPS was developed as a military system, several additional features are available to "authorized" users. For example, each satellite actually broadcasts three separate ranging signals. The first, called C/A-code, is transmitted at 1575.42 MHz (referred to as the L_1 frequency) and is available to all users. However, the accuracy of this signal is intentionally degraded by a process known as selective availability (SA) to prevent an enemy from using it to guide weapons. (This intentional degradation is one of the error sources that is removed by a technique called "differential GPS," which is covered in a later discussion.) In addition to the C/A code, the satellite also transmits a precision (P)-code signal on the L_1 frequency, which is modulated 90 degrees out of phase of the C/A code. The P-code is transmitted at a 10-MHz rate, a bandwidth ten times that of C/A code. The P-code signal is also transmitted on a second frequency, known as L_2, at 1227.6 MHz. The P-code signals are encrypted (then called Y-code) in a process called anti-spoofing (A-S), and can be interpreted only by receivers that are equipped with special decoding circuitry and an encryption key. The P-code signals offer two advantages, in addition to not being intentionally degraded by SA. First, because the bandwidth is larger (10 MHz rather than 1 MHz), more precise ranging measurements are possible. Second, because the delay through the ionosphere is a function of frequency, a dual-frequency, P-code receiver can directly measure the code ionospheric delay rather than having to rely on an approximate mathematical model, as do C/A-code receivers. This is somewhat less important in differential applications, because the ionospheric delay is one of the error sources that can be removed in the differential process.

4. Error Sources

GPS error sources can be grouped into four categories: satellite clock and ephemeris; ionospheric and tropospheric; multipath; and selective availability (SA). Figure 3 illustrates the GPS measurement environment.

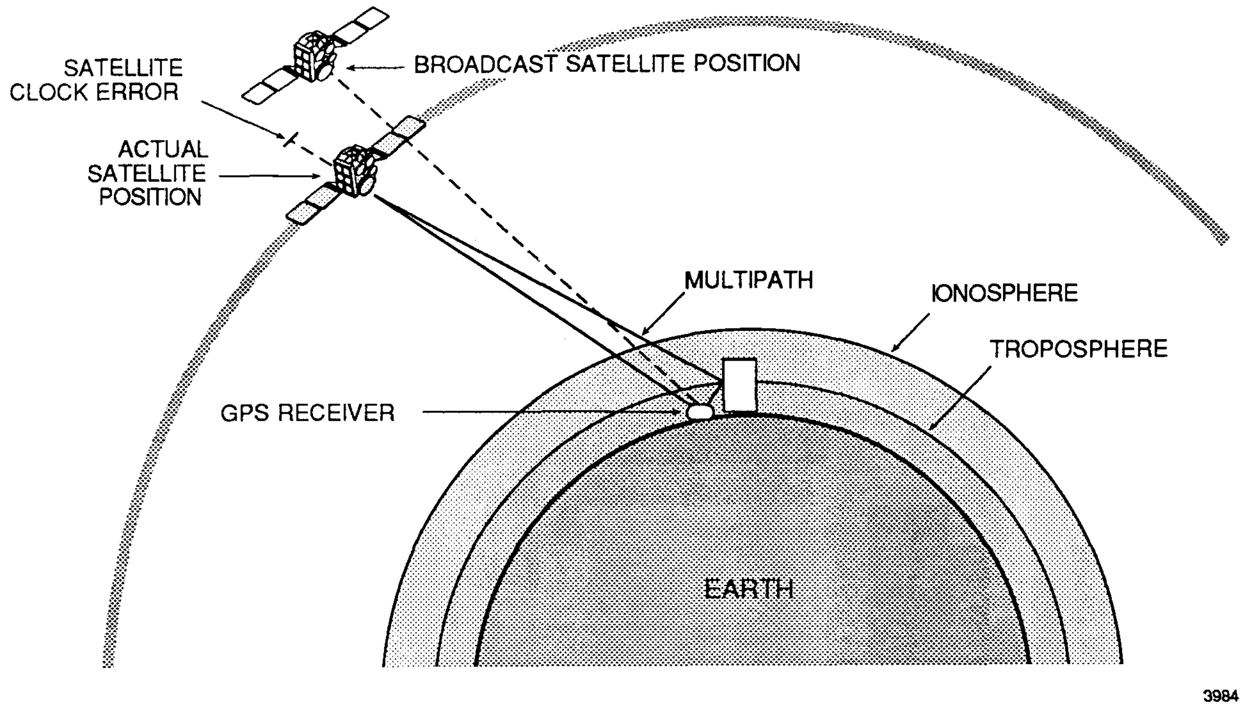

Figure 3. GPS measurement environment.

- The satellite clock error occurs because the clock does not keep perfect time and its drift rate is not absolutely constant. Satellite ephemeris errors result from the fact that the satellite position is not known exactly. Typically the clock and ephemeris errors are about 3 m each. Together, they become a 4.3-m error over a 24-hour period (between updates from the GPS ground control system to the satellites).
- The radio signals from the satellites travel at different speeds in the ionosphere and troposphere than in free-space. The speed in each of these media can be estimated from the parameters of the medium--such as electron density, commonly called total electron content (TEC), of the ionosphere and the temperature and humidity of the troposphere. However, these estimates are never exact; consequently, a residual, unmodeled delay of a few meters is not accounted for. The delay through the ionosphere is a function of frequency and, therefore, can be measured directly if available on more than one carrier frequency. Each GPS satellite transmits P-code on two separate frequencies specifically to allow measurement of the ionospheric delay. However, very few commercial receivers are currently able to directly measure and correct for errors induced by the ionosphere because the U.S. government encrypts the P-code signal modulations required to calculate the delay. Errors induced by the ionosphere and troposphere are more prevalent when receivers are tracking satellites less than 20 deg above the horizon because the signal path from the GPS satellites to the GPS receiver passes through a longer path in the ionosphere and troposphere than the signals from satellites higher above the horizon.

- Multipath occurs when a receiver antenna, located in the vicinty of reflecting objects such as buildings, trees, vehicles, or the Earth's surface, receives (in addition to or instead of the direct signal from the satellite) energy that has bounced off one or more of the nearby surfaces. When multipath occurs, both the modulation and phase of the signal will be distorted, and the timing measurements are likely to exhibit increased errors. Multipath errors are more prevalent when receivers are tracking satellites less than 20 deg above the horizon because signals along low grazing angles are more likely to encounter a surface that will reflect the signal.
- Selective Availability (SA) is a satellite clock dither error intentionally introduced by the DoD to reduce the accuracy available to non-authorized users, and thereby preclude adversarial use of GPS to their military advantage. SA location errors are typically 40-60 m, and can range as high as 100 m. SA-induced velocity errors are typically 0.5 m/s.

Of these four types of error sources, all but multipath can be substantially reduced by employing differential GPS.

5. Differential GPS

Differential GPS[6] is based on the principle that two receivers in the same general region of the Earth's surface will make approximately the same errors in measuring satellite signals. The reason for this is that the major sources of error are common: uncertainties in the satellite's orbital position, errors through the Earth's ionosphere and troposphere, errors in the satellite's clock, and intentional degradation of GPS accuracy by the U.S. military (i.e., selective availability). Therefore, GPS accuracy can be improved significantly by placing a "reference" receiver at a fixed, surveyed location and measuring the aggregate effect of these errors. The errors can be estimated by comparing the calculated distance between the satellites and the reference receiver with the measured distance. Similarly, because the reference receiver is fixed, velocity errors experienced by the navigating receiver are known. When this information is provided to another receiver, that receiver can correct its own location and velocity accordingly. Because of a decoupling of atmospheric errors with increasing distance between the reference receiver and the navigating receiver, the ionospheric and tropospheric corrections become less valid at increasing distance from the reference receiver. This is especially true for tropospheric corrections when the reference receiver and the navigating receiver are at increasingly different altitudes.

Figure 4 shows the magnitude of errors resultant from individual satellites during a particular period of time; the bulk of the errors are due to SA. How often differential corrections need to be calculated and applied, and the separation distance between the reference receiver and the navigating receiver, are dependent upon the desired accuracies. An authorized receiver, which does not experience SA, requires differential correction updates at a much slower rate, and the corrections can be from a reference receiver at a larger separation than required by an unauthorized

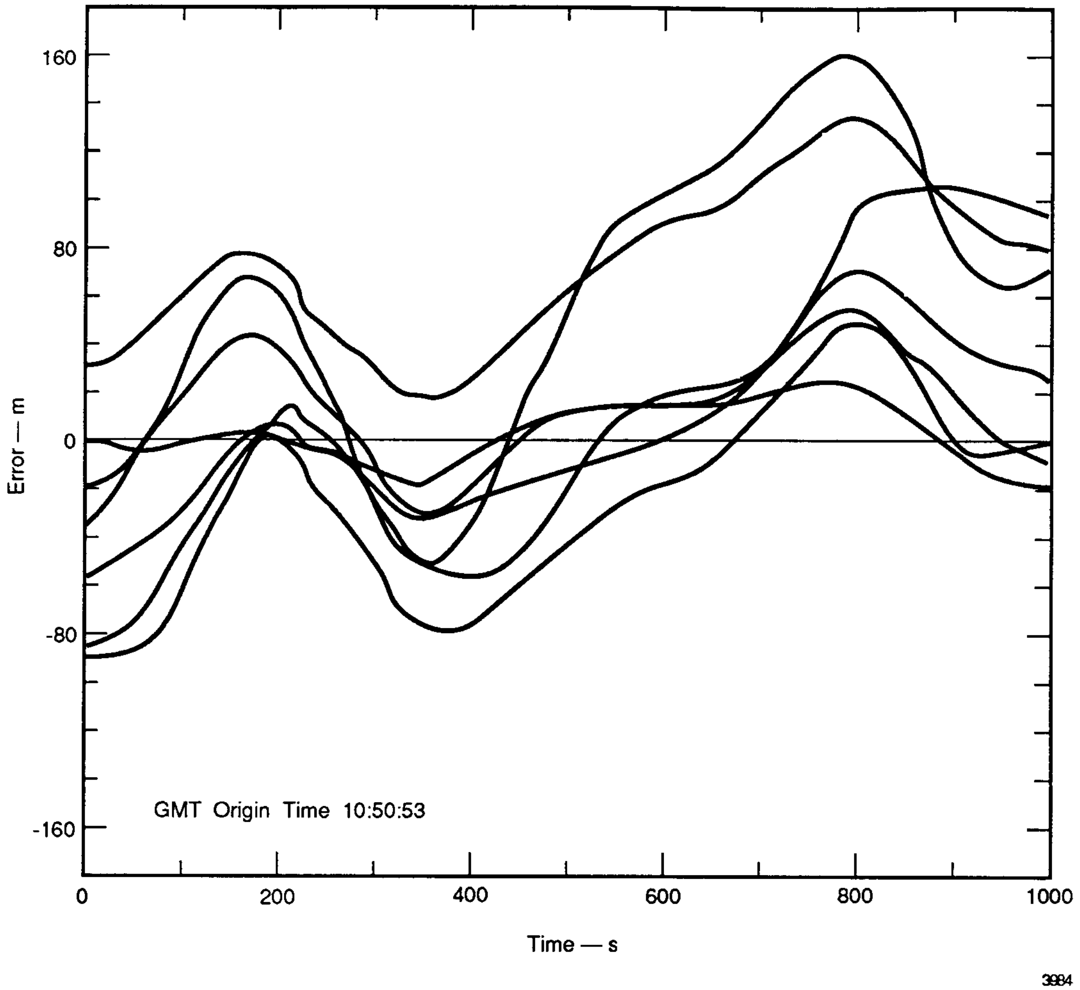

Figure 4. Magnitude of pseudorange errors removed during differential correction process for individual satellites. Data were taken using commercial receivers during a time period when selective availability was imposed.

receiver to maintain the same accuracy. Current experiments being conducted by SRI[7] indicate that for authorized, dual-frequency receivers (not experiencing SA and capable of autonomously calculating ionospheric corrections), differential corrections supplied at 30-min intervals from a reference receiver up to 1000 miles away can maintain submeter x,y location accuracies.

When corrections to individual satellite measurements are employed--in the form of pseudorange corrections (PRCs) and pseudorange rate corrections--the calculations are said to be performed in "range space." When corrections such as x, y, and z offsets are applied to a location already calculated by a receiver, "solution space" is being operated on. Range space corrections are generally preferred because if a reference receiver provides corrections for measurements from eight satellites, a navigating receiver seeing those eight satellites or a subset thereof can apply the corrections individually. In solution space, both the reference receiver and the navigating receiver would have to be seeing the exact same set of satellites for the correction to be valid, or the reference receiver would have to supply different corrections for all of the different combinations of the subsets of the eight satellites, which is untenable. The accuracies achievable from applying either type of corrections (when the situations allow either to be applied) are the same.

