ABSTRACT

Title of thesis: TRACKING VEHICLES USING THE GEOLOCATION CAPABILITIES OF A CELLULAR PHONE: IS IT FEASIBLE?

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In 1996, the U.S. Federal Communications Commission (FCC) made it mandatory for all wireless communications services, such as mobile phones, to be equipped with Automatic Location Identification (ALI) capability. This required that all public safety answering point (PSAP) attendants who answer a 911 call from a cellular phone be able to locate the caller to a specified degree of accuracy. This requirement was the impetus that led to momentous technological activity to provide means to geo-locate wireless phone calls. The interest amongst transportation professionals in using this technology for fleet management applications was supervenient. This thesis investigates the feasibility of tracking vehicles, for example school buses, using the cellular phone geo-location technology. Specifically, the accuracy (or errors) of the RadioCamera™ technology of TrafficMaster (formerly US Wireless Corporation) will be evaluated and a conclusion on its suitability for vehicular tracking made.

TRACKING VEHICLES USING THE GEOLOCATION CAPABILITIES OF CELLULAR PHONES: IS IT FEASIBLE?

by

Leon Ffloyd Anderson

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1. Introduction

One of the most important elements in managing a fleet of vehicles is the ability to locate where the vehicles are at a particular time. In recent years many transportation agencies have been installing Automatic Vehicle Location (AVL) components into their fleet management systems to help in location of the vehicular fleet, and to improve upon the safety and efficiency of the system through more educated transportation management strategies. An AVL system tracks the position of a fleet of vehicles in a particular area and relays the information to a host (which may take several forms, such as a dispatch center or traffic information center) via some communication infrastructure. They have been promoted as being beneficial to the transit industry by offering transit agencies more flexibility in monitoring and managing their vehicles and by reducing customers' wait time and increasing riders' (perceived) security (Gomez et al. 1998)

Advances in wireless communications technology hold potential to provide new transportation solutions in the area of vehicle tracking and positioning. In the United States, most of the Enhanced 911 (E911) wire-line emergency calls are now served with Automatic Location Identification (ALI) capability, which informs emergency services personnel of the location of the originating call. In 1996, the U.S. Federal Communications Commission (FCC) made it mandatory for all wireless communications services, such as mobile phones, be ALI capable. A deadline for October 1, 2001 was set, and it was required that all public safety answering point

(PSAP) attendants who answer a 911 call be able to locate the caller to a specified degree of accuracy. This requirement was the impetus that led to momentous technological activity to provide means to geo-locate wireless phone calls. Although the deadline has passed and the accuracy requirements have changed since the original FCC mandate, without either compliance or a significant punitive response on the part of the FCC against wireless carriers who have not complied, the interest amongst transportation professionals in using this technology for fleet management applications remains unabated. There is also considerable interest being put into the system by the business community hoping to capitalize on providing location-based services through the ability to geo-locate wireless devices.

The FCC mandate could potentially facilitate the development of many vehicle location and navigation applications that use "spatially" enhanced wireless communications infrastructure. The system's latent ability to achieve the vehicle tracking needs of fleet management systems is a question that is worth answering, since the locating of a cell phone used inside a vehicle amounts to locating the vehicle itself. In this thesis, an attempt is made to determine if the location capability of a particular method of cellular phone geo-location, namely the RadioCamera™ system, invented by the US Wireless Corporation (now Traffic Master) would be suitable for vehicle tracking or the AVL element of a fleet management system. In so doing, the analysis scheme employed within the thesis may be mirrored as an effective framework for the evaluation of similar location devices and systems.

1.1 Motivation

The radical stimulus that incited this study and thesis was based on an evident need to achieve a cheaper alternative (than GPS and other location systems) for tracking vehicular fleets. The use of cellular phones, if found suitable, could provide a less expensive means of achieving pertinent temporal and spatial information that will help in improving improve safety on buses (for example, children's safety on yellow school buses) and ameliorate schedule adherence (for transit buses, such as Metro buses in the DC area). Two fleet types stand to gain almost immediately if the system was found to be useful in tracking: Yellow School Buses and public transit buses.

