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OFFICE OF SECRETARY

Mr. William F. Caton
Acting Secretary
Federal Communications Commission
1919 M Street, N.W., Room 222
Washington, D.C. 20554
STOP CODE: 1170

Re: Notice of Ex Parte Presentation in PR Docket No. 93-61

Dear Mr. Caton:

Pursuant to Section 1.1206(a)(1) of the Commission's Rules, notice is hereby given of a written ex parte presentation in the above-referenced proceeding. Two copies of the presentation are enclosed herewith as required by the rule.

Please contact the undersigned if there are any questions regarding this matter.

Respectfully submitted,

David E. Hilliard
Attorney for Pinpoint
Communications, Inc.

EAY/ean
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May 27, 1994

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Dr. Michael J. Marcus
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Re: Ex Parte Presentation in PR Docket No. 93-61

Dear Dr. Marcus:

On May 11, 1994, representatives of Pinpoint Communications Inc. ("Pinpoint") and I were fortunate to have the opportunity to meet with you and Richard Smith, Chief of the Field Operations Bureau, to discuss Pinpoint's positions in the above-referenced docket, in which the Commission is considering new rules for Automatic Vehicle Monitoring ("AVM"). One of the issues raised at our meeting was whether, *if all economic considerations were ignored,* there were Automated Vehicle Location ("VL") applications that wide-area AVM could serve that the Global Positioning System ("GPS") could not serve. This letter supplements the answer given orally at the meeting that GPS cannot and should not be considered as an acceptable alternative to AVM. Rather, the two technologies are complementary and each provides part of the solution to Intelligent Vehicle Highway System ("IVHS") requirements.

Before making an operational comparison of AVM and GPS as approaches to VL, what is meant by AVM and GPS must be clarified. An AVM network is a terrestrial stand-alone system complete in itself for the tasks of VL. It need not be supplemented by other location, positioning, or radio communications technologies in order to provide VL services. In contrast, GPS, which was designed for in-vehicle (or in-craft) navigation, requires augmentation on a number of different levels in order for it to support VL applications, particularly in urban markets.

Such augmentation includes a substantial communications capability to allow mobiles to report back location information to a central manager — 13.75 MHz to report 1000 vehicle positions per second. GPS will also require enhanced or additional positioning technologies, such as Differential GPS, dead reckoning, and map matching to overcome serious shortcomings in the availability and accuracy of GPS. These are discussed in greater detail below. Even after GPS has been so enhanced, it will still be impractical for certain VL applications such as large commercial and governmental fleet dispatch and others that are sure to be a central part of the IVHS.

Finally, this letter closes with a comparison of the costs of AVM and GPS after the latter has been supplemented to enable it to serve IVHS VL applications. That comparison reveals that GPS will cost approximately nine times more than AVM on a per unit basis, or approximately $2,700 for GPS

to $300 for AVM. In addition, the communications costs of GPS, assuming a very low frequency of updates, can be expected to be over $100 monthly per mobile unit for GPS, assuming very conservative usage levels, compared to $15 per month for AVM, regardless of usage. For applications requiring a high frequency of updates, including many critical IVHS applications, the cost disparity between GPS and AVM will be exacerbated several-fold.

Making GPS Compatible with Automated Vehicle Location Applications

GPS was neither intended nor designed to serve VL applications. To enable it to serve any VL needs, let alone the high-capacity needs of IVHS, GPS must be supplemented with significant radio capacity to enable mobiles to transmit position information to a central monitor. Additionally, GPS, standing alone, does not exhibit adequate accuracy or availability, particularly in urban areas, to meet the location requirements of many important VL applications. Accordingly, significant augmentation of GPS location ability is required before a comparison with AVM capabilities can even be considered.

GPS must be augmented with substantial radio network capability

GPS was originally designed to provide high functionality in-craft or in-vehicle navigation capabilities for the United States military. Because GPS is a navigation system, however, the position of a mobile is inherently known only in the mobile housing the GPS receiver unit. VL applications, by definition, require that information about the location of the mobile be available at a central application that manages and monitors a group of mobiles. Thus, to enable GPS, a navigation technology, to perform a remote locating function, some form of wireless data communications technology must be married to the GPS receiver to transmit the GPS-determined location information from the mobile to the fixed, central application.

A GPS position fix is an extremely short data transmission, ranging from 20 to 60 bytes or characters. Position fixes are required periodically in some VL applications, on demand in other applications, and some combination of both in yet other applications. Depending on the application, the location of a particular vehicle may be required once a minute or once an hour by the central manager. Market-wide, over one thousand position fixes per second are likely to be required during peak use periods in medium-size metropolitan areas in such fundamental IVHS applications as traffic management and control.

Wireless data communications technologies, whether land mobile radio or cellular, are not designed to deal with such a large number of short, non-periodic, "bursty" data transmissions. Because spectrum is relatively scarce, all wireless communications technologies essentially share the available frequencies or channels among a large population of users, relying on the statistical fact that most users will not be attempting to transmit information all at the same instant. These wireless communications technologies all use some form of contention access protocol to arbitrate automatically which users gain access to the radio channel without interfering with each other. Wireless data networks are designed to maximize the time when the radio channel is usefully employed for transmitting information relative to the time wasted in arbitrating the user's access to the channel. If average network transmissions are relatively long, then the network can be designed to tolerate a lengthier (and

less complex and expensive) channel access method. Conversely, if average network transmissions are very short, as required by many VL applications, then the network must be designed with a relatively quick access method in order to operate with acceptable spectral efficiency.

The dilemma for GPS-based VL approaches is that no existing or planned wireless communications networks have been designed to support efficiently their very short transmissions. As a result, existing wireless networks are relatively inefficient at handling GPS transmissions. A significant number of GPS position fix transmissions places a significant burden on the capacity of existing networks, disproportionate to the capacity implied by the stated channel data rates of those networks.

To illustrate this point, the GPS-based VL transaction capacity per channel for a number of existing and planned wireless data networks is listed below:

	GPS Transactions Per Second Per Channel
Cellular telephone (analog)	0.03
Cellular telephone (digital)	0.03
Specialized Mobile Radio (analog, circuit)	0.1
Specialized Mobile Radio (digital, packet)	1.8
Enhanced-Specialized Mobile Radio	3.0
Packet data network (dedicated)	8.5
Packet data network (cellular overlay)	8.5

These wireless data networks can be expected to have the capacity in any typical metropolitan area to handle only a modest level of demand for VL services. These networks individually do not have the capacity, however, to provide service to a large population of VL users or to handle the peak capacity demands of time-sensitive applications. For example, to update the locations of a 1,000-vehicle metropolitan police department within a 5 second window would require *dedicated* use of 24 channels of a packet data network over the 5 seconds (assuming no frequency reuse across the jurisdiction). This requires more channel capacity than any dedicated packet data network is licensed to use, and more capacity than the cellular overlay packet data network plans to offer. Capacity limitations of other wireless data technologies are only more severe.