Differential corrections are routinely provided by ground-based or satellite radio transmissions to GPS receivers interfaced with a suitable differential correction radio datalink receiver. The U.S. Coast Guard (USGS) is currently deploying a differential correction network called the Low Frequency (LF)/Medium Frequency (MF) Radiobeacon System or the USCG's Local Area Differential GPS (LADGPS), which is intended to cover coastal and inland waterways. A total of 61 radiobeacon sites are expected to be operating by January 1996. An accuracy of 5 m, two-dimensional rms, is specified, but 3-m accuracies are generally available with "high end" equipment when operating within 300 km of the radiobeacon. It has been recommended by a joint U.S. Department of Transportation and Department of Commerce study group[8] that this system be expanded to provide nationwide coverage. An additional 20-50 radiobeacon sites will be needed to provide nationwide coverage.

Although the accuracy available from the USCG's LADGPS system is not sufficient to satisfy AHS requirements, the system provides a framework for developing and implementing a system that will satisfy AHS requirements. With the advent of a possible civilian-controlled Global Navigation Satellite System (GNSS) (discussed in a later section) that provides performance capabilities comparable to those available from authorized GPS receivers (dual frequencies for ionospheric corrections and no SA degradation), a differential correction network optimized for AHS would require very few reference stations nationwide and very low update rates to provide submeter accuracies.

6. Relative GPS

Relative GPS is a form of differential GPS. However, instead of employing a stationary reference receiver at a surveyed location, relative GPS removes the common errors between two GPS receivers, one or both of which may be moving. Relative GPS corrections have historically been operating in solution space, the technique used when two identical GPS receivers are tracking a common set of satellites. For AHS, relative GPS corrections to the raw measurements are likely to be preferable because it eliminates the requirement that the two vehicles track identical satellites with identical receivers.

Using relative GPS techniques, submeter relative locations and centimeter-per-second relative velocities between two receivers can be calculated. For AHS applications, this technique may be valuable when a lead vehicle in a platoon is driven manually, and the following vehicles use relative GPS to "follow the leader," maintaining a constant separation between vehicles while following the lead vehicle's path. Relative GPS for AHS requires a datalink between the vehicles.

D. ADVANCED GPS TECHNIQUES

As currently deployed, GPS provides approximately 100-m accuracy to the "unauthorized," non-military user. C/A-code differential GPS techniques can provide location accuracies of 1-3 m. However, techniques are available to commercial users that can yield position accuracies of a few centimeters and velocity accuracies of a few centimeters per second. These techniques explain properties of GPS satellite carrier frequency signals.

1. Narrow Correlator Technology

C/A-code measurements have traditionally been made using one-chip-width, early-late correlator spacings. C/A-code receivers manufactured by NovAtel Communicatons Ltd., a Canadian firm, use a patented "narrow correlator" technique[9]* that provides code measurement accuracies approaching those available from authorized P-code receivers. Submeter differential tracking accuracies have been achieved in low-multipath environments. In addition to increased measurement accuracy, superior multipath rejection using the narrow correlator technique has been demonstrated.

2. Carrier Phase Tracking and Carrier Smoothing

In addition to using code measurements to determine the range between a GPS receiver and GPS satellites, many GPS receivers track the phase of the carrier frequency. "Carrier phase tracking" means that the receiver monitors the total number of whole and partial carrier cycles that elapse between successive measurements. This parameter, also referred to as "integrated carrier phase" or "accumulated delta range," is statistically independent of the code measurement. Carrier phase information is useful because phase can be measured to about 1/200 of the 19-cm L_1 carrier wavelength--about two orders of magnitude better than the accuracy of code measurements. GPS carrier signals are also much less susceptible to multi-path than are code measurements.

The number of elapsed cycles is measured for several reasons. First, it provides Doppler information that can be used to more accurately determine vehicle velocity. Second, the integrated phase data provide an independent measure of how far the receiver has traveled since the preceding measurement, and therefore can be used to smooth the noisier "code" measurements from which the receiver's position is initially computed. This smoothing process reduces the error-inducing effects of multipath and receiver noise.

To illustrate the accuracies associated with code and carrier measurements, SRI connected two stationary GPS receivers to a common antenna (to minimize multipath effects) and

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*The narrow correlator technique makes use of the fact that the modulation on the signal broadcast by the GPS satellites actually has much greater bandwidth than the 2 MHz nominally allotted to the C/A code. The technique uses variable (0.05-C/A chip-width) correlator spacing, a 10-MHz precorrelator bandwidth, and noncoherent delay lock loops.

measured the difference between the code and carrier measurements for individual satellites tracked by both receivers. In Figure 5, the circles and squares represent the noise associated with code measurements from two different satellites. In Figure 6, the same procedure was followed, except that the circles and squares represent the noise associated with carrier measurements.

3. Carrier Cycle Ambiguity Resolution

As described above, comparing the relative phase of carrier signal measurements from common satellites or two receivers (such as a stationary reference receiver and a receiver on a moving vehicle) offers the potential of determining, to within a few centimeters or less, the position of the moving receiver relative to the fixed receiver. To reap the benefits of this measurement, however, the "total" cycle and phase difference between the two receivers must be determined. The phase measurement provides only the single-cycle fraction (0 to 360 deg) of the difference, and the number of whole cycles must be determined by another process, referred to as "carrier cycle ambiguity resolution."

Until recently ambiguity resolution has been largely a trial-and-error effort, in which various whole wavelength combinations (of the signals from all the tracked satellites) are tried until a solution is found that "fits" and continues to fit over time as the vehicle and the satellites move. This requires setting up an initial search volume that has a high degree of certainty of containing the correct location. Moreover, the ambiguities often cannot be resolved instantaneously. A time interval varying from several seconds to several minutes is often needed to completely determine the carrier integer values.

Ambiguity resolution can be performed more quickly if the receiver tracks both the L_1 and L_2 frequencies, rather than just L_1. If phase information on both carriers is known, the effect is mathematically equivalent to having a single carrier at the wavelength of the difference frequency or, in this case, 86 cm. This technique is referred to as "wide-laning." GPS receivers are currently available that, in low-multipath environments, have differential code measurement accuracies of less than 1 m. Since the wavelength of the wide-laning difference frequency is close to a meter, the carrier phase ambiguities can be nearly determined by examining the code measurement, thus simplifying considerably the ambiguity resolution process because there are fewer combinations within the search volume.

Carrier cycle ambiguity resolution techniques that do not require lengthy static initialization routines[10,11] are necessary to satisfy AHS position location requirements. Techniques developed for surveying and aviation applications hold great potential for AHS. Because an AHS will not be deployed for 10-15 years, there is a long lead time available to benefit from future advances and to develop techniques optimized for the AHS environment.

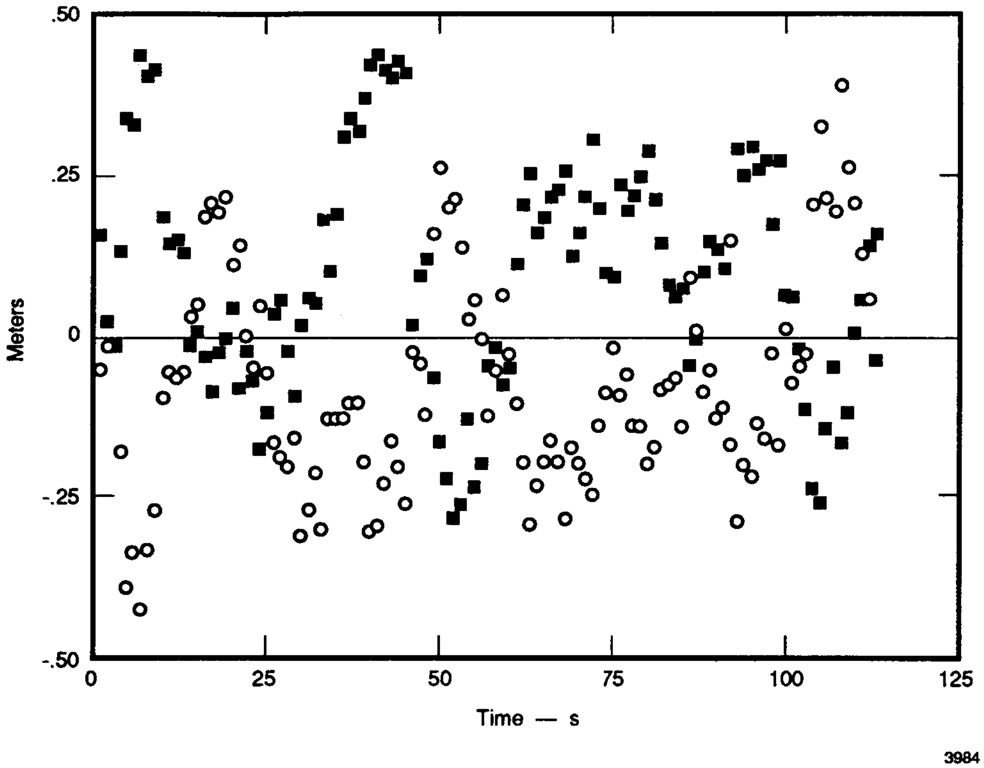


Figure 5. Differential C/A code measurement noise (co-located).

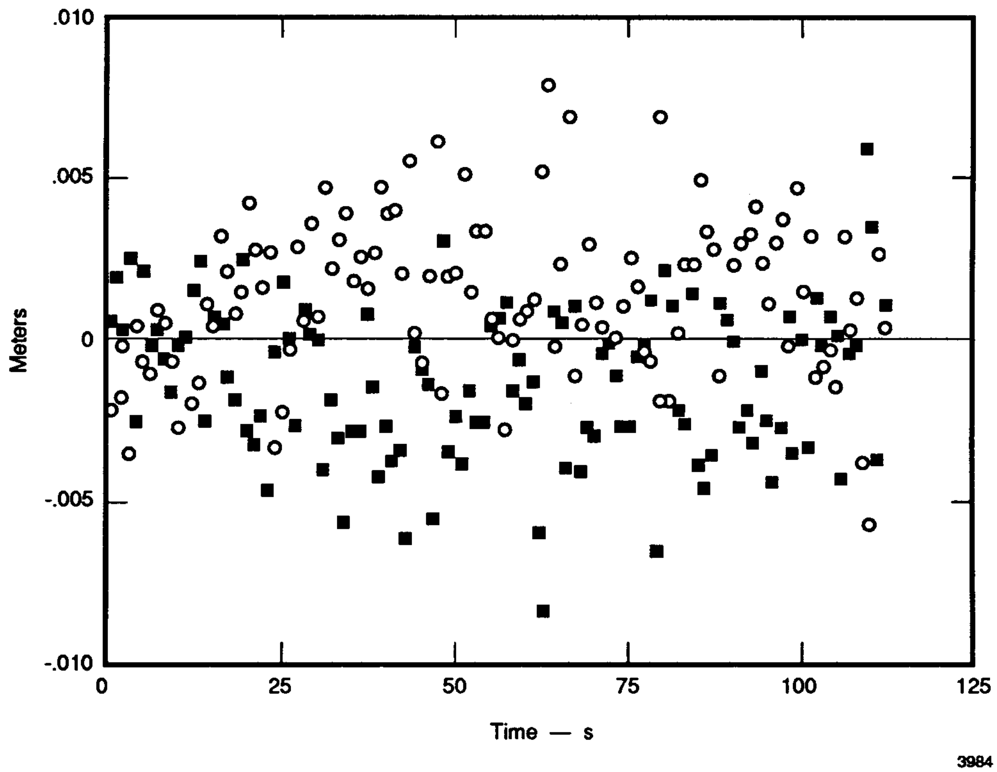


Figure 6. Differential carrier phase measurement noise (co-located).

4. Attitude Determination

Attitude measurements could be used in an AHS implementation to enable precise calibration of additional sensor instrumentation aboard the vehicle or to describe the angular orientation or motion of a vehicle. GPS satellite signals can also be used to determine attitude. For example, with two antennas placed a known distance apart and at a known orientation relative to the longitudinal axis of a vehicle, the heading and pitch of that vehicle can be determined because the relative horizontal and vertical positions of the antennas can be determined by a common receiver. Figure 7 shows a diagram of the measurements needed to calculate attitude. For each tracked satellite, the total phase difference between the two antennas is determined and converted to the angle the antennas make with respect to the satellite. Attitude accuracies of 1/10 degree are currently available for antenna separations of 1 m.