Due to rigid financial constraints, only a few of the so-called 'yellow school buses' are equipped with AVL devices - although they are equally significant within the transportation infrastructure. Statistics from a School Transportation News survey has shown that 450,000 yellow school buses provide transportation service daily nationwide. Through various services, these buses provide 23.5 million elementary and secondary school children ride school buses daily throughout the United States, twice a day, resulting in about 47,000,000 student trips daily. This is before adding an estimated 5,000,000 more for activities and trips that occur on a daily basis. It is estimated that school buses carry 52.4 million passenger journeys each school day. School Transportation News developed an annual ridership estimate of 9.322 billion passenger journeys, which are generally taken during 180 days per year (the school year). The length of the school year (in days) ranges from 170 days in Alaska to 184 in Hawaii. This amounts to nearly two and one-half times as many daily passenger journeys as that carried by all of the nation's public transit such as, buses, subways, light rail commuter rail, Para transit, ferries, etc. (School Transportation Group).

These statistics indicates that there is a potential need for the yellow school buses to have good fleet management systems, equipped with some device to enable fast location of these buses – in essence, an automatic vehicle location technology. But if that does not serve to be convincing enough, the direct need for this system, from a safety and functionality point of view, was exposed on January 24, 2002: A school bus driver, with a loaded shotgun, took more than a dozen students, aged six to 16, of The Berks Christian School in Pennsylvania on a 160-mile, six-hour odyssey that ended when he was arrested by an off-duty officer in Washington DC who saw the youngsters waving frantically from the windows. Officials from the school, along with dispatchers, were not immediately aware that the bus had detoured from its normal fifteen-minute journey, and after that dispatchers from the bus company were unable to communicate with the driver on the two-way radio.

Even though the children were rescued safely and unharmed, they should never have experienced such a horrific event and one that lasted for so long because officials were unable to locate the bus. The implementation of suitable AVL units in the buses would be a very good solution and/or deterrent to incidents of this kind. If an AVL system or tracking device were operating on this bus, then it would be highly likely that the duration of this ordeal would have been shortened or may not have happened in the first place.

Schedule adherence could also be improved on a fleet of vehicles that requires operation on a strict timetable. Case in point, within the Washington D.C. metro region just about half a million people a day ride the metro bus – nearly as many as those that ride the train. In a recent test conducted by Elisabeth Leamy, a senior investigative reporter of Fox News network, it was found that more than 65 percent of Metro buses were late. Buses are considered on time if they arrive up to three minutes behind schedule, but even with that grace period the frequency with which buses arrives late are still relatively high. The study showed that buses were late by as much as 19 minutes.

The study also revealed cases of 'bunching buses'. Metro says that this is a domino effect. Once a bus starts running late, with the arrival rate of passenger at a bus stops remaining constant, then more and more people are waiting as the bus reaches each stop. The bus is eventually delayed even more as it slowly progresses along its route, while other buses catch up to it.

It is a well-known transportation theory that commuters wish to reduce travel time. One means of accomplishing this is to have buses arrive at their respective stops on time. For true on time performance, buses should not be early or late. It is therefore necessary to have good reliable temporal data on how buses traverse their routes.

For the Washington D.C. metro bus, the means of obtaining this valuable data is less than scientific. In fact, every 18 months, employees would ride all the routes and write down what time buses reach each stop. The problems that can arise from this practice are very obvious, and stands a great chance of being improved upon if the cellular phones were able to keep track on (or log) the times the buses arrive at each stop – this data could then be used to optimize the system's performance. AVL systems can help improve the reliability by providing bus route controllers with more information in the face of non-recurrent traffic congestion (which can arise due to a combination of illegal parking, road works, accidents and inconsiderate driving, and which is, by its nature, impossible to predict) and can also help in identifying buses that are starting to bunch before bunching occur. A reduction of bus bunching should provide a more regular service for passengers and improve the quality of service offered (Horbury, 1999).