In contrast, Pinpoint's ARRAY™ network can update the positions of a 1,000-vehicle fleet in approximately 1/3 of a second. As described in the report on the Pinpoint AVM system, prepared by Hatfield Associates, Inc. and filed with the FCC in this docket on January 24, 1994, the ARRAY™ network has a random-vehicle addressing capacity of 1,500 position fixes per second. However, a single group-position-fix-poll can prompt entire groups or fleets of mobiles to transmit vehicle location pulses. In this manner, the capacity of the ARRAY™ network can be made to approach 3,000 fixes per second.

Moving beyond the 1000-vehicle fleet example, existing wireless data communications technologies cannot begin to provide adequate capacity for conveying GPS-based VL information from mobiles to monitors for a mass market application such as traffic management and control under IVHS. This IVHS application depends on obtaining VL data from an extremely large pool of mobile vehicles for traffic management, by using a sample of vehicles on a roadway as "probes" for

determining traffic density, traffic speed, and exceptional conditions (*i.e.*, accidents). In any good-sized metropolitan area, reliable traffic sampling will require that between many hundreds and possibly thousands of vehicle positions per second be determined continuously (in addition to the peak demands discussed in greater detail under "Functional Comparison Between GPS and AVM" below). IVHS will also require the capability to send in-vehicle information to a large number of vehicles to provide traffic management directions, rerouting, and similar information (which depend on knowing the location of individual vehicles) over and above the communications capacity needed to report vehicle location. Wide-area AVM technologies such as Pinpoint's ARRAY™ system are the only economically feasible method of providing such services covering secondary traffic arteries in a metropolitan area as well as the major highways. GPS-based VL information is not feasible for these mass market IVHS applications because the available wireless communications technologies to communicate GPS data from the mobile cannot handle the necessary traffic volume.

In a letter I sent to the Secretary of the Commission, dated May 11, 1994, I explained the data transmission requirements to support GPS in an application requiring 1,000 vehicle location updates per second. Specifically, I developed an estimate that 500 independent channels would be required, plus considerable access control channel capacity. The total bandwidth required merely for position updates, at 25 kHz per channel, was in the vicinity of 14 MHz. By way of comparison, in 12 to 16 MHz, Pinpoint's ARRAY™ network can provide up to 3,000 location updates per second, as well as capacity for messaging to support a variety of data-intensive IVHS applications, such as those described above.

In short, the time required to obtain location updates for a vehicle fleet of moderate size will be unacceptable under a GPS scenario unless sufficient radio communications capacity is dedicated to handle peak demand requirements. Such capacity is not available now with existing radio technologies and systems. Making it available would represent a daunting task for the Commission. Even if sufficient spectrum allocations were to be found, however, the required level of capacity would not come cheaply with today's wireless data communications technologies. This aspect of the problem is discussed toward the end of this letter.

The relative unavailability of GPS in urban environments requires supplementation by other location technologies

The standard GPS receiver cannot resolve a mobile's two-dimensional position when it fails to receive signals from at least three satellites (or four satellites for a more accurate three dimensional position). In a metropolitan environment, GPS signals are often blocked by a number of natural obstructions, such as buildings, foliage, overpasses, billboards, or parking garages. GPS frequently is unable to provide a position fix in metropolitan environments because signals cannot be received at the desired time. Further, once a mobile loses "lock" on a sufficient number of satellites, it may be tens of seconds, or even over a minute, before contact with at least three satellites is again achieved. AVM approaches, however, are significantly better able to determine the position of the mobile, even in built-up urban environments, as long as it is within the coverage area of the metropolitan area network.

The shortcomings of GPS in this regard are illustrated clearly in a study of several GPS receivers performed last August in Calgary, Alberta. T.E. Melgard *et al.*, "GPS Signal Availability in an Urban Area — Receiver Performance Analysis," presented at the IEEE 1994 Position Location and Navigation Symposium (April, 1994) (copy attached). In the Calgary study, it was found that, *in urban*

areas, GPS receivers were unavailable for up to about 86% of the time. Indeed, the best of the three receivers tested, with a 10-satellite card, could not maintain contact with a sufficient number of satellites approximately 31-49% of the time in tests described in the article.

While certain mobile applications may be able to tolerate the frequent unavailability of GPS-based position fixes, this is not acceptable for most commercial and government VL applications. These applications use location information about mobiles, typically in an urban environment, to improve the management of fleets of vehicles, with the objectives of improving both productivity and customer service levels. If valid position fixes on all target mobiles cannot be obtained reliably on demand or with sufficient regularity, then the potential to improve operations will be severely compromised. The shortcomings of GPS in this regard are one of the major reasons GPS-based VL approaches have not been more broadly deployed in metropolitan commercial operations to date, apart from cost considerations, which are substantial.

Base function GPS technology can be augmented by additional radio communications technologies to improve the availability of reliable, real-time position fixes of mobiles' locations. These augmentation technologies operate by estimating an updated position of the mobile using previous GPS-based locations for the mobile and other information. It is important to note at the outset that these technologies typically provide location information with less accuracy than GPS itself, as their use introduces errors that compound with the last available GPS position fix.

At a minimum, once the unit has lost the ability to determine location from the GPS satellites, new position fixes for the mobile are estimated simply by extrapolating from the most recent position determinations from the GPS receiver. The "extrapolative projection" approach assumes that the speed and direction of the mobile will remain unchanged during the period of GPS signal blockage, and that the period of blockage between valid GPS position fixes is relatively limited. In many urban situations, these will not be reliable assumptions.

A more sophisticated approach to augmenting GPS-based position fixes in a metropolitan environment is to employ "dead reckoning" technology. Under this approach, updated positions for the mobile are estimated from the last valid GPS position fix using data on the velocity of the mobile. Velocity information is obtained from sensors mounted on the mobile. These usually involve some combination of wheel rotation counter, electronic compass, and accelerometers.