5. GPS Timing Accuracy

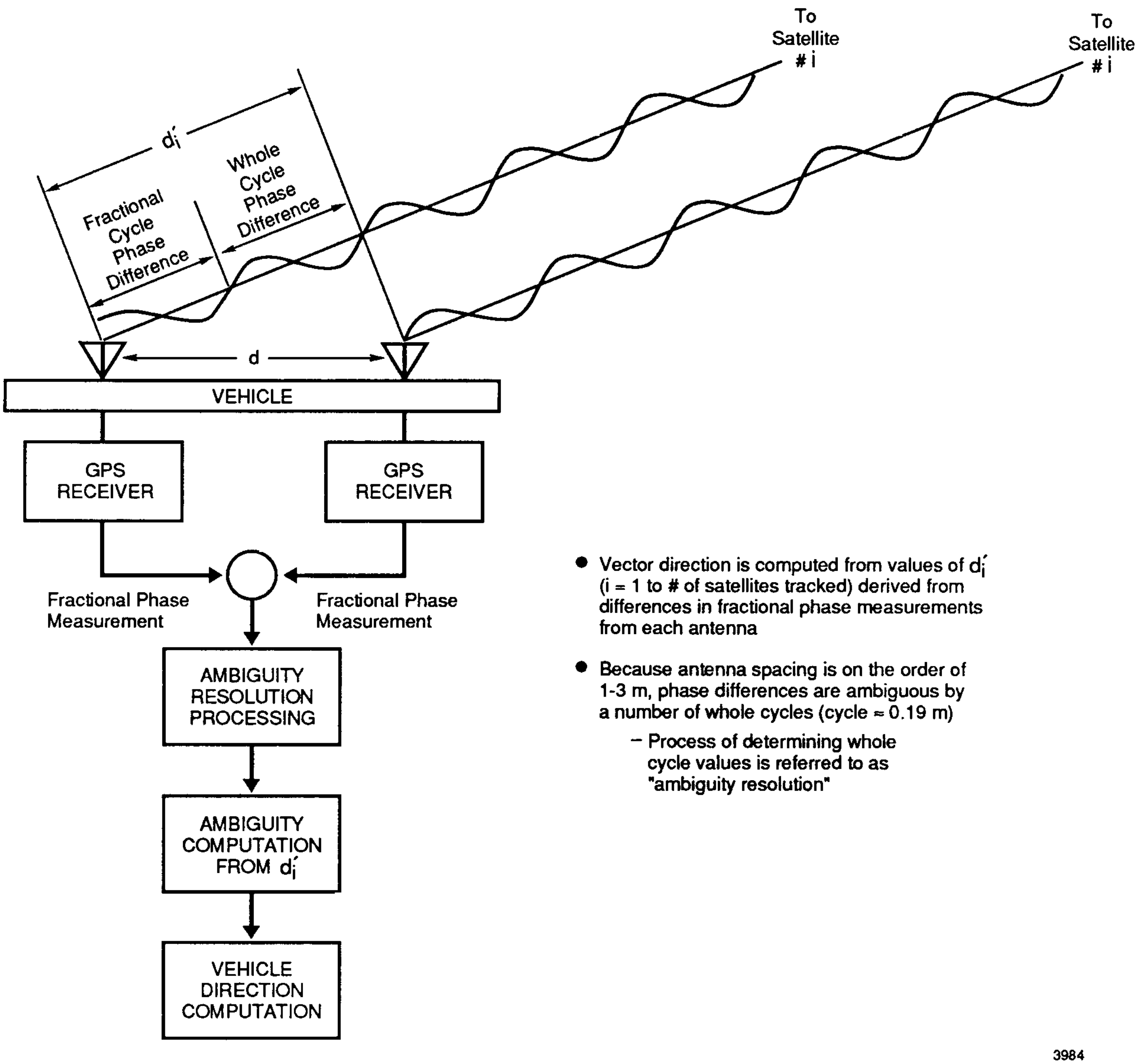
Because time is one of the four unknowns calculated by a GPS receiver, very accurate timing is available from a GPS receiver in addition to location and velocity. Signals accurate to between 50 and 100 ns of a worldwide time standard are commonly available from GPS receivers. These signals can be used in AHS for synchronizing datalinks and coordinating manuevers.

6. Integrity Monitoring

An active area of GPS research that can be applied to AHS concerns GPS performance integrity monitoring, which is defined as the ability to detect when the accuracy available from GPS does not meet the necessary requirements. Integrity requirements for AHS are currently undefined. A representative integrity figure for aircraft landings dictates a time-to-alarm of 2 s, and a probability of undetected error that corresponds to one event in 200,000,000 landings.[12]

Receiver autonomous integrity monitoring (RAIM) refers to algorithms that continuously compare data from a set of five or more satellites to detect any inconsistencies. If a problem is sensed, the data are invalidated and a warning is issued. It has been shown that with five satellites in view and proper geometry, the malfunction of one satellite can be detected. Six satellites are required to identify which satellite is malfunctioning. Many commercial receivers track six or more satellites.

Several characteristics of the AHS environment will facilitate monitoring of GPS integrity. Inertial reference units (IRUs) (described in Section II-F) will be useful in that IRU-derived data can be compared to GPS data. If the velocity and acceleration data derived from GPS are significantly different from the values independently produced by the IRU, then an error is present. Also, with the inclusion of an AHS roadway map database, GPS integrity can be monitored by comparing GPS-derived data to the map data.



- Vector direction is computed from values of d_i' (i = 1 to # of satellites tracked) derived from differences in fractional phase measurements from each antenna
- Because antenna spacing is on the order of 1-3 m, phase differences are ambiguous by a number of whole cycles (cycle ≈ 0.19 m)
  - Process of determining whole cycle values is referred to as "ambiguity resolution"

Figure 7. GPS attitude determination.

A GPS Integrity Channel (GIC) has been proposed to notify users when GPS satellites are broadcasting incorrect data. Using GIC, a series of worldwide stations would monitor the signals being broadcast by all GPS satellites and detect when data are incorrect. An as-yet-undetermined datalink would be used to notify users in real time when errors occur. A combined differential correction and GIC datalink may be available within five years.[13]

E. EXAMPLES OF GPS LOCATION AND VELOCITY ACCURACIES

Figures 8 through 12 present results of GPS accuracy experiments conducted by SRI. Figure 8 illustrates the horizontal (east and north) errors encountered in tracking a single stationary C/A-code GPS receiver for approximately 30 minutes without using differential corrections. Errors up to 40 m are common, predominantly because of the intentional degradation of the C/A code signal by the DoD (SA). Figure 9 illustrates the errors resulting after differential corrections are applied to the same data (note the change in scale). Figure 10 presents location errors associated with the same data in Figures 8 and 9 after the carrier cycle ambiguties have been resolved.

Figure 11 illustrates the uncorrected velocity error associated with a single stationary receiver. Velocity errors up to 1 m/s are common, predominantly resulting from SA. Figure 12 presents the velocity difference between two stationary receivers, and is thus an indication of differential velocity noise.

F. TECHNIQUES FOR AUGMENTING GPS

1. Inertial Reference Units (IRUs)

An IRU is an instrument that measures the orientation of a vehicle and the accelerations that the vehicle undergoes relative to its own longitudinal, latitudinal, and vertical axes. IRUs are very accurate over short intervals, but drift significantly with time. These devices are often used in conjunction with GPS receivers, because the two tend to complement each other: the GPS provides long-term absolute reference for the IRU, to keep it from drifting very far; and the IRU provides very accurate navigation during brief periods when GPS data are unavailable due to loss of satellite track.

In AHS applications, loss of GPS track can be expected when a vehicle is beneath an underpass, in a tunnel, or on a bridge with significant superstructure. When the duration of the GPS outage is short, an IRU can be used to maintain navigational continuity.

In the general situation, error build-up in an IRU is a relatively complex issue and requires a detailed analysis of the error sources within the hardware itself. However, for the purposes of this discussion, in those situations where an IRU is coupled to a GPS receiver and is used to navigate during relatively short GPS outages, the main source of position error build-up is likely to be the

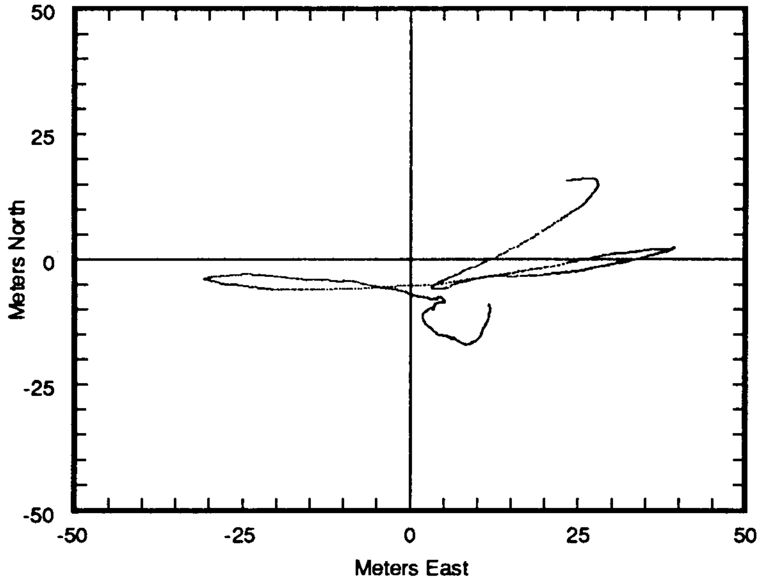


Figure 8. Tracking errors without differential corrections.

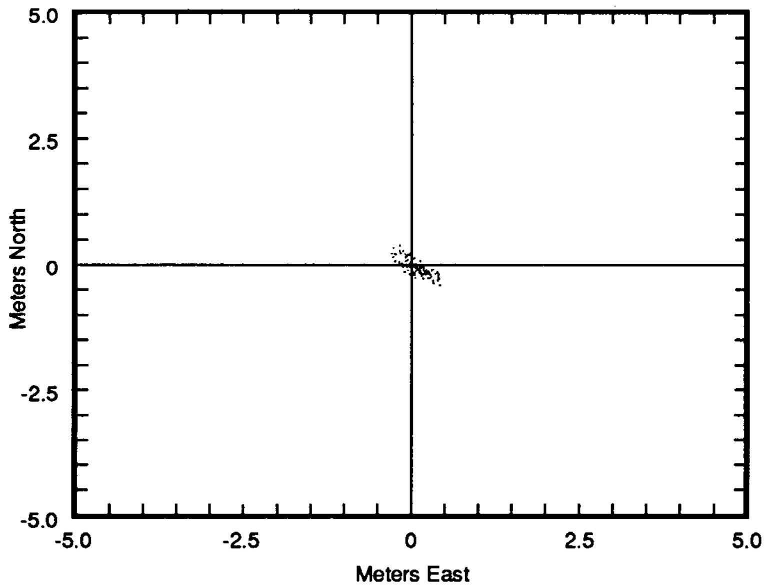


Figure 9. Tracking errors with differential corrections.

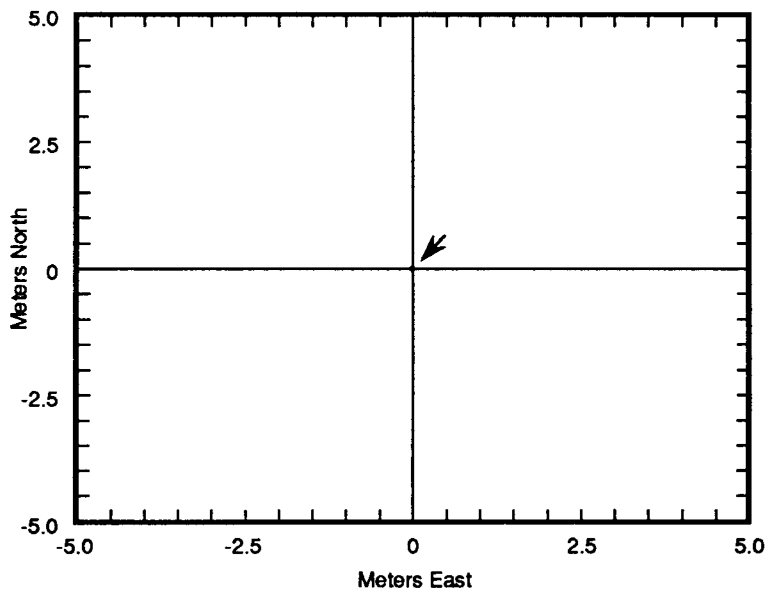


Figure 10. Tracking errors after carrier cycle ambiguities are resolved.

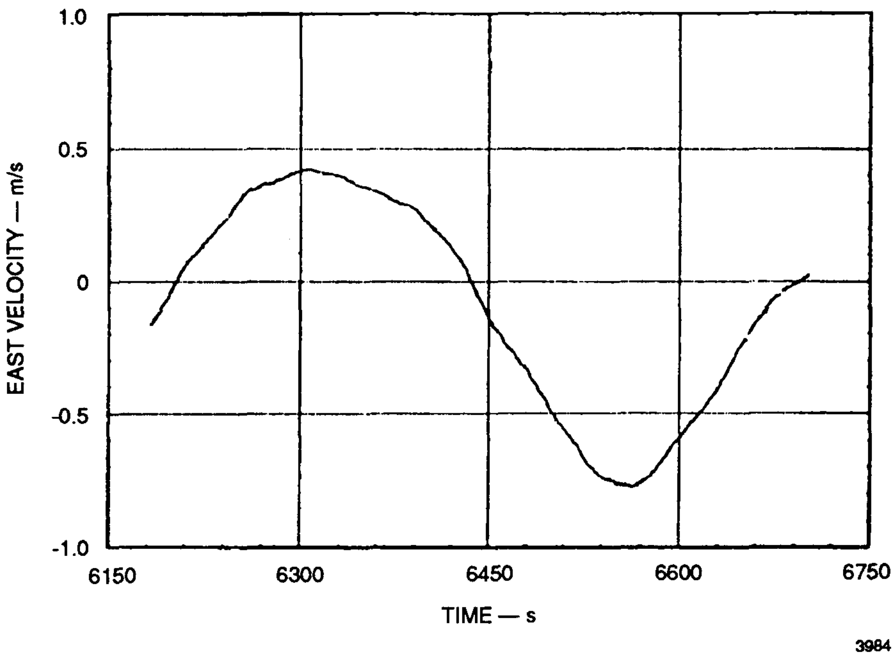


Figure 11. Velocity error of a stationary C/A code GPS receiver without differential corrections.