2. Review of geo-location techniques.

The area of AVL is related to a broader set of topics such as automated vehicle monitoring/control (AVM/c), computer-aided dispatch (CAD), and fleet management, which includes vehicle performance monitoring and service control, for commercial, emergency, paratransit, bus, and rail - this according to a synthesis of AVL Systems for Bus Transit, sponsored by the Federal Highway Administration in 1997 (TCRP Synthesis 24, 1997). AVL acts as a computer-based vehicle tracking system. The actual real-time position of each vehicle is measured and its location is relayed to a control center. It complements systems that perform a variety of functions, such as (1) measuring system's performance, ridership, and schedule adherence, (2) providing estimated times of arrival, and (3) displaying vehicles on an electronic map. In an automatic process, AVL collects, processes, and communicates location information to other applications that require accurate, and timely, location data. By associating time and location attributes, AVL technology enables the collection of disaggregated data by other on-board systems without the expense of assigning a person to the task.

2.1 Location Technologies

Position systems may be broadly grouped with respects to functionality. They may be divided into two categories: self-positioning and remote positioning (Drane and Rizos, 1998). In self-positioning, as the name implies, the objects determines its own location. For example, a global positioning (GPS) hand held device will give you its current location (this will be looked at in more detail later). On the other hand, remote positioning involves locating a distant object via some central operations center[1]. A quick example of this is an airport traffic operations tower or center, where aircraft are located on radar wherever they are in the network.

Location or navigation systems may be also divided into three basic classes - based on the technologies used. These are signpost systems, wave based, and dead reckoning (DR) systems. Other methods such as magnetic, optical, and acoustic sensors are used to track vehicles, but since no agencies have reported extensive use of these technologies (TCRP Synthesis 24, 1997), they will not be discussed in this document. The taxonomy of positioning systems is represented in Figure 1.

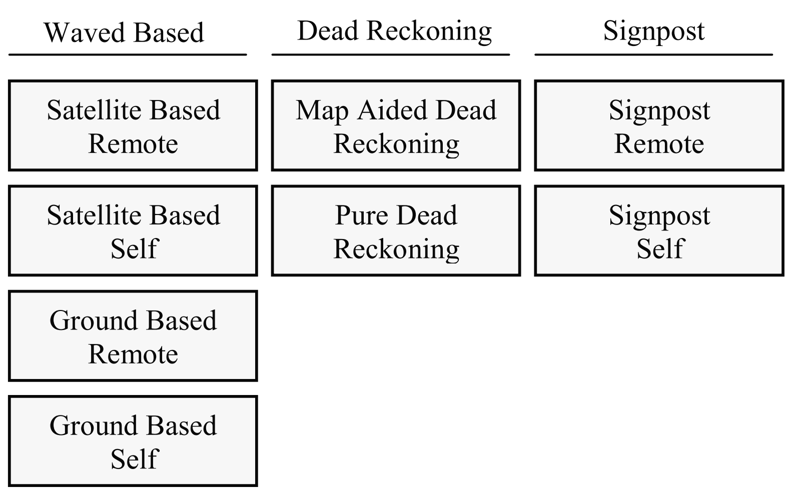
Radio navigation systems are defined as any location technology that relies on a radio signal to determine position. In most cases these systems require official certification of their radio spectrum, which is a part of the natural spectrum of electromagnetic radiation lying between the frequency limits of 9 kilohertz and 300 gigahertz. In the United States, regulatory responsibility for the radio spectrum is divided between the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA). The FCC, which is an independent regulatory agency, administers spectrum for non-Federal government use and the NTIA, which is an operating unit of the Department of Commerce,

[1] A bus dispatch center or air traffic control center serves as a central operations center.

administers spectrum for Federal government use. Among the technologies that rely on radio waves are GPS, satellite and radio triangulation, signposts, wayside transponders and the new "fingerprinting" technology.

Dead-reckoning sensors use direction/bearing and distance/speed to determine relative location from a fixed point. Compasses, odometers, and inertial platforms (gyroscopes and accelerometers) are all dead-reckoning sensors (TCRP Synthesis 24, 1997).

Figure 1 - Taxonomy of Position Systems



2.1.1 Sign Post

Signpost systems are conceptually the simplest form of positioning system. Most early AVL deployment projects used this technology, which measure positions based on the fact that the vehicle is located around a specific reference point, a signpost. A simplified way of explaining how the signpost system works is a person at a particular location receiving directions via a cell phone, and effectively describing to the other party some readily identifiable landmark he or she is nearby. This would give the other party a good idea of where this person is located, and thus may direct them further. A signpost system may be composed of an on-board short-range communication device and an infrastructure mounted beacon usually placed higher than buses. Signal density and placement are some of the factors that determine system effectiveness. Table 1 summarizes the relative advantages and disadvantages of the signpost for AVL.