The most elaborate (and expensive) approach to augmenting GPS position fixes during periods of satellite unavailability is to *add* "map matching" technology *to* dead reckoning. With this approach, the raw GPS or dead reckoning position fix is compared to an on-board database of streets. Because the mobile is presumably on a street, the reported position fix for the mobile is assumed to be a location on the street closest to the raw position fix.

The accuracy of GPS, standing alone, is inadequate

Standard GPS is typically less accurate in determining the position of mobiles when compared to AVM approaches. The mean error radius of GPS is 2 to 15 times greater than that of AVM, depending on the specific AVM technology.

There are some circumscribed VL applications in which the relatively limited accuracy provided by GPS is adequate to serve the requirements of the application, such as with over-the-road, interstate trucking. Even in urban areas there may be applications which can be adequately served with the accuracy provided by GPS (ignoring the availability problems). As a general matter, however, many of the critical characteristics in the terrain of metropolitan areas are smaller than the inherent accuracy of standard, commercial GPS receivers. These features include block sizes, street address frontages, and the separation between highways and service roads. Many metropolitan VL applications require knowledge of the location of the mobile to this level of accuracy, particularly dispatch applications. Terrestrial AVM provides the necessary accuracy without further enhancement.

For GPS to provide the greater accuracy necessary to differentiate the position of mobiles against these smaller terrain features, GPS must employ a technology called Differential GPS. For VL, Differential GPS requires calibration of the mobile's GPS position estimate using correction data derived from a GPS receiver located at a stationary reference point. Differential GPS incurs additional system costs in several areas, which can be significant. The additional costs may result from adding the reference receiver or from subscribing to a third-party provider of Differential GPS correction signals.

Functional Comparison Between GPS and AVM

Provided that all of the augmentation described above is implemented, many of the inherent weaknesses of the GPS-based approach to high capacity VL can be overcome. Obviously, some of the augmentation solutions required will incur costs which are absurd even to the casual observer. In almost every case, the costs required to make a GPS-based solution perform with a functionality approaching an AVM solution in an urban environment are significant. These will be described in some additional detail later. However, it is worth noting here that the GPS receiver itself is only a small part of the total life-cycle costs of a fully functional VL solution using GPS. This helps explain why GPS-based VL approaches have not had more success in the commercial market despite recent reductions in the prices of GPS receivers themselves.

There are several applications that require the position information of large numbers of mobiles to be known within extremely small time frames. Dispatch is perhaps the best example of such an application, whether for public safety, taxi, courier, towing, or mass transit. The dispatch application must be able to assign the closest available mobile unit to a new call for service, at the instant that the call is received. The dispatch assignment usually must be made quickly, whether to save lives (*e.g.*, public safety), to provide competitive service (*e.g.*, courier and taxi), or to provide information on the unit responding and estimated time of arrival to the on-line caller (*e.g.*, towing).

To make the optimal dispatch assignment, the application must be able to update the position and status of all mobiles very quickly on demand. This "bursty" or peak load requirement places a severe strain on the capacity of wireless data networks to send a request for a position update to each mobile and receive the information from its GPS unit, as explained above. For large fleets of hundreds of vehicles, such as commonly operate in major cities, the wireless network must have sufficient capacity to handle this peak transaction load while either preempting or continuing to handle normal

traffic. If sufficient network capacity is unavailable, then dispatch decisions in many instances will be suboptimal because they will be made with out-of-date information. In other cases, dispatch decisions will be delayed until current positions can be updated over a lower capacity wireless network. Both outcomes are inimical to the fundamental purpose of employing computer-aided dispatch augmented with VL information.

No existing wireless network has the capacity to handle the peak position update data demands for dispatch which can be generated by the large organization fleets which exist in major metropolitan markets while still continuing to serve normal traffic. (Often voice communications have priority by regulatory mandate.) This capacity constraint can only be addressed by assembling a large, dedicated wireless data network from existing or new spectrum allocations dedicated to the purpose of handling GPS-derived VL transmissions.

Of course, if the application is traffic management and control of an entire metropolitan area of over a million people, the problems discussed above would be increased several-fold. Instead of hundreds of vehicle position fixes per second, a few thousand may be required. As explained in my letter to the Secretary of the FCC on May 11, 1994, a GPS-linked radio system of 13.75 MHz bandwidth would be necessary to accommodate 1,000 updates of vehicle locations per second. Two to three thousand position fixes per second (which the Pinpoint ARRAY™ network can handle), as required in the largest metropolitan areas, would require 26.25 to 38.75 MHz of spectrum dedicated to vehicle position transmissions alone during peak periods (*i.e.*, 12.5 MHz for each additional 1,000 location fixes/second).

Economic Comparison

By now, it should be clear that considerable augmentation to the GPS receiver is required to permit a realistic functional comparison between AVM and GPS. This, in turn, mandates a comparison between the economics of the two solutions. The issue is whether GPS can serve VL applications at a total life-cycle cost approaching that provided by AVM technology. This factor will weigh very heavily in any evaluation and selection of appropriate technology by the marketplace. Consumers will select the approach that provides adequate functionality and performance at the lowest total cost to the end user. In order to evaluate fully the appropriate VL public policy, therefore, the FCC must consider not only functional but economic comparisons between AVM and GPS-based solutions as well.

As explained below, the costs of augmenting GPS to perform at a minimal functional level far exceed those incurred using AVM technologies.

Per Unit Costs of AVM

The costs of AVM systems for the user are those of the on-board radio and the recurring costs, which typically will take the form of monthly fees. Pinpoint's ARRAY™ TransModem will retail for approximately $300. Monthly fees are discussed below.

Per Unit Costs of GPS

The costs of GPS are more substantial. The three basic approaches to augmenting the undependable availability of GPS in a metropolitan environment — extrapolative projection, dead reckoning, and map matching — all increase the cost and complexity of the GPS-based VL system to a considerable degree. The increase varies with the improvement in reliability and accuracy they provide.

Extrapolative projection adds the least cost to the GPS system and can even be incorporated into the receiver, but it provides the least reliable improvement. Extrapolative projection does not improve position determination when the mobile is moving on a path of prolonged signal blockage (*e.g.*, tree-lined street, sunken roadway, below multi-tiered roadway) or is parked in an area of signal blockage.

Map matching provides the most reliable augmentation to GPS-based position fixing functions, but it requires the availability, and unavoidable cost, of dead reckoning augmentation. However, it can still provide unreliable results on occasions when vehicle paths are not in its database (*e.g.*, inside parking garages, alleys, new streets). Map matching, on the other hand, adds the greatest expense to the GPS system and usually costs a minimum of $1,500 per unit in addition to the costs of dead reckoning, to which it must be combined.