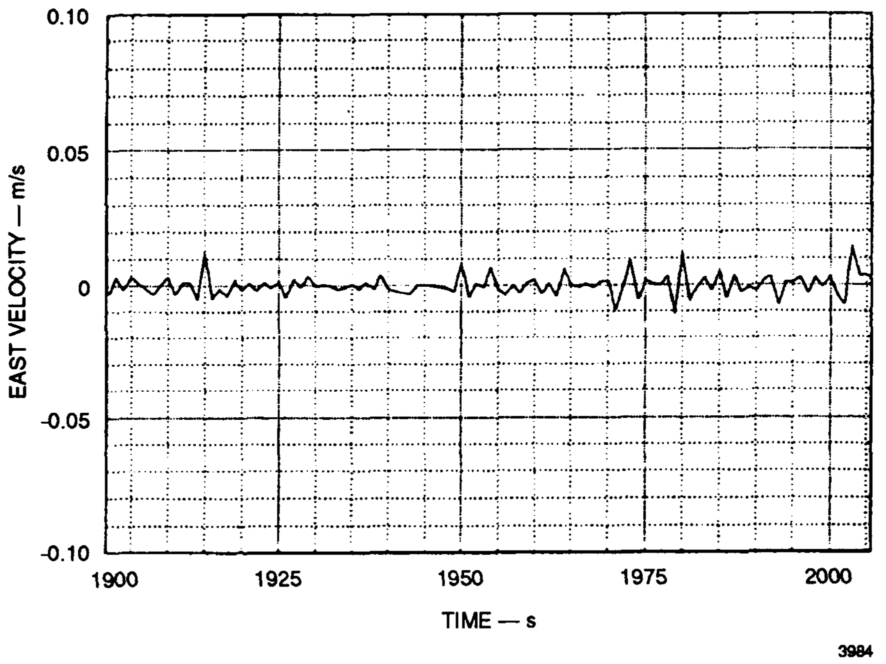


Figure 12. Differential velocity noise of a stationary C/A code GPS receiver.

error in GPS velocity at the onset of the outage. This velocity error will be integrated until the GPS receiver is again able to navigate. A typical differential GPS velocity error is about 1 cm/s, which would become a 30-cm position error when integrated over 30 seconds.

2. Dead Reckoning

Dead reckoning can be performed using measurements of the distance travelled by a vehicle (usually provided by an odometer output or pulses from an anti-lock braking system) or vehicle speed, and a measurement of the direction of vehicle travel, typically available from an electronic compass. These data can be used to propagate the original vehicle position and velocity to yield updated vehicle location, speed, and heading during short periods of GPS outage. Accuracy is limited because of motion experienced in turns, tire slippage on the roadway, and errors associated with measuring magnetic heading (due to iron on the vehicle or features along the roadway, such as bridges and manhole covers). The location accuracy typically available from dead reckoning systems is approximately two percent of the distance travelled. Advanced systems have been developed that require mounting magnets on wheel rims and multiple sensors to provide measurements of the relative motion of two wheels during turns, thus providing wheel differential data.

3. Pseudolites

A GPS innovation that can be applied to GPS-based AHS vehicle control is the "pseudolite," a ground-based transmitter that broadcasts signals identical to or approximating GPS satellite signals.[14] Pseudolites can be used in situations where insufficient satellites are visible, such as in an urban, foliated, or mountainous environment where satellite signals can be blocked by buildings, trees, or terrain. For example, pseudolites deployed in long tunnels have the potential to provide continous, high-accuracy tracking even when no satellite signals are available. A pseudolite signal can also be used to speed the process of carrier cycle ambiguity resolution.[15] This is done by taking advantage of the changing angular geometry from the vehicle to the pseudolite as the vehicle passes near the pseudolite.

A significant difficulty in using GPS pseudolites has been to ensure that their transmitted signals do not interfere with reception of GPS satellite signals. The GPS C/A code has a dynamic range of about 21.6 dB, limited by the cross-correlation properties between code sequences. This translates into what has been referred to as a "near/far ratio" of about 10:1, meaning that a GPS receiver that is closer than a certain minimum distance to a pseudolite--the distance being a function of pseudolite transmit power and antenna pattern gains--will not be able to receive satellite signals because they are "drowned out" by the pseudolite, whereas a receiver at roughly ten times this distance will not be able to track the pseudolite. Techniques that have been proposed to mitigate the near/far ratio problem include: using codes longer than the 1024 bits in the C/A code transmitted by GPS satellites; transmitting pseudolite signals at a different frequency than the L_1 GPS satellite frequency; pulsing or time-multiplexing the signal from pseudolites so that satellite signals are overpowered for only a fraction of a second; or using a combination of these techniques.[16]

A notional implementation of pseudolites to provide vehicle tracking in a tunnel is described in Section IV-D.

4. Additional Satellite Signals

In addition to vehicle and ground-based augmentations, other satellite navigation systems can provide increased availability, accuracy, and integrity for a GPS-based AHS. Although these additional satellite systems are subject to the same line-of-sight limitations as GPS, additional satellites increase the probability of a vehicle receiving signals in a partially blocked environment, such as the downtown urban canyon or when foliation is present. The three satellite systems discussed in the following subsections also have the potential of increasing the accuracy available for AHS because there is no intentional degradation of signals. The integrity, and therefore safety, of a GPS-based AHS is increased by the use of additional satellite systems because the greater number of distinct systems used, the lower the probability that a single system error will cause an AHS failure.

a. Global Navigation Satellite System (GLONASS)

GLONASS is a satellite navigation system similar to GPS that is being deployed by the Commonwealth of Independent States (formerly the Soviet Union).[17] Like GPS, GLONASS employs C/A and P-code modulation, dual frequencies in L-band, and 24 satellites. The major difference between GLONASS and GPS is that, instead of using a code division multiple access (CDMA) encoding technique, in which all satellites are broadcasting on the same frequencies, GLONASS employs a frequency division multiple access (FDMA) technique that uses different frequencies for each satellite. Two augmentations of GPS can be provided by GLONASS: an increase in the number of satellites available to users with combined GPS and GLONASS receivers, and the use of GLONASS pseudolites.[18] As discussed earlier, C/A-code GPS pseudolites would have a near/far ratio of approximately 1-to-10 because of the 21.6-dB channel isolation. In contrast, GLONASS pseudolites would have a near-far ratio approximately 20 times larger, allowing greater flexibility in the placement of pseudolites. SA-like intentional degradation of the signals has not been imposed thus far, and system operators have stated that they have no intention or capability of doing so. Combined GPS/GLONASS receivers are currently available commercially, but there has been limited acceptance of GLONASS because of the political and economic situation in the former Soviet Union. Sixteen GLONASS satellites are currently usable, and the system is scheduled to become fully operational in 1995-1996.[19,20]

b. INMARSAT Satellite Signals

The INMARSAT communications satellites currently being developed will provide ranging signals by use of "bent-pipe" repeaters, whereby signals initiated on the ground are transmitted to the satellites and repeated using transponders on the satellites.[21] The downlink frequency has been chosen to be very close to the GPS L_1 frequency to minimize GPS receiver modifications, but far enough away to minimize interference with GPS satellite signals.

c. Civilian Global Navigation Satellite System (GNSS)

Both GPS and GLONASS have been developed and deployed primarily for military use. International civilian aviation organizations have expressed the need for a civilian controlled and operated Global Navigation Satellite System (GNSS).

"Econosats"--small, non-militarized navigation satellites that are less expensive than GPS satellites--have been proposed as a way to initially augment GPS, and possibly GLONASS, and later to possibly provide a completely civilian GNSS.[22] The small payloads and low to medium Earth orbits will considerably reduce launch costs. Like the INMARSAT satellites currently under development, the Econosats would employ a GPS-like signal separated from the GPS L_1 frequency. A C/A-code modulated signal near the GPS L_2 frequency is proposed to enable the user to calculate ionospheric corrections.

5. Summary of Techniques for Augmenting GPS

Figure 13 summarizes the techniques available for enhancing GPS to meet the types of accuracy and coverage requirements expected for AHS.

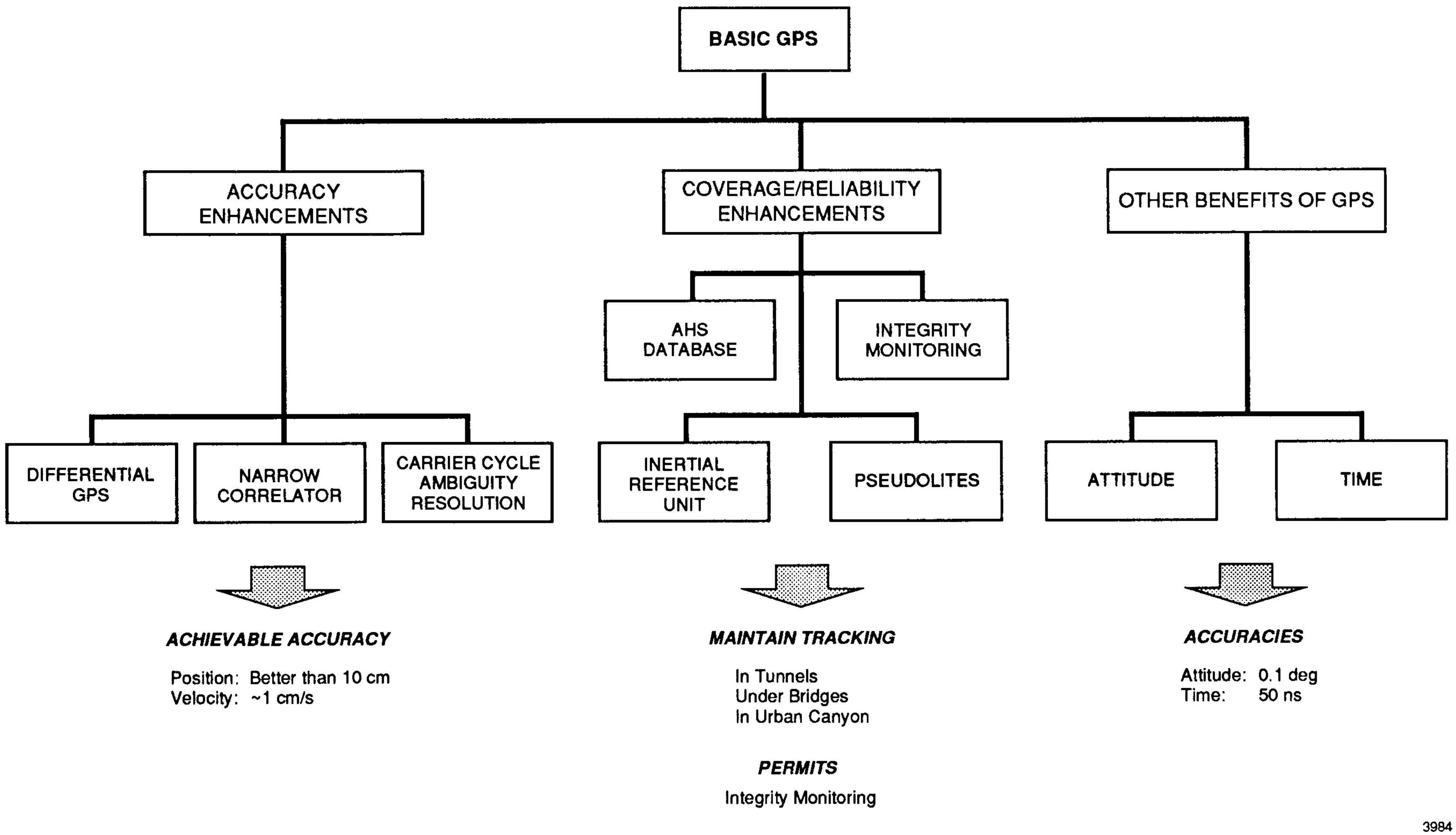


Figure 13. GPS enhancements.

III OTHER PROPOSED LATERAL AND LONGITUDINAL CONTROL SENSORS

Other promising sensor technologies being proposed, evaluated, or developed by AHS researchers and the automotive electronics industry for providing AHS lateral and/or longitudinal control information include magnetic, radar, laser radar, and vision-based systems. This section provides an overview of these sensor technologies and then summarizes the advantages and disadvantages of these technologies and GPS for AHS vehicle control applications. Table 2, located at the conclusion of this section, summarizes the comparison of these technologies.