Table 1 – Signpost Technology (TCRP Synthesis 24, 1997)

Advantages and Disadvantages of Signpost Technology for AVL	
Advantages	Disadvantages
▪ Low in-vehicle cost ▪ Little or no blind spots ▪ Repeatable accuracy (good for measuring time points against performance) ▪ Robust	▪ Requires well-equipped infrastructure ▪ Frequency of updates depends on the density of the signposts. ▪ Assumes fixed routes unless detection points are widely deployed

2.1.2 Dead Reckoning

Dead-reckoning sensors are amongst the oldest navigation technologies and measures distances and directions from a fixed point. These systems rely on sensing components of the vehicle's acceleration and velocity, which are integrated to determine the track of the vehicle. A simple example, as used in Drane and Rizos (1998), involves using a compass and an odometer system. The odometer integrates the angular velocity of the vehicle's wheels in order to estimate the distance traveled. The compass determines the direction of travel. This information may be integrated to derive the location or track of the vehicle. From the earliest test and deployment of AVL for bus transit, the wheel odometer or compass provided the backbone or backup system of every navigation suite. These sensors are still found on many fleets as a secondary sensor. There is no pure DR system that has seen widespread implementation in ITS application.

Table 2 – Dead Reckoning – (TCRP Synthesis 24, 1997)

Advantages and Disadvantages of Dead Reckoning Sensors for AVL	
Advantages	Disadvantages
▪ Relatively inexpensive ▪ Self contained on vehicle (no infrastructure cost) ▪ Only odometer needed (if assume on route)	▪ Accuracy degrades with distance traveled (errors can accumulate between known locations) ▪ Requires direction indicator and maybe map matching for off-route use. ▪ Corrupted by uneven pavements, surfaces and steep hills.

2.1.3 Wave Based Systems

Wave based systems are ones that use wave propagation properties to derive position data. These systems use one or more reference sites to determine the location of vehicles relative to these sites. The sites may be equipped with a transmitter or receiver, or sometimes both. The vehicle itself may also be equipped with a transmitter, receiver, reflective elements or a combination of these depending on the functional nature of the location system[2]. The two types of wave based systems that are widely used today are Ground Based (Terrestrial) Radio Positioning and Satellite Based Radio Positioning.

2.1.3.1 Ground Based Radio Positioning (GBRP)

GBRP involves measuring the time difference of signal reception with respect to a known position of remote stationary transmitters or receivers. The position is calculated using geometry by radio triangulation or trilateration. Radio triangulation is where location is derived by obtaining the bearing of the moving object with reference to two or more fixed radio stations which are a known distance apart; this measurement provides the values of one side and all angles of a triangle from which a position may be computed. The other, radio trilateration, is based on deriving the distances between the moving object and fixed stations, producing the three legs of the triangle. The term trilateration is mainly used in the context of surveying. Major GBRP systems include Loran-C, a long-range aid to navigation, and simulcast paging services. Table 3 summarizes the advantages and disadvantages of GBRP using Simulcast Paging (TCRP Synthesis 24, 1997).

As depicted in Figure 1 GBRP can be self-positioning. In self positioning GBRP, a series of transmitters are placed around the area of interest. Receivers are mounted in the vehicle and methods used to determine position include round-trip time, phase

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[2] The vehicle may be self-positioning, remote positioning or indirect remote positioning: refer to section 2.1

measurements, and Time Difference of Arrival, TDOA. Loran-C [(Elliot and Dailey, 1995), (Morlock et al., 1993)], and Omega (Swanson, 1993) are two examples of these systems.

Ground Based remote positioning requires transmitters in the vehicle and the receivers at fixed locations around the area of interest. These systems can use a variety of methods for location. These include round-trip time, TDOA, Angle of Arrival, AOA. Quicktrak, discussed in section 7.2 of (Drane and Rizos, 1998), is an example of this kind of system using TDOA for location estimates.