The performance of dead reckoning lies between these two approaches in both reliability/ accuracy and incremental cost.

The anticipated costs of on-board equipment, assuming dead reckoning alone is used to augment the availability of the GPS receiver, will be as follows:

Differential GPS receiver	$ 500.00
Radio	$ 500.00
Modem	$ 200.00
Dead reckoning system	$1500.00

Thus, the total hardware costs for "functionally comparable" GPS will be approximately $2,700 or nine times as much as Pinpoint's TransModem. Even if the per unit costs associated with GPS were to fall by 50 percent in the next few years, they would still be more than four times the per unit costs of the ARRAY™ TransModems today.

Communications costs of GPS and AVM

There are several components to the total life-cycle communications cost for ownership and operation of a GPS-based VL system. Most prospective users do not have licensed frequencies with which to establish a private radio network over which to communicate GPS data from the mobiles to the monitoring application. As a result, users are generally required to transmit this data over a public wireless network. Charges for such network services are almost universally incurred on an "as used" basis, so that more frequent use generates higher total usage fees. Because existing wireless data networks are not designed to subdivide access to the network for transmissions as short as GPS transactions, a GPS transmission incurs the same charges as the transmission of a much larger block of data. As a result, the communications cost of GPS-based VL approaches is the overwhelmingly

largest component of the total life-cycle cost of such GPS systems. (It is noteworthy that no such communications charges are incurred when GPS is used in its intended role as a navigation technology.)

There are mobile applications requiring VL information in which these charges are not significant. This may be because position updates are so infrequent (*i.e.*, a few times per day) that communications costs are low in absolute terms. In other situations, the application may require the frequent transmission of such large volumes of data that the incremental charges for transmissions for VL purposes are a relatively insignificant portion of total communications charges. These are unusual application situations, however, and do not describe the vast majority of situations in which VL will be used. In most mobile applications, VL transmissions are at least as frequent as data transmissions (usually at least a few times per hour), and can be the predominant transaction in computer-aided dispatch applications. In many of these applications, the data transmissions are short and transactional in nature (*i.e.*, local traffic update, point of sale transaction, vehicle status), and the charges for such data transmissions do not overwhelm the fees for VL data transmissions.

Typically, the transmission of vehicle update information can be expected to be on the order of $ 0.05 per transaction. If ten updates per hour are required during the course of a nine-hour business day — a rather minimal rate for many dispatch applications — then the total incremental communications cost per vehicle will be on the order of $4.50 per day, or $100.00 per month.

In most mobile applications, therefore, the usage fees for transmission of GPS-based VL data will be significant. Indeed, they will exceed the acquisition cost of the GPS receiver itself in a matter of months. It can be seen why the communications cost incurred by GPS-based VL approaches is probably the single most significant reason why this technology is still not broadly deployed today, and why the infrequent GPS-based VL systems currently in use are in organizations that can communicate GPS data over private radio networks.

Assembling a network with sufficient capacity to provide rapid response time to peak demand for IVHS applications would involve prohibitive costs. As explained above, scores, if not hundreds, of channels would be required per market. The value of a single 25 kHz channel alone is well over $1,000,000 (based on cellular telephone valuations). The cost of a radio network per market will run into the hundreds of millions of dollars and may easily exceed one billion dollars in the largest metropolitan areas. (In the Baltimore-Washington market, up to 150 base stations would be required.) Of course, this discussion ignores the serious question whether sufficient spectrum is available to support the necessary capacity, particularly if vehicle location services are to be provided on a competitive basis.

In comparison, the subscriber to an AVM system may pay tens of dollars per month per vehicle. In fact, users of the Pinpoint ARRAY™ system can expect to pay approximately $15 monthly. The costs to construct the ARRAY™ network in a market the size of Baltimore-Washington, will be under two million dollars. ($10,000 to $15,000 dollars per base station; approximately 100-150 base stations.)

* * *

In conclusion, provided that increases in costs of over an order of magnitude are ignored, and

the practical problems of dedicating tens of MHz of spectrum for the transmission of vehicle updates are set aside, then GPS may be able to approach the functionality of terrestrial AVM in urban markets. Even then, unlike AVM, the GPS system would probably not be able to offer the rapidity of data updates that are required by many large fleet dispatch and market-wide IVHS applications.

Pursuant to Section 1.1206(a)(1) of the Commission's Rules, two copies of this letter and its attachments are being filed with the Secretary of the Commission.

Respectfully submitted,

Louis H.M. Jandrell
Vice President - Design and Development

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IEEE Catalog Number:	94CH3358-9	
ISBN:	0-7803-1435-2	Softbound Edition
	0-7803-1436-0	Casebound Edition
	0-7803-1437-9	Microfiche Edition
Library of Congress Catalog Number:	93-80009	

GPS Signal Availability in an Urban Area - Receiver Performance Analysis

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ABSTRACT

GPS signal availability and DGPS positioning accuracy for two-dimensional navigation in two types of urban area, namely a downtown type with buildings up to 50 stories, and a residential area with two-story housing and tree-lined streets, is investigated using three multi-channel C/A code receiver types, including a fast-reacquisition narrow correlator spacing receiver. Signal availability, defined as the percentage of time during which HDOP ≤ 5, is shown to be strongly dependent on the receiver signal tracking performance. Signal availability variations between receivers exceed 25% in some cases. The DGPS positions obtained with various receivers are intercompared and analysed as a function of satellite geometry and of the multipath environment. The narrow correlator spacing receiver is shown to produce superior positioning results, in terms of repeatability, as compared to the standard wide correlator spacing receivers used. Performance statistics based on repeated test runs are presented for the various scenarios described above.

INTRODUCTION

During the past few years, the comparative availability of Loran-C and GPS for vehicular navigation in urban areas has been investigated by the authors. A study conducted in 1991 using a 6-channel GPS receiver and a multi-chain digital Loran-C receiver showed that the availability of Loran-C was superior to that of GPS for a mixed trajectory consisting of downtown streets, 4-lane access roads and tree-lined residential streets. The test was conducted in Calgary under summer foliage (Lachapelle et al 1991). The lesser availability of GPS was attributed to a partial constellation available at that time and to the relatively slow reacquisition time of GPS signals during short periods of visibility between buildings.