A. MAGNETIC SENSORS AND MARKERS

The California PATH (Partners for Advanced Transit and Highways) Program has demonstrated a lateral vehicle control scheme on a full-scale vehicle test track based on the installation of discrete magnetic markers mounted on the lane centerline and sensed by a magnetometer aboard the vehicle. The sensed magnetic field is used to determine the vehicle's deviation from the centerline. In these experiments conducted under the PATH Program, steering angle sensors, yaw rate sensor, and an accelerometer were also mounted on the vehicle. A full-state, closed-loop controller provides steering angle control based on vehicle state estimates, which are corrected using the tracking error measurements provided by the magnetic markers.

By varying the polarity of the magnetic markers on the roadway, very limited information on the characteristics of the upcoming roadway can be encoded in the marker polarity sequencing and transferred to the vehicle. Alternatively, upcoming roadway geometry information can be stored in an on-board database constructed from a road survey. PATH experiments have shown that this "anticipatory" information--e.g. information on the curvature characteristics of the upcoming roadway--is critical for a lateral control system based on magnetic roadway markers at higher vehicle speeds.[23]

PATH conducted a set of "robustness" experiments to determine the magnetic marker/ controller system performance under adverse conditions, including hard braking, low tire pressure, and slippery roadways. The maximum tracking error observed was less than 15 cm for the worst-case scenarios. PATH tests conducted to verify the accuracy of the magnetic marker reference/
sensing system showed a standard deviation of error of 5 mm when the lateral displacement is 25 cm or less, while resolution and accuracy degrade at higher displacements from the markers. The effective range of the magnetic marker system is approximatly 40 cm.[2]

B. RADAR

Radar sensors developed for collision avoidance and intelligent cruise control applications employ pulsed radar and frequency-modulated continuous wave (FMCW). These sensors operate in the microwave and millimeter wave frequency range, with maximum detection ranges on the order of 100-150 m. Radars developed for automotive applications in the United States operate at 24 GHz.

Doppler effect processing is also being used to provide more accurate relative velocity than ranging radar. The drawback of Doppler is that when vehicle closing speeds are small, the accuracy of the measured absolute distance degrades significantly.[24]

Radar systems provide better performance in a broader range of environmental conditions than does the other most widely used sensor, LIDAR (described in the following discussion). Disadvantages of radar include sidelobe clutter that can lead to spurious detections outside the field of interest, the large transmitter and antenna size, and a currently higher cost/performance ratio than LIDAR.

C. LASER RADAR (LIDAR)

LIDAR (light detection and ranging) is the optical equivalent of radar; lasers transmit light beams and the signal reflected from the target is received by an optical sensor. LIDAR systems developed for automotive applications use infrared (IR) lasers at wavelengths of approximately 900 nm. Current LIDAR sensor systems developed for intelligent cruise control applications use a 1.5-3.0 deg field of view, and provide range and relative speed accuracies of approximately 0.1-1.5 m and 0.5-1.5 m/s respectively, at less than 100-m ranges. These performance values degrade rapidly at higher ranges. LIDARs require multiple scans to determine relative vehicle speed, therefore requiring a time delay between distance and relative speed determination. Maximum detection ranges are approximately 100-150 m in good conditions and are substantially reduced in adverse weather conditions such as fog, a major limitation to AHS operations.

D. VISION SYSTEMS

Computer vision systems are currently being developed and evaluated for collision avoidance, obstacle detection, and vehicle/lane-following applications, as well as for autonomous vehicle driving both on and off roadways. Both two- and three-dimensional systems are potential candidates. Two-dimensional systems have the limitation that they cannot measure absolute distances to objects; rather, they can measure changes in relative distance. Three-dimensional stereo-vision systems can measure the absolute distances to objects based on comparisons between two or more camera images. Three-dimensional systems also have the potential to provide both lateral and longitudinal control information (e.g., image-based lane following and headway control).

"Model" and "learning" approaches to vehicle control systems based on computer vision are being developed and evaluated for IVHS applications. Model-base approaches correlate images to model features such as other vehicles, roadway edges, or roadway centerline markings. Learning-based approaches use artificial intelligence systems to "learn" and then control using their knowledge base of driver behavior in similar situations. The Robotics Institute at Carnegie Mellon University has developed and demonstrated a vehicle called the Autonomous Land Vehicle in a Neural Network (Alvinn), that uses artificial intelligence and image recognition techniques to autonomously navigate on highways. Alvinn must be manually driven for a short period, during which the multiple processors "learn" driving behavior by compiling and comparing data such as path followed between lane markers.

Computer vision systems are very processing-intensive, costly, and require substantial reliability improvements for AHS applications. More development is required; therefore, vision systems are generally regarded as a very promising but longer-term AHS sensor technology.

Table 2: COMPARISON OF CONTROL SENSOR TECHNOLOGIES

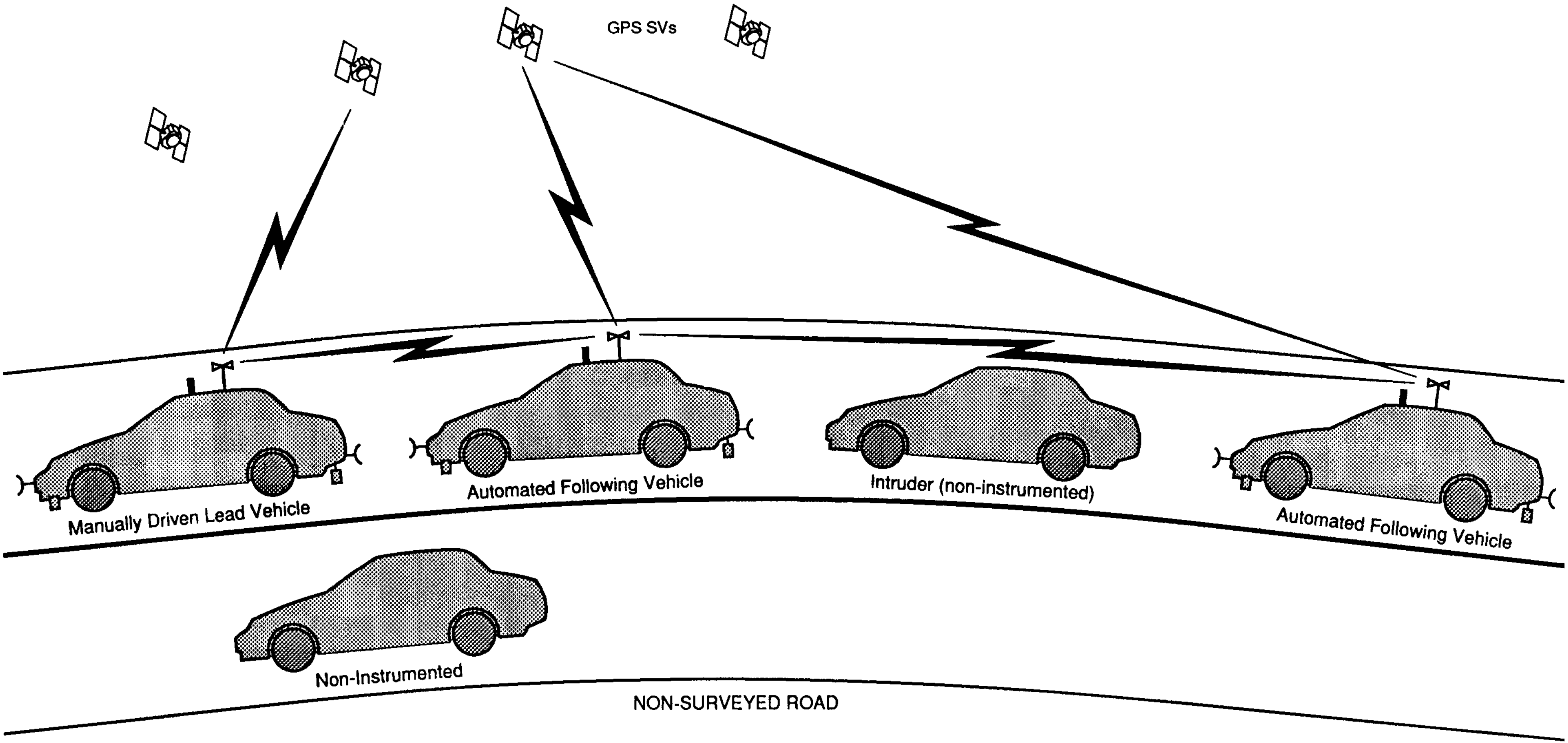
Control Sensor Technology	Advantages	Disadvantages
Magnetic sensors and roadway magnetic markers	• Precise lateral control technology • Low-cost, passive sensor • Very low data rate transfer of roadway turn information via magnetic marker polarity • Low susceptibility to poor environmental conditions	• Very high roadway infrastructure costs (installation and maintenance of markers) • Susceptible to electromagnetic interference from vehicle and other sources
Radar	• Accurate range and range rate (for Doppler radars) when performing optimally • Low susceptibility to poor weather conditions • Longer range sensing capability than infrared or vision systems	• Problems with very short range • Susceptible to multipath and clutter • For high accuracy may require cooperative target (e.g, reflectors on vehicle bumpers) • Higher cost sensor, and larger size • Frequency allocation uncertainties • Interference from other radar-equipped vehicles • Potential health concerns from electromagnetic emissions exposure
Laser Radar (LIDAR)	• Significantly lower sensor cost than radar, and smaller size • Accurate range measurements at short range. Maximum detection range ~100 m in good conditions with target retroreflector • More focused beam than radar	• Sensitive to rain and very limited in fog • Lower accuracy at longer range (for acceptable power levels) • Lower angular accuracy • At longer ranges, requires cooperative target (retroreflector) • Difficulty detecting mud-covered vehicles • Requires target reflectors for reliable performance • Positioning of source and target must be "favorable" • Power output limited by safety concerns
Vision systems	• Passive sensor • Can potentially provide both lateral and longitudinal control information • Interference not a problem • Can detect obstacles • Can differentiate between lanes	• Degraded performance in poor weather and low lighting conditions • Processing intensive • Very high relative cost • Much further development required
GPS	• Provides highly accurate, 3-D absolute position and velocity for both lateral and longitudinal control from single sensor • Extremely accurate time • Passive sensor • Absolute position enables direct mapping to upcoming roadway characteristics in stored roadway database • Most processing for information needed by control system performed by the sensor (GPS receiver) • Commercially available, receiver costs decreasing rapidly	• Differential correction network required • Requires augmentation with other sensors or pseudolites in areas where satellites are obstructed • Initialization period required to achieve high accuracy • Susceptible to multipath errors

IV NOTIONAL ARCHITECTURES AND OPERATIONS OF AN EARLY DEPLOYMENT AND A FULLY AUTOMATED/AUTONOMOUS GPS-BASED AHS

A. NOTIONAL ARCHITECTURE OF AN EARLY DEPLOYMENT "FOLLOW-THE-LEADER," GPS-BASED AHS

Figure 14 illustrates a notional architecture of an early deployment project that employs relative GPS techniques to provide a "follow-the-leader," GPS-based AHS capability. This capability is consistent with the popular AHS concept of platoons. The manually driven lead vehicle, operating on an unsurveyed road with a clear view of GPS satellites, collects GPS code and carrier phase data from its own GPS receiver and broadcasts the data to the vehicle(s) following behind. The second vehicle compares its own code and carrier phase data to that of the lead vehicle and calculates what manuevers are necessary to (1) maintain a safe separation distance from the lead vehicle and (2) follow the same path as the lead vehicle. A stereoscopic vision system, laser, or radar on the second vehicle is used (in a redundant role) to maintain a safe separation distance from the lead vehicle and to detect if an intruder vehicle cuts in between the two AHS cars. It may also be advantageous to use redundant ranging sensor data to aid in carrier cycle ambiguity processing. The second car in the platoon broadcasts its own GPS code and carrier data so that the third vehicle may calculate what manuevers are necessary for lanekeeping and maintaining a safe separation distance between itself and the vehicle in front. This relative GPS processing scheme is repeated down the length of the platoon; any vehicle in the platoon, except for the manually driven lead vehicle, receives data from the vehicle immediately in front of it for lateral and longitudinal control. By using the raw code and carrier measurements instead of calculated locations, the vehicles would not be required to be tracking exactly the same set of satellites. Instead, each vehicle pair (lead/lead+1, lead+1/lead+2, etc.) would be required to be tracking at least a common set of four satellites.

This project would be appropriate for early deployment because no infrastructure improvements such as a highly accurate differential correction datalink and road surveys and databases would be required. If the inter-vehicle datalink used was of sufficient bandwidth and broadcast characteristics, all of the vehicles within a certain area of interest would have access to the broadcast transmissions from all of the other vehicles--that is, the very accurate relative positioning data between the AHS vehicles would be known by all vehicles and could be used for manuevers and collision avoidance. An IRU would be required for short periods of occlusion such as underpasses. Longer sections of roadway in which satellite signals are occluded, such as in long tunnels, would require augmentation in the form of pseudolites or some other system such as magnetic markers or a vision-based system, or the following vehicles would be manually driven.