Table 3 – Simulcast Paging (TCRP Synthesis 24, 1997)

Advantages and Disadvantages of Simulcast Paging Service for AVL	
Advantages	Disadvantages
▪ Low capital cost ▪ Moderate accuracy ▪ Low maintenance costs	▪ Monthly service fees (relatively high depending on usage) ▪ Signal attenuation by foliage and tunnels (inside buildings); blocked by tall buildings.

2.1.3.2 Satellite Based Radio Positioning

This involves the use of satellites orbiting the earth to determine location. Satellites may be Circular or Geostationary. Circular orbiting satellites, like GPS and/or "Big" and "Little" Low Earth-Orbit Satellite (LEO), are ones that orbit the earth in a predetermined path, at a set inclination and period, while geostationary satellites, like QUALCOMM or INMARSAT, circle the earth in the same direction and period as the earth's rotation (Drane and Rizos, 1998).

Satellite based systems may also be self-positioning or remote positioning systems. Satellite based self positioning systems have transmitters in the satellites orbiting the Earth and receivers are affixed to the vehicles in order to determine the position by processing the signals received from the satellite-based transmitters. The methods used to determine the positions include round-trip time and TDOA. Example of this includes GPS. On the other hand, Satellite Based remote positioning systems involve having the receivers on the satellites and the transmitters on the vehicle. These could be implemented as add-ons to LEO satellite systems. Methods of arriving at position data include TDOA, AOA or round-trip time. Table 4 gives the relative advantages and disadvantages of using GPS as a means of AVL.

Table 4 – Source: TCRP Synthesis 24, 1997

Advantages and Disadvantages of GPS for AVL	
Advantages	Disadvantages
▪ Moderately accurate ▪ Global coverage ▪ Moderate cost per vehicle	▪ Signal attenuation by foliage and tunnels (inside buildings); blocked by tall buildings. ▪ Subject to multi-path errors.

3. Cellular Telephone Positioning Systems

Cellular telephone systems are radio-based mobile communications systems. Instead of one large base station covering a wide area, this system acquires its name from the fact that it uses many based stations, distributed over a service area in a hexagonal pattern, to transmit and/or receive signals from mobile telephones. The hexagonal area that surrounds the base station is referred to as a cell (refer to Figure 2). Each cell is a self-contained calling area. Although the way the cells are depicted in Figure 2 is the way it is seen in much of the literature on this topic, the actual positional relationship of the cell and base station is shown in Figure 1. The figure shows that a single base station is at the vertex of three cells, and not at the center as shown as the right – allowing three cells to be served by a single base station. Additionally, the hexagonal shape used to represent the cell area is only used to indicate the totality of coverage by the base station. In reality, the cells cover irregular circular-like regions with overlap. However this cannot be properly represented diagrammatically, so hexagons are used.

Figure 2 – Cell-like Structure of Cellular Telephone System

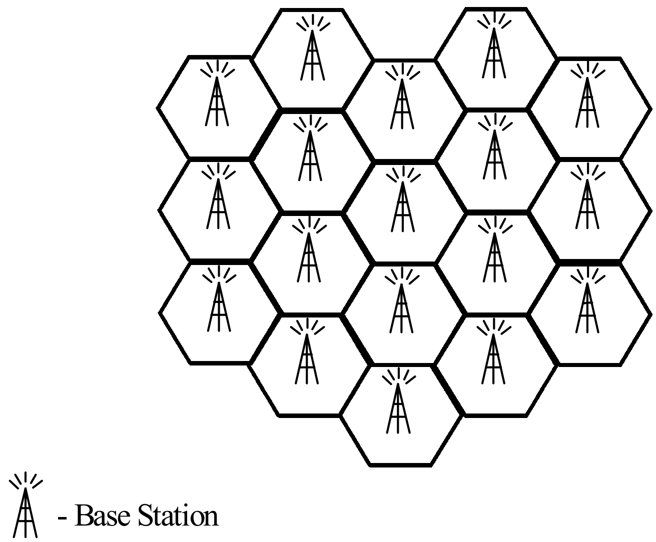
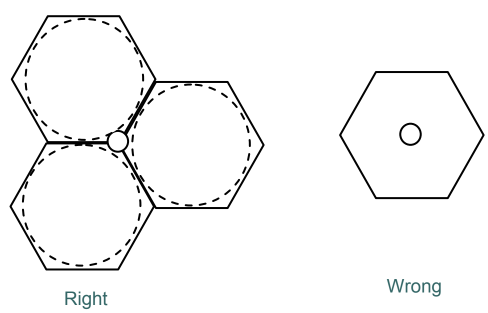