In June 1993, the same trajectory was re-observed using the same Loran-C receiver technology and a narrow correlator spacing C/A code receiver, namely the NovAtel GPSCard™ (Lachapelle et al 1993). The major advantages of this 10-channel receiver are a relatively fast reacquisition time and an effective code multipath rejection capability (Cannon & Lachapelle 1992, Van Dierendonck et al 1992), which might be important in urban canyons. The relative availability of GPS and Loran-C (HDOP ≤ 5) determined from this test is given in Table 1. The results are the opposite from those obtained in 1991. The availability of GPS is superior to that of Loran-C for each type of street selected. An analysis of the results also showed that the use of the best six satellites (minimum HDOP) among the satellites tracked resulted in nearly the same level of availability as that obtained with all the satellites tracked.

In order to determine the impact of GPS receiver technology on signal availability and accuracy, another test with several GPS receivers was performed in August 1993. The results of this test are reported herein.

Table 1: GPS[1] and Loran-C Availability Statistics June 93 Test

Trajectory	GPS	Multi-Chain Loran-C
Entire Traj.	88-93%	56-76%
Downtown	60-77	14-29
Residential	97-99	83-99

1 Using NovAtel GPSCard™

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GPS RECEIVER SELECTION AND FIELD TESTS

Three C/A receiver types were selected for the August 1993 test, namely (1) the NovAtel GPSCard™, (2) a commercially available 6-channel standard (wide) correlator spacing receiver , and (3) another commercially available 6-channel standard correlator spacing receiver. Receivers (2) and (3) became available during the past four years. All three antennas have a relatively high gain near the horizon. Two receivers of each type were used to operate in differential mode. The three receiver types were tested simultaneously and the antennas were mounted on the same vehicle, some 50 cm apart. Three runs were made on August 17, each lasting approximately 1.5 hours. The trajectory, which was identical in each case, is shown in Figure 1. The GPS time tags shown in this figure correspond to the first run which began at 9:45. The first and second runs began at 18:00 and 19:45, respectively. The downtown city core, which is located around 232750 s in Figure 1, has buildings of up to 50 stories. The residential area selected consists of tree-lined streets where GPS signals may be shaded by the canopy. The three monitor stations were located on the roof of the Engineering building of The University of Calgary.

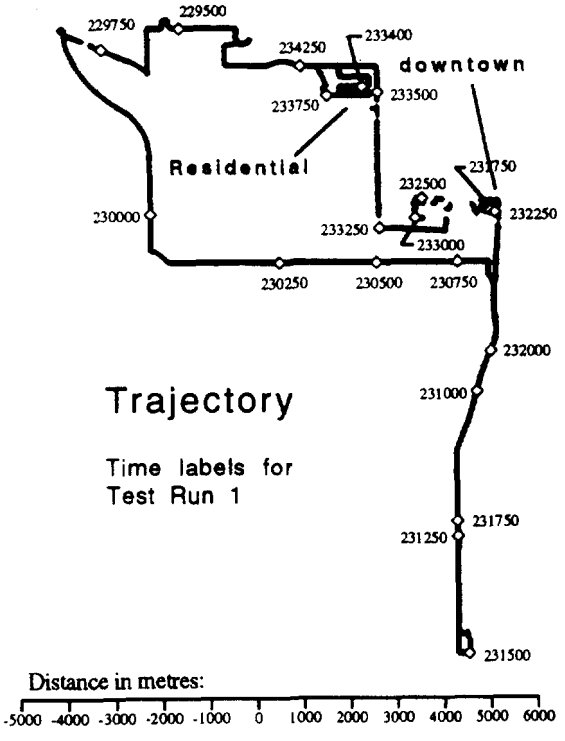


Figure 1: Trajectory Used to Test GPS Signal Availability With Three Receiver Types

The maximum distance between the monitor stations and the vehicle did not exceed 15 km. The theoretical GPS availability during the test runs was satisfactory. The number of satellites above 5° ranged from 7 to 9 and the corresponding HDOP was ≤ 1.5. The GPS measurements were collected every one second and the differentially corrected data were post-processed using The University of Calgary's C^3NAV™ software. The heights were resolved at each point instead of being held fixed to an approximate value in order not to bias the differentially corrected positions. An exception to this was made when the GDOP was greater than 5 or when only three satellites were available. In such cases, the height was held fixed to the average of the five previously estimated heights that were obtained with unconstrained solutions.

ANALYSIS OF RESULTS

The first performance criterion analyzed is GPS availability (which is defined herein as a sufficient number of satellites to obtain an HDOP ≤ 5) and is summarized in Table 2 for each of the three receiver types used. The differences in availability between the GPSCard™ and the other receivers exceed 25% for the downtown area. For the residential area, the differences range from 7 to 69%. The consistency between runs is highest for the GPSCard™, with a maximum difference of 18% between runs #1 and #2 in the downtown area. The corresponding differences for the other two receivers reach 67%. These differences are due to the effect of different satellite constellations and signal tracking performance, in particular to the signal reacquisition delay.

The number of satellites tracked by each receiver as a function of time during test run #1 is shown in Figure 2. The corresponding HDOP's are shown in Figure 3. The GPScard™ tracks the maximum number of satellites available, namely eight, during the part of the trajectory between GPS time 231100 and 232100 seconds. During the same time, receiver 2 tracks its maximum of six. The HDOP is however similar in both cases, except for more frequent dropouts in the case of receiver 2. The major disadvantage of receiver 2 therefore appears to be a slower signal reacquisition time and less stable signal tracking under interference. Receiver 3, which also has six channels, could not generally track more than four satellites, even during periods when the horizon was relatively clear. During the downtown portion of the test run, receiver 3 lost the signals on most

Table 2: GPS Availability Statistics (%) - August 93 Test

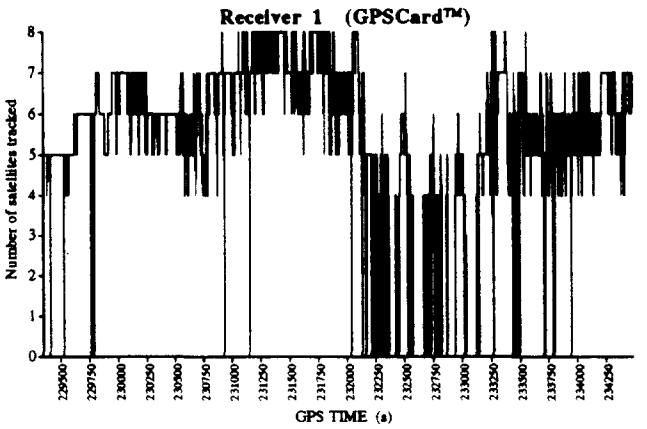
Test Run #	Trajectory	Receiver Type		
		1 (GPSCard™)	2	3
	Downtown	51	16	40
1	Residential	98	91	78
	Entire Traj.	88	67	73
	Downtown	69	39	43
2	Residential	100	68	61
	Entire Traj.	92	66	75
	Downtown	57	31	35
3	Residential	92	24	23
	Entire Traj.	88	51	60