MANUALLY DRIVEN LEAD VEHICLE:

- COLLECTS OWN VEHICLE CODE AND CARRIER PHASE GPS DATA
- TRANSMITS DATA TO FOLLOWING VEHICLES

AUTOMATED FOLLOWING VEHICLES:

- COMPARES OWN VEHICLE GPS DATA TO DATA RECEIVED FROM CLOSEST AUTOMATED VEHICLE IN FRONT
- FOLLOWS SAME PATH (lane keeping)
- MAINTAINS SEPARATION
- MONITORS NON-INSTRUMENTED VEHICLES (radar & imaging)

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Figure 14. Notional architecture of a completely automated "follow-the-leader" GPS-based AHS.

B. NOTIONAL ARCHITECTURE OF A FULLY AUTOMATED/AUTONOMOUS, GPS-BASED AHS

Figure 15 illustrates a notional architecture of an AHS that uses GPS for autonomous lateral and longitudinal control. Figure 16 is a block diagram of GPS AHS instrumentation and data flow. Following are the major constituents:

- GPS Receiver--A 10-channel (or more) high-performance GPS receiver with carrier phase outputs and the capability to resolve carrier cycle ambiguities.
- IRU--Required to provide update rates up to 100 Hz and to allow for seamless tracking during short periods of occlusion from obstacles such as bridges, short tunnels, and buildings.
- Map Database--A very reliable, accurate, up-to-the-minute database containing the surveyed coordinates of the AHS roadway in a coordinate system compatible with WGS-84. A map database will be required for the vehicle to know its location relative to the roadway in order to follow lanes.
- AHS System Control Datalink--A roadway-to-vehicle (and probably vehicle-to-roadway) datalink that provides data on road conditions and current lane survey data, should data in the Map Database be in error because of road repair. A roadway-to-vehicle control system will be needed to advise drivers of AHS system status, emergency situations, and detours. Having the roadway map in a database offers the advantage of identifying detours, road changes, known obstructions, and the like, by altering the data and retransmitting the map to the vehicles, rather than by installing physical barriers or other hardware on the roadway.
- Differential Correction Datalink--A datalink that provides differential corrections via ground-based transmitter, satellite, or possibly via the AHS System Control Datalink. The GPS receiver in the vehicle must have access to accurate, timely differential corrections to calculate accurate position and velocity.
- Vehicle-to-Vehicle Datalink--A datalink that provides communications between vehicles for headway maintenance and collision avoidance. A vehicle-to-vehicle datalink must be provided so that vehicles in proximity to one another can inform each other of their locations, velocities, and status. The lateral and longitudinal control systems can then use this information to "negotiate" manuevers and maintain intervehicular distances and speeds.
- Proximity/Lane Sensors--Other sensors installed on vehicle for redundancy. Possible sensors include radar, optics, and magnetic nail sensors.
- Pseudolites--Transmitters deployed on the ground that duplicate the signals of GPS satellites. During long stretches where all or nearly all of the satellites are occluded (as in long tunnels), pseudolites will be installed to allow continuity of GPS tracking. Some form of roadway infrastructure may be desirable to expedite the carrier cycle ambiguity resolution process to ensure sufficiently accurate data. Pseudolites at the AHS entry points are being considered for this purpose. The pseudolites may be controlled via the AHS System Control Datalink.

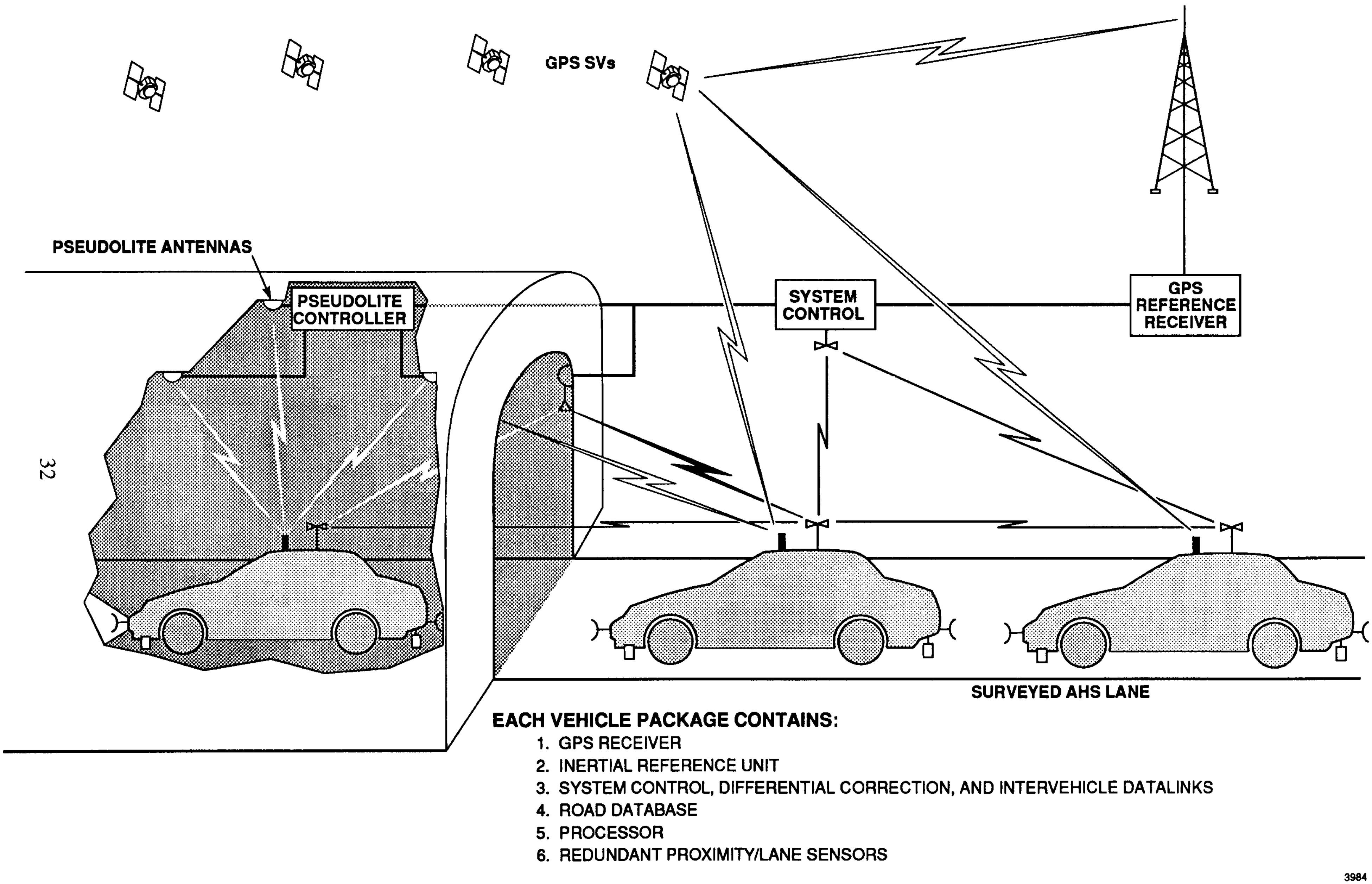

Figure 15. Notional architecture of an autonomous GPS-based AHS.

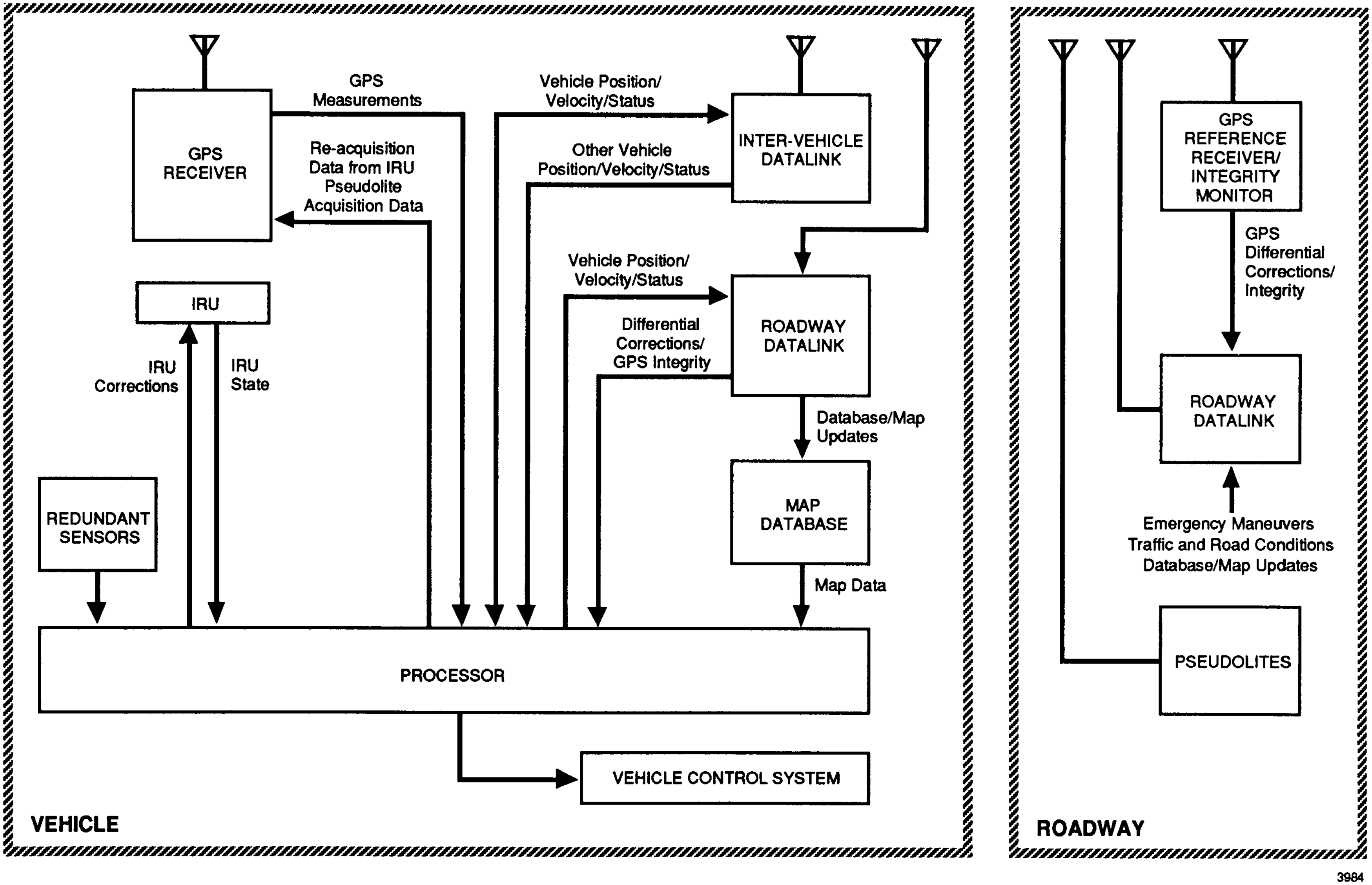

Figure 16. Block diagram of GPS AHS instrumentation and data flow.

NOTE: Road databases, roadway-to-vehicle datalinks, and vehicle-to-vehicle datalinks are common elements of the U.S. DOT Intelligent Transportation System (ITS) National Architecture Development Program now under way and are not unique requirements of a GPS-based AHS, although a road database optimized for AHS will probably be more accurate and detailed than a generic ITS road database.

C. OVERVIEW OF OPERATIONS RELEVANT TO GPS

Entry of Vehicle Onto AHS. Before vehicles are allowed entry onto an automated highway, rigorous vehicle system checks will be performed to ensure that the vehicle is functioning correctly. Relevant to the GPS instrumentation, system tests will be performed that exercise and verify operation of the relevant datalinks; evaluate the operation and accuracy of the GPS receiver and antenna/s; calibrate the operation of the IRU; and ensure that the map database is up-to-date.

Station Keeping and Manuevers. During normal operations, vehicles will compute their position, velocity, and acceleration using data from a GPS receiver and a differential corrections datalink. An IRU will supply position, velocity, and acceleration data when GPS satellite signals are unavailable for short periods, perhaps as much as 30 s. For lateral control data, each vehicle will compare its GPS-calculated location to the surveyed lane coordinates contained within a road database. An independent system, such as magnetic markers, infrared (IR) sensors, or an image recognition system, can be used to provide redundancy. For longitudinal control data, each vehicle will broadcast its own location, velocity, and acceleration data to other vehicles within a certain sphere of influence. By knowing its own state vector and the state vectors of all other local vehicles, each vehicle will calculate intervehicle distances and closing velocities, and perform the manuevers necessary to maintain predetermined intervehicle separation distances. Again, an independent system, such as radar, IR sensors, or image recognition system, can be used for providing redundant longitudinal control data.