Figure 3 - Correct representation of base station and cells



The operation of the system is such that the power level of the mobile and base stations' transmitters are adjusted so that signal from a mobile is unlikely to be received by base stations that are not in the immediate vicinity of the mobile. This, in addition to the hexagonally designed cells, makes it possible to reuse frequencies, at the same time, and in different cells without causing signal interference. For example, if a single wide-area base station were to be used, 100 channels or frequency could support 100 simultaneous calls. But if we use the same 100 channels and divide them up among 100 different cell sites, reusing channels as appropriate, thousands of simultaneous calls may be supported. Also, the fact that the mobile is always in close vicinity of the base station with which it's communicating, reduces the power requirements for transmission, and lengthening time between required charges of the unit's battery. Cell size varies depending on the propagation characteristic of the area. For example, in central business districts of large cities, the cell size might be less than 1 km, while in rural areas it may be as large as 30 Km. The number of user in an area may also determine the cell size (Drane and Rizos, 1998).

Several advantages in using the cellular telephone positioning system exist. These include, amongst others:

1. The system makes use of the existing cellular telephone infrastructure, thus reducing the "capital" cost.
2. The system already has a spectrum allocation

3. In areas of worst propagation, the cellular telephone system has the greatest number of cells.
4. The is an already large data base
5. The system provides a two-way communication link.

The primary disadvantage of using cellular phone positioning is the simple fact that the system is not designed with consideration for its positioning capabilities. Therefore engineers have to work around certain characteristics of the cellular system. These are:

1. The cellular system are designed so that it is only necessary for one base station to receive signal from a mobile
2. The bandwidth tends to be narrower than is optimal for higher accuracy positioning systems.

These disadvantages are expected to be short lived as more and more cellular telephone designers realize the revenue potential of these as a part of larger positioning systems (Drane and Rizos, 1998).

3.1 Geometric Methods of Positioning for Cellular Phones

Several geometric alternatives exist to derive position estimates from cellular telephone systems. In this chapter we will introduce a few of the more widely used methods and eventually discuss the multi-path fingerprinting method utilized by the RadioCamera™ technology.

3.1.1 Cell Origin of Cell ID

In this system, the position of the mobile phone is derived from the cell serving the mobile phone at the time. It is evident that the accuracy of this system depends on the cell size. Smaller cells will result in more accurate position measurements. Thus, more accurate measures could be made in urban areas where the layout of base station is denser than in other areas. Accuracy may be as good as 150m in urban areas with cells that are relatively small.

3.1.2 Signal Strength

The Signal strength method uses the power of the signal to estimate the position of the mobile phone. Either the mobile phone or the base station can calculate the distance from each other from the strength of the signal received. This is possible through the use of path loss equations if the transmit power is known. If the signals from three base stations can be measured and the respective distances estimated, the location of the handset may be determined through some process, such as trilateration or database matching.

The obvious problem with this method lies with the fact that there may be ambiguity in the measurement of signal strength. Locations that are various distances away from a transmitter might result in signal strengths that are identical. It might therefore be necessary to map actual signal strengths at different location and this mapping would be very responsive to environmental changes (Drane and Rizos, 1998).

3.1.3 Time of Arrival

The Time of Arrival method involves estimating how long it takes a transmission to reach a receiver. Since radio waves travels at the speed of light, then the arrival time is a function of the distance traveled and the distance could therefore be estimated from transmission delay. The estimated distance from the receiver represents the radius of a circle whose center represents the receiver (most likely to be the base station) and whose circumference represent an infinite number of points that the mobile phone could be located. For the location of the transmitter (usually the mobile phone) to be located, it is therefore necessary to make estimations from at least three base stations. Since the location is a function of only the distances, this method is therefore more accurate than that of signal strength (Drane and Rizos, 1998).