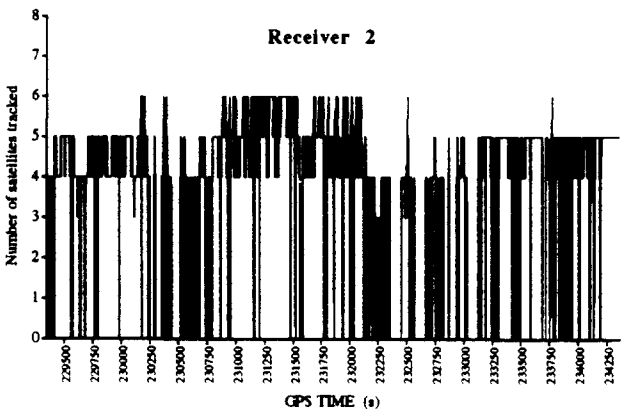
satellites for some seven minutes. Signal reacquisition times with this receiver are comparatively slow. In the residential area, where most of the streets were tree-lined, the GPSCard™ proved to be superior to the other two receivers, with an availability of 92 to 100%.

The second performance criterion investigated is the accuracy of the differentially corrected GPS positions of the vehicle. In the absence of multipath, the rms accuracy in each of the coordinates would be expected to be at the 50 - 100 cm level for the GPSCard™ and at the 3 m level for the other two receivers. Since no positioning system was available onboard the vehicle to obtain independent reference positions, the method used here to obtain a qualitative estimate of the position accuracy was to intercompare the GPS-derived trajectories obtained during each of the three test runs. This comparison provides a reliable estimate of the across-track position errors. The horizontal positions obtained during the three test runs in the residential and downtown areas are shown in Figures 4 and 5, respectively.

In the residential area, the across-track repeatability of the GPSCard™ DGPS positions is generally better than 5 m, except in a few isolated cases where it reaches 10 m. In the case of the other two receivers, not only are there many positions completely missing due to signal shading by the tree canopy, but the across-track errors between test runs exceed 50 m, especially in the case of receiver 3.

Figure 5, which shows the corresponding results for the downtown area, also show the approximate positions of the streets. The across-track GPSCard™ positions errors are due to multipath caused by the high buildings. In the case of the two other receivers, fewer positions are available and their across-track errors exceed 50 m in some cases. Figure 5 also shows that the fixes are grouped in clusters, with few or no positions between the clusters.





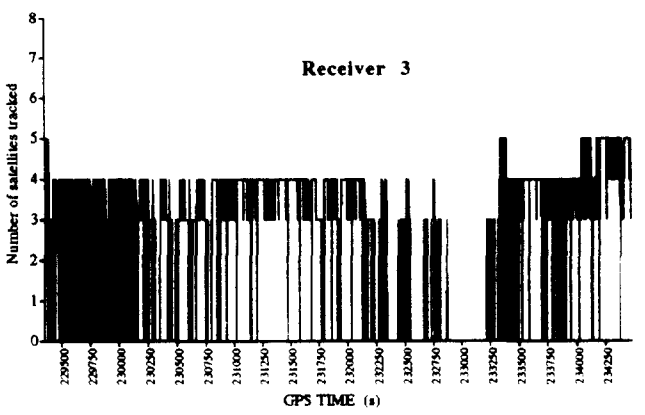
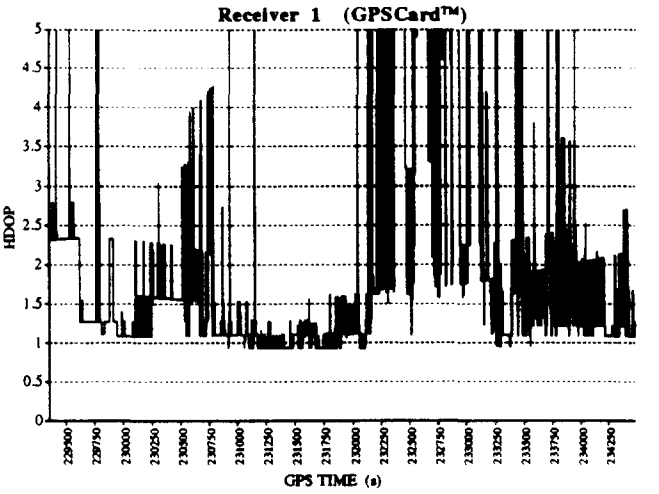
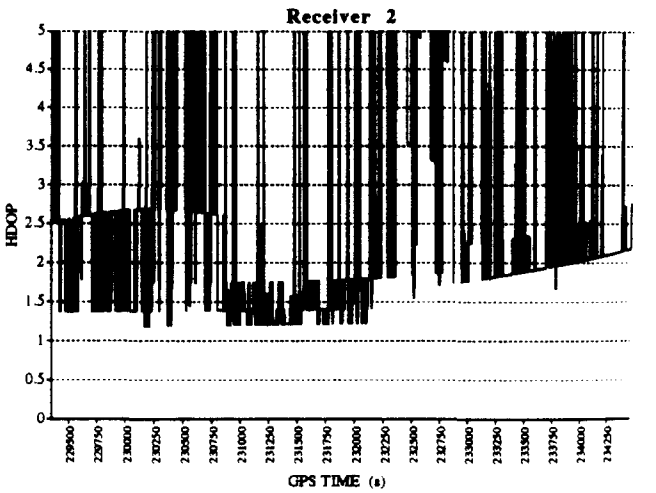