Manuevers such as lane changes will be negotiated between vehicles, with a vehicle broadcasting a message to the other local vehicles (and possibly to a roadside controller) when a manuever is neccesary that affects the group. For example, a single vehicle wanting to join a platoon of vehicles will broadcast its pertinent data along with a request to join. Using algorithms contained within each vehicle processor, or dictated by the AHS system controller, instructions will be given to each vehicle on what manuever to perform (such as slow down to create a wider separation between two platoon vehicles) so that the new vehicle can join. A big advantage of using GPS data (instead of lane marker sensors) for manuevering is that when an unexpected occurence takes place, such as a stationary or moving obstruction in the roadway, all of the vehicles can react, even if only one vehicle or the infrastructure senses the danger, provided the information is distributed.

Use of Pseudolites Within a Tunnel. In a long tunnel, where GPS satellite signals will be occluded for a long period of time (tens of seconds or more), an IRU is likely to drift too much to be used for lateral and longitudinal control during the entire time the vehicle is in the tunnel. In this situation, a network of pseudolites broadcasting GPS-like signals within the tunnel appears feasible. Vehicles will be alerted to the existence of the pseudolites, along with the necessary pseudolite data (PRN and location), either by entries in the Map Database or by the AHS System Control Datalink. Pseudolites positioned at the tunnel entrance would provide signals for the vehicle's GPS receiver to change from a satellite signal-only environment, to a combined satellite and pseudolite signal environment, and finally to a pseudolite signal-only environment. Because most tunnels are bi-directional, each pseudolite will likely be seen by vehicles traveling in both directions; consequently, "entry" pseudolites will also serve as "exit" pseudolites for vehicles going from a pseudolite signal-only environment, to a combined pseudolite and satellite signal environment, and finally to a satellite signal-only environment.

Because of the ability of an IRU to provide data of sufficient accuracy for short periods of time when GPS satellite or pseudolite signals are not available, it will not be necessary to instrument the tunnel so that four or more pseudolite signals are constantly available throughout the entire length of the tunnel. Rather, it will be sufficient to position clusters of four or more pseudolites at periodic distances along the tunnel, with the distances determined by the "coasting" capabilities of the IRUs eventually chosen for AHS vehicles, the lateral and longitudinal position accuracies required, and the dimensions of the tunnel.

To "align" the pseudolite clock(s) with GPS time, it will be necessary for a pseudolite controller to have an integral GPS reference receiver and a GPS antenna located outside the tunnel to track the GPS satellites in view. An integrated pseudolite controller/reference receiver, located so that it can receive both GPS satellite and pseudolite signals, can be used to dynamically correct pseudolite clock errors, likely eliminating the need for a differential correction datalink inside the tunnel.

D. CANDIDATE DEPLOYMENT GEOMETRY OF PSEUDOLITES WITHIN A TUNNEL

A simulation and analysis was conducted to arrive at the number of pseudolites and a candidate deployment geometry that would be required to instrument the interior of a tunnel. The tunnel is of sufficient length that a “coasting” IRU would be unable to provide data for a long enough period to traverse the tunnel, so pseudolites are being used to provide GPS-like signals to the vehicle’s GPS receiver to update the IRU for a short period. As discussed earlier, it is unnecessary to provide continous GPS-like signals along the entire length of the tunnel. Multipath problems that might be encountered when operating pseudolites in tunnels of different materials, types of construction, and geometries were not addressed. Figure 17 presents the geometry of the tunnel and the candidate locations for the placement of six pseudolites. The number of pseudolites and locations for their installation were arrived at by taking the following into consideration:

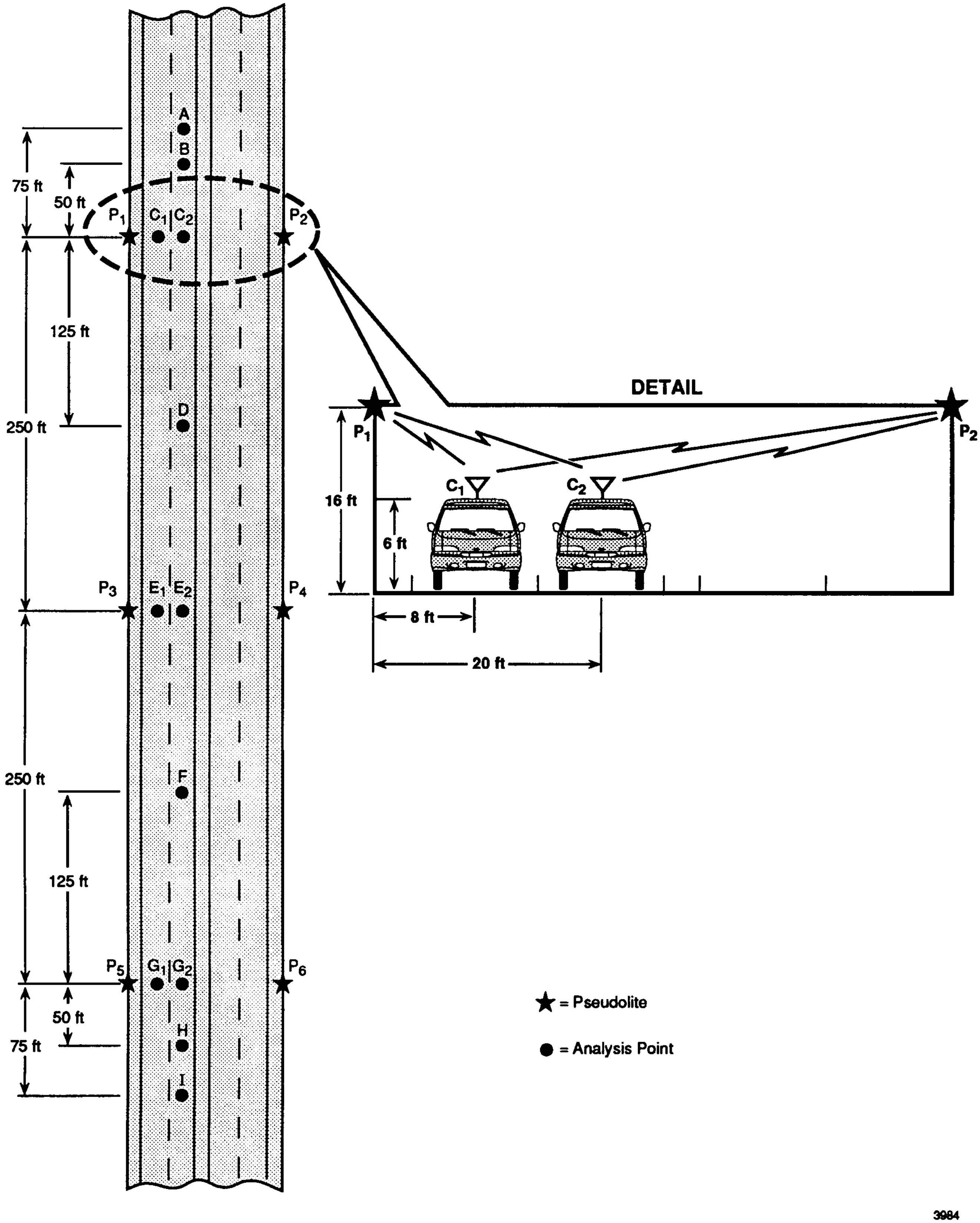

Figure 17. Candidate geometry of pseudolites in tunnel.

Tunnel Geometry. The simulated tunnel has four 12-ft wide lanes (two in each direction), with a 4-ft center median, and a 2-ft shoulder along each side, making the total width of the tunnel 56 ft. The tunnel is 16 ft high, with square corners suitable for mounting antennas. Line of sight visibility is at least 575 ft.

AHS Operations. The nominal speed for AHS vehicles operating within the tunnel was taken to be 55 miles per hour, with all types of AHS vehicles, including tall trucks, operating and manuevering on any of the four lanes.

GPS Signal Reacquisition Time. Many modern GPS receivers are capable of resuming tracking of GPS signals in under one or two seconds, even after the loss of signals for longer than one minute, provided the receiver maintains current ephemeris data and approximate estimates of time and position. The location of the pseudolites, in a format similar to ephemeris data, will be available to the GPS receiver either by broadcast before entering the tunnel or on an AHS database. For the simulation, it was assumed that time and position will have been maintained sufficiently by the vehicle’s processor and IRU to allow acquisition of pseudolite signals by the vehicle’s GPS receiver within 1 s of having access to the signals.

Minimum Accuracies and Update Time. For the simulation, absolute (as opposed to relative) horizontal location accuracies of approximately 5 cm were taken as being required for a minimum period of 5 s to update the IRU. With the AHS vehicles operating at 55 miles per hour (81 ft/s), sufficient pseudolite signals must be provided for a minimum of 6 s (reaquisition time plus time needed for update) or 486 ft. The nominal degraded accuracy of the solution available from the IRU was assumed to be 0.5-1.0 m.

Altitude Hold and Altitude Aiding. GPS receivers normally require the signals from at least four satellites to calculate the four unknowns: x, y, z, and time. AHS vehicles will have the advantage of only needing a two-dimensional solution because altitude is irrelevant to a vehicle operating on the ground, although there are reliability advantages to comparing the known altitude from an AHS database to the altitude calculated from the GPS receiver. In the case of an AHS vehicle operating in a tunnel, a very accurate AHS database will contain the altitude for all locations along the roadway, and a technique known as "altitude hold" can be employed. A GPS receiver in "altitude hold" mode calculates only x, y, and time, which only requires three signal inputs (with good geometry). Alternately, altitude data from an additional sensor, such as an altimeter, can be used to “aid” the solution, also lowering the required number of signal inputs to three, subject to geometry constraints. Altitude hold or calculating a two-dimensional solution becomes particularly important in the discussion of pseudolites in a tunnel because of the constraints imposed upon the locations of instrumentation within a tunnel.

Geometry and Dilution of Precision. A common method of determining the accuracies available from GPS involves determination of two quantities: user equivalent ranging error (UERE) and dilution of precision (DOP). UERE is a characteristic of a particular GPS receiver and is dependent upon the electronics and processing software used in the receiver. UERE is commonly expressed in meters with typical values being 1.5-4 m when using C/A-code differential techniques. DOP is a dimensionless term that is a characteristic of the relative geometry of the GPS satellites when viewed from a particular location at a particular time. DOP is calculated using the angles of the line-of-sight vectors from the user to the set of satellites (or pseudolites) to be used for tracking. Many different types of DOP values can be calculated, depending upon the accuracy characteristics that need to be quantified. The four most commonly used DOPs are geometric (GDOP), position (PDOP), horizontal (HDOP), and vertical (VDOP), with some of the more specialized DOPs being time (TDOP), azimuth (AZDOP), and elevation (ELDOP). For this discussion concerning ground vehicles, HDOP is the most relevant. A typical range of values of HDOP for a ground vehicle in the Continental United States with an unobstructed view of the GPS satellites is 1.5-3. The value of UEREs and DOPs is that, when multiplied together, a prediction of the accuracy available from a particular GPS receiver when operating at a particular location and time (and thus a particular view of the GPS satellites) is obtained. A GPS receiver with a UERE of 1.5 m operating when the HDOP is 1.5 will provide an estimate of its horizontal location accurate to approximately 2.25 m. UERE values have historically been calculated for GPS receivers using code or carrier-smoothed code measurements. With the advent of carrier phase tracking and carrier cycle ambiguity resolution techniques, calculation of UERE values commensurate with carrier measurement accuracies, as compared to code measurement accuracies, is useful. Thus, UERE values of 1.5 cm, as opposed to meters, can be used to calculate predicted errors after carrier cycle ambiguities have been resolved.

Simulation Results. Table 3 presents the results of a simulation that was run to predict the HDOP values and nominal accuracies to be expected from the pseudolite deployment geometry shown in Figure 17. A vehicle approaching point A (from the top of the page moving down) would still be within acceptable accuracy limits because of its use of an IRU, and will have acquired pseudolite signals before reaching point A. The HDOP value of 7.3 at point A indicates that with a UERE value of 1.5 m, commensurate with code tracking, a horizontal position accuracy of approximately 11 m would be available at point A, an accuracy that would be of little use in updating the IRU. However, with a UERE of 1.5 cm, a conservative estimate with carrier tracking, a horizontal location accuracy of approximately 11 cm would be available at point A, if the carrier cycle ambiguities have been resolved. Carrier cycle ambiguities are more easily resolved with lower DOP values and large angular geometry changes between the GPS antenna and the pseudolites. To allow more time for angular geometry change between the vehicle and the array of pseudolites, and to provide lower DOP values, the ambiguity resolution process is not assumed to be completed until somewhere between points B and C1 or C2. Location accuracies were analyzed at points C1 and C2 to assess whether there is any appreciable difference between the accuracies available in either of the two lanes. No difference was found, a result consistent with analysis at points E1 and E2, and G1 and G2. Location accuracies of 1-5 cm were predicted to be available continuously along a 500-ft path from points C1 and C2 to points G1 and G2. Because the carrier

Table 3: SIMULATION RESULTS OF CANDIDATE PSEUDOLITE GEOMETRY WITHIN A TUNNEL

Point	HDOP*	Expected Nominal X,Y Accuracies	Pseudolites Used in Solution
A	7.3	0.5 m (Note 1)	P2, P5, P6
B	4.2	0.1-0.5 m (Note 2)	P2, P5, P6
C1	1.5	1-5 cm (Note 3)	P1, P5, P6
C2	1.5	1-5 cm	P1, P5, P6
D	1.5	1-5 cm	P1, P5, P6
E1	1.2	1-5 cm	P2, P3, P6
E2	1.2	1-5 cm	P2, P3, P6
F	1.5	1-5 cm	P1, P2, P6
G1	1.5	1-5 cm	P1, P2, P5
G2	1.5	1-5 cm	P1, P2, P5
H	4.2	1-5 cm	P1, P2, P6
I	7.3	5-11 cm (Note 4)	P1, P2, P6

*HDOP = Horizontal Dilution of Precision.

Note 1 Location data from IRU.
2 Start of GPS tracking.
3 Carrier cycle ambiguities resolved.
4 Ambiguities are resolved, but increasing HDOP limits available accuracy.

cycle ambiguities are expected to remain resolved until loss of carrier lock, the relatively high DOP value of 7.3 at point I is still sufficient to provide a horizontal accuracy of 5-11 cm.

Near-Far Ratio. For the tunnel geometry depicted in Figure 17, the minimum separation distance between an antenna mounted on an AHS vehicle operating in the center of the outside lane and a pseudolite antenna would be approximately 9 to 13 ft, depending on the height of the vehicle (6-ft passenger vehicle height vs 12-ft truck height). For the extreme case of a 12-ft tall vehicle on the shoulder, directly beneath a pseudolite antenna, the minimum separation distance could be as small as 5 ft. As discussed earlier in Section II-F, deployment of pseudolites is complicated by the effects of the near-far ratio, with C/A-code CDMA GPS-style pseudolites having a near-far ratio of 10:1, and FDMA GLONASS-style pseudolites predicted to have a near-far ratio of at least 200:1. A minimum separation distance of 5 ft and a maximum desired vehicle to pseudolite distance of 600 ft would indicate that even in the most stressing case, a maximum near-far ratio of 120:1 is required--well within the theoretical limits. In addition to code, frequency, and time division multiple access (TDMA) techniques available for optimizing pseudolite transmissions within a tunnel, pseudolite antennas with special gain patterns could be deployed to limit interference.

V PRELIMINARY EVALUATION OF GPS OPERATION IN AN AHS ENVIRONMENT

GPS receiver performance can be significantly affected by the environment in which it operates. In particular, the accuracy and continuity of navigation depend on good satellite visibility, minimal propagation anomolies such as multipath, and negligible RF interference. Today's highways are often bordered by walls, trees, or (in urban areas) tall buildings. These structures can block satellite signal reception or cause reflections that distort the signal at the receiver.

To determine the effect of AHS environment factors, SRI collected GPS performance data in a comparable environment. Two different types of receivers were tested simultaneously during this analysis: a NovAtel 10-channel C/A-code narrow correlator receiver, and an Ashtech Z-12 12-channel, dual-frequency P/W-tracking receiver. The receivers were connected to separate antenna/preamplifier units.

The receivers were tested on three highways with two different highway environments along the San Francisco peninsula: two highways with numerous bridge, tunnel, building, and foliage obstructions (Highways 101 and 92, heading north and west from Menlo Park, CA, to San Mateo, CA); and a rural freeway with long periods of nearly unobstructed access to GPS satellite signals (Highway 280, heading south from San Mateo to Menlo Park).

Figures 18 and 19 show, for the two receivers tested, the locations along the travel path where at least four satellites were in phase-lock. The annotations indicate the duration of each dropout (in seconds). The vehicle was traveling at average freeway speeds. The transition from Highway 92 to Highway 280 is a tunnel, which caused an 18-s dropout for the NovAtel and a 48-s dropout for the Ashtech. With the exception of one dropout caused by surrounding hills, all of the other dropouts were caused by underpasses. Of the 17 dropouts experienced by the NovAtel, only two were longer than 10 seconds in duration, and both were less than 20 seconds. Of the 18 dropouts experienced by the Ashtech, six were longer than 10 seconds, with four ranging from 35 to 48 seconds, and one dropout lasted 98 seconds.

Figure 20 is a plot of altitude, measured over a 60-s period, for a vehicle traveling at 24 m/s. The plot demonstrates the smoothness of the data after the carrier cycle ambiguities are resolved. (Altitude was chosen because it is usually the least accurate data.) The carrier cycle ambiguities were resolved using the wide-laning technique (the L_1/L_2 difference frequency phase observable) with the outputs from an Ashtech Z-12 receiver. Data plotted from a NovAtel receiver operating on the same vehicle over the same time period was of almost identical shape after a search algorithm[25] was used to resolve the L_1 carrier cycle ambiguities. (The experimental technique was not sufficiently rigorous to justify direct comparison of the absolute altitudes from the two receivers.)

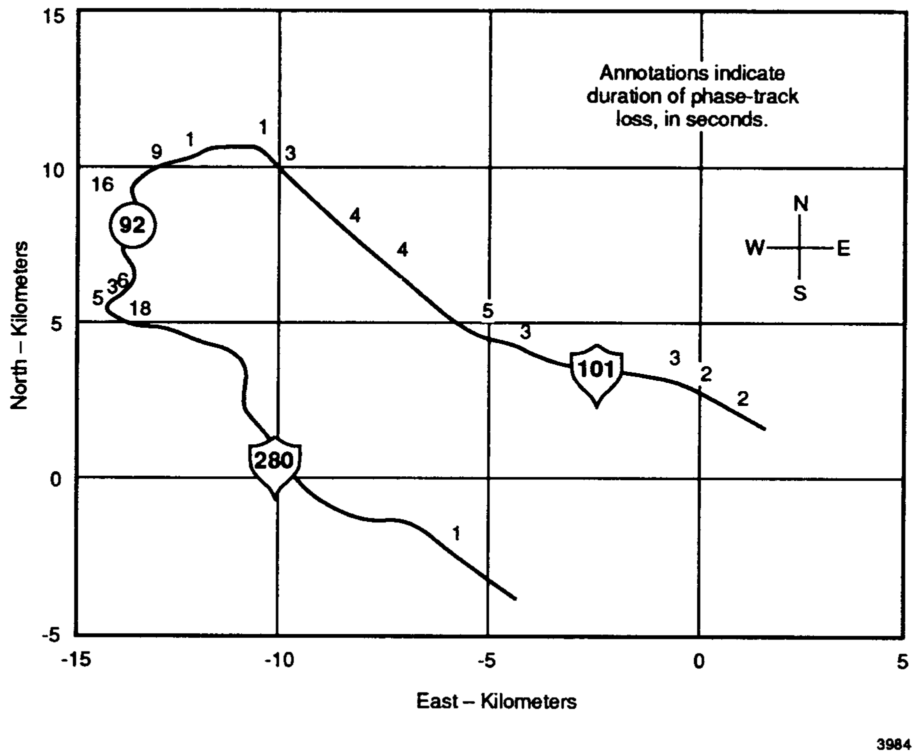

Figure 18. Track continuity of NovAtel narrow correlator receiver on highways 101. 92, and 280.

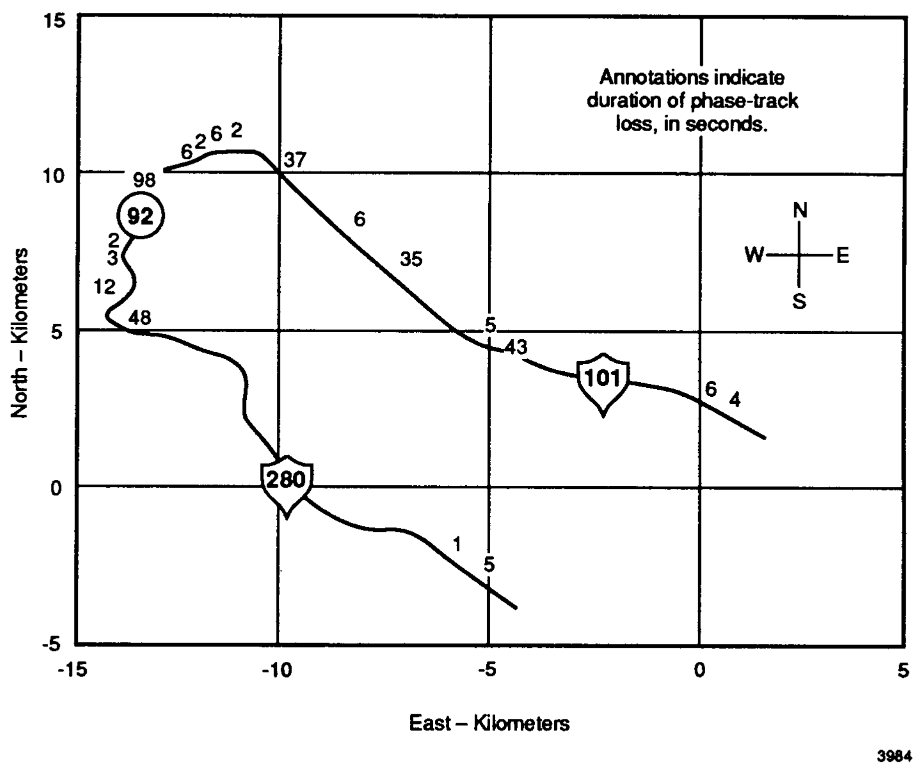

Figure 19. Track continuity of Ashtech Z-12 receiver on highways 101, 92, and 280.

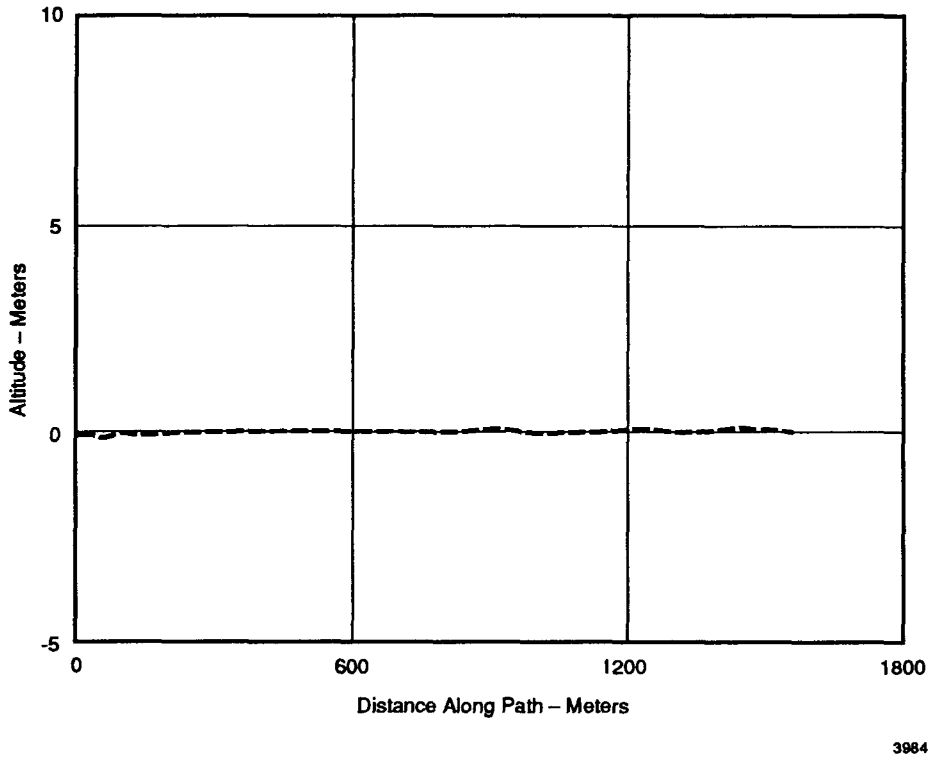

Figure 20. Altitude noise over 60-s period after carrier cycle ambiguities are resolved. (Ashtech wide-lane solution at 24 m/s)

VI SUMMARY AND CONCLUSIONS

Considering its current capabilities and projected near-term developments, GPS--in conjunction with appropriate augmentations--is very likely to be a viable means of providing data for lateral and longitudinal control of vehicles in an AHS environment. The major augmentations required for ensuring that continuous data are available is development of integrated GPS IRU sensors and pseudolites suitable for operation in tunnels. To take full advantage of GPS capabilities for AHS, very accurate road databases and roadway-to-vehicle and vehicle-to-vehicle datalinks will be required, although there is the possibility of an early deployment of a "follow-the-leader" type system that only requires a vehicle-to-vehicle datalink. GPS technology advances in other fields will increase the viability of GPS for AHS, and opportunities exist to optimize existing GPS technology to meet AHS requirements.

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