Figure 2: Number of Satellites Tracked During Test Run #2, 17 Aug 93





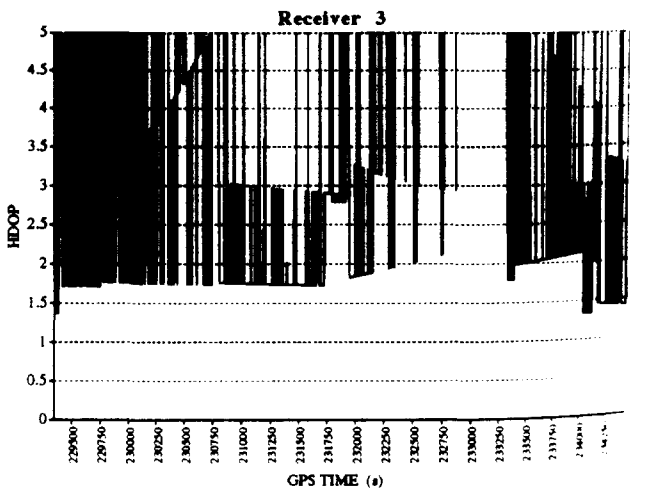


Figure 3: HDOP's Based on Satellites Tracked During Test Run #2, 17 Aug 93

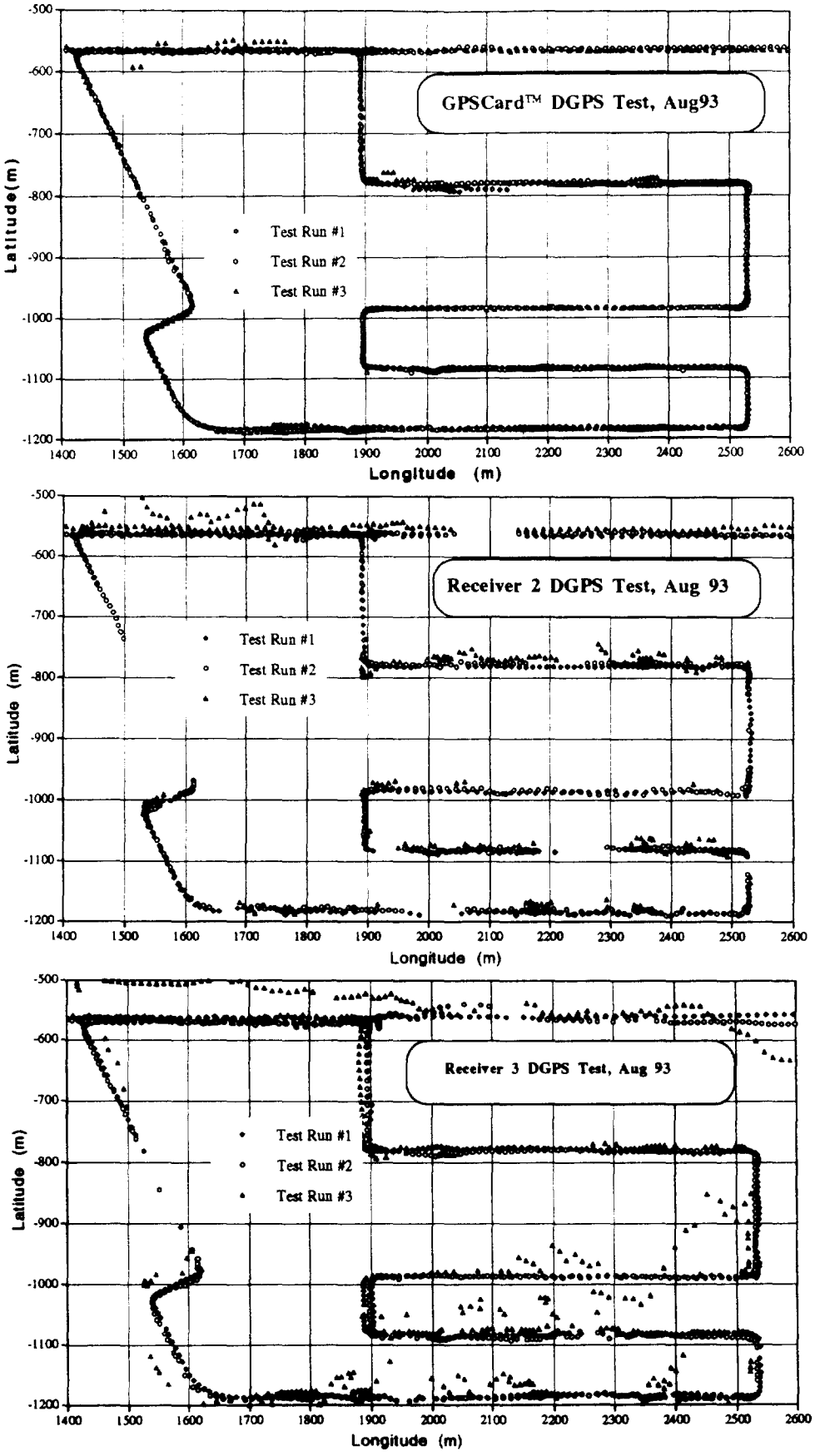
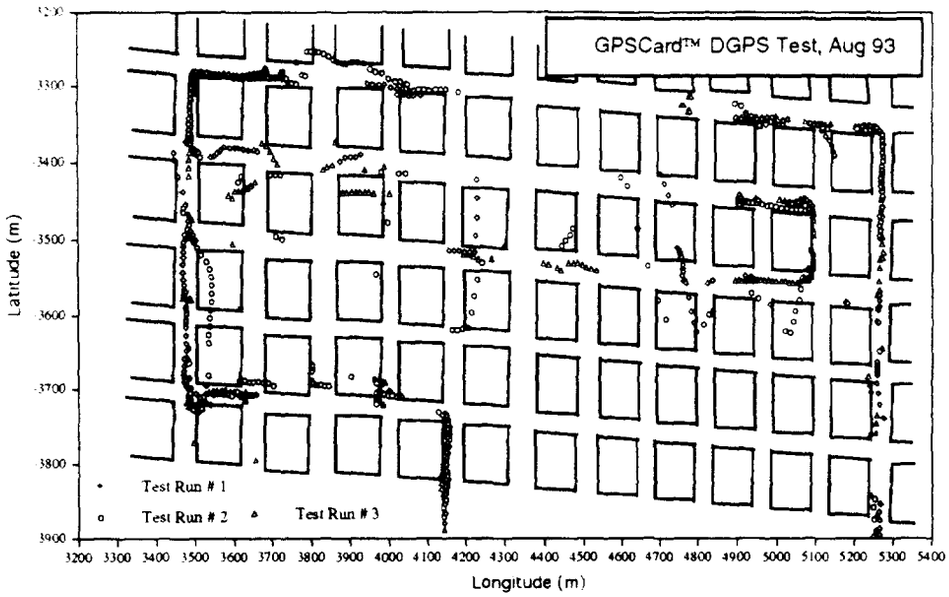
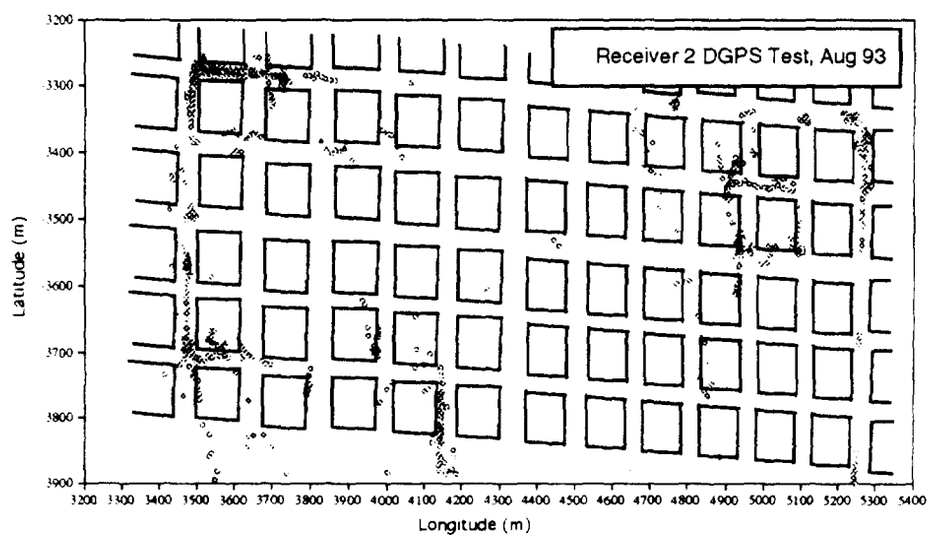


Figure 4: GPS Repeatability in Residential Area





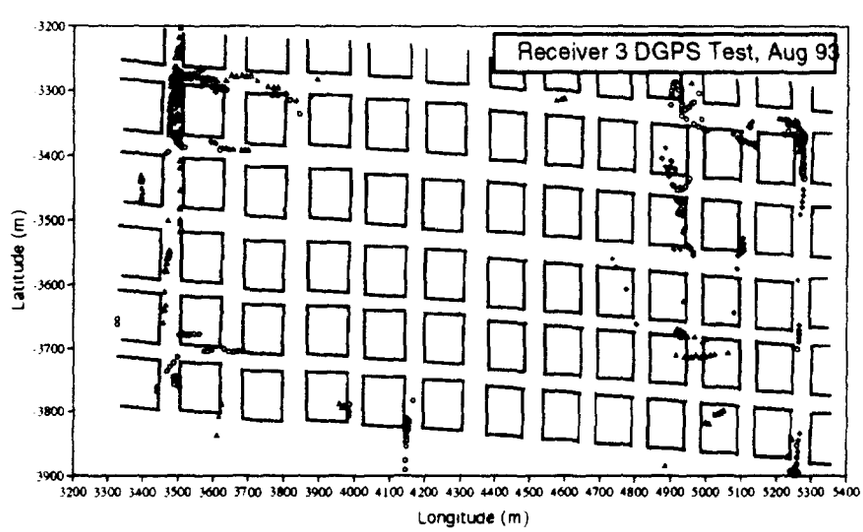


Figure 5: GPS Repeatability in Downtown Area

The along-track errors were of the same order of magnitude as the across-track errors. This can be seen in Figure 6 which shows the latitude and longitude differences between the GPSCard™ and receiver 2 for test run #2. The GPS epochs can be correlated to the location of the vehicle by using the GPS time tags shown in Figure 1. In the downtown area, the vehicle was moving mostly in east-west directions between epochs 232250 and 233250 s. The longitude differences shown in Figure 6 during that portion of the trajectory are therefore due to along-track errors. These exceed 40 m in some cases. The latitude differences are of the same order as the longitude differences.

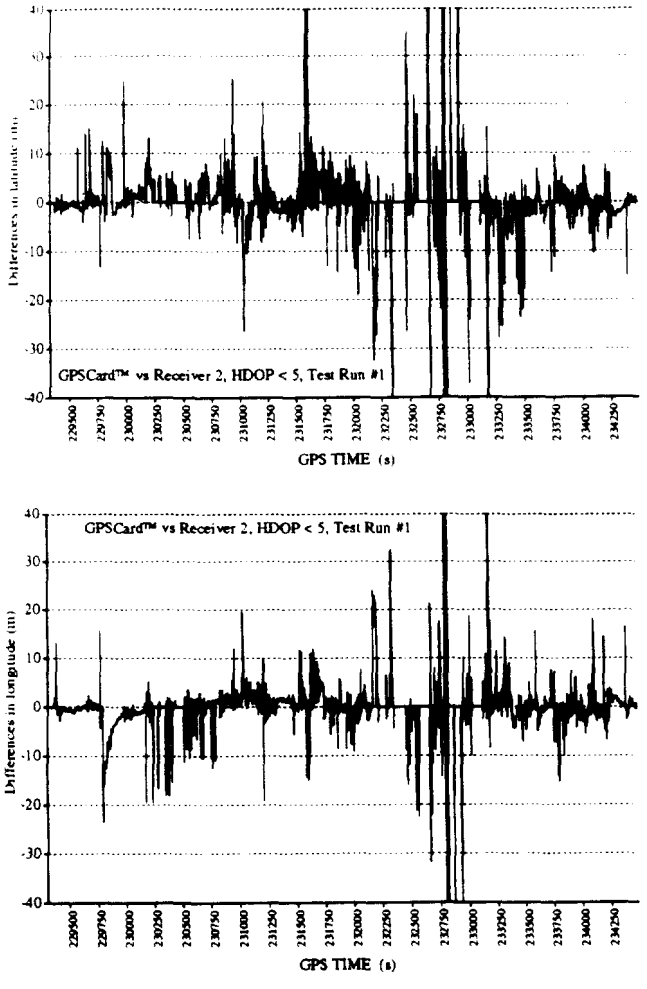


Figure 6: Differences in GPS-Derived Longitudes Between GPSCard™ and Receiver 2

CONCLUSIONS

The analysis of the test runs presented here demonstrates that in a urban environment subject to much signal shading, the differences in GPS signal availability between different receivers can be as large as 60% (as shown in Table 2). The results also demonstrate the effectiveness of narrow correlator spacing technology in reducing the position errors caused by multipath from buildings in urban canyons.

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