3.1.4 Time Difference of Arrival

Time Difference of Arrival, TDOA, follows a similar concept of time measurement embraced in the TOA, except that the pairs of base stations compare the difference in time of arrival they measure from the same transmitter. The difference in arrival times will define a hyperbola (or circle) with the base stations being at the loci (or center for circular operations). TDOA normally uses a total of three base stations. This results in three sets of time differences, three hyperbolic (or circular) equations, which would provide an estimate of the position.

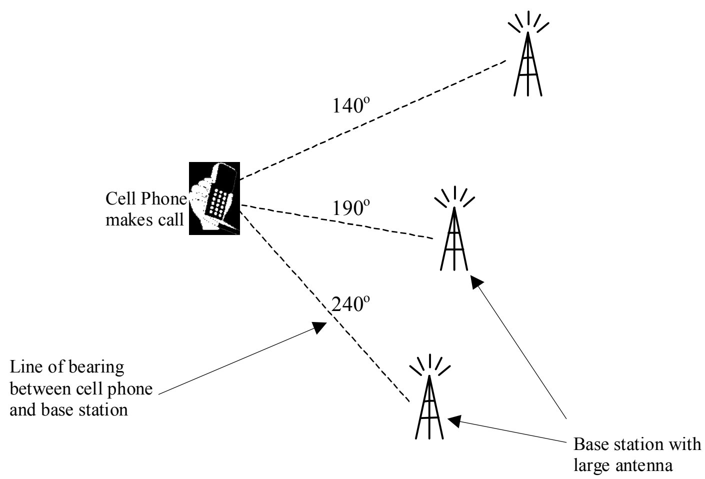
TDOA can be self-positioning or remote positioning. The self-positioning techniques are primarily hyperbolic, but while using a Global System for Mobile (GSM) Communications the mode is circular. The fact that GSM is a two-way communication system makes it possible to measure the round trip time the signal takes from the base station to the mobile and back again making a circular loci (Drane and Rizos, 1998).

The fact that there is less data exchange over air when using TDOA, it is favored over the TOA technique. However, a key issue with TDOA is accurate timing and proper synchronization between base stations. For example, an error of 100ns in the TDOA estimates can translate into a range error of 30m (Breslin, 1997).

3.1.5 Angle of Arrival

The angle of arrival, as the name implies, refers to the technique of using a highly directional antenna (fixed or electronically steered) to determine a line of bearing between a base station and mobile phone. An estimate of the position may be obtained if the lines of bearing of two base stations intersect each other. Usually, three or more base stations are used to obtain position estimates, which may be calculated through triangulation (Figure 4).

Figure 4 - Triangulation (Angle of Arrival)



It is obvious that an important factor in using this method is its necessity for a line of sight between receiver and transmitter. Reflected signals will lead to incorrect bearing reading and subsequent incorrect positioning. It is for this reason that this system is often used in tandem with other techniques, such as TDOA.

3.1.6 Hybrid Systems

Recently, so-called "hybrid" techniques have been successfully adopted by the wireless location industry and there exist several schemes that combine one or more methods from terrestrial TOA, AOA, TDOA and signal strength measurements and GPS to achieve the desired accuracy. These techniques are essential for various reasons that include the use of minimum network resources and satisfying the hearability concerns, reducing signaling overhead, servicing older generation handsets without hardware modifications and high accuracy of positioning to name a few.

3.2 Disadvantage of Geometric methods

3.2.1 Base Station requirement

Geometric techniques of signal location for position estimates, while not disqualified from use for E-911 purposes, do share two essential and limiting disadvantages. The first requires that the signal be received by several antennae simultaneously in order to satisfy, or fully specify, the set of equations used to estimate location. It becomes evident that, in sparse networks, it may not be reasonable to expect that signals can be "seen" by multiple receivers. Additionally, from the perspective of handling the communication traffic itself, "visibility" at multiple locations causes problems, such as system confusion over which base station should interact with a particular mobile phone. For this reason, a common feature included in modern cellular protocols is dynamic power management, which allows, among other things, cellular phones to reduce their broadcast power until only one antenna can receive their transmission.

3.2.2 Multi-path effects

The second limitation has to do with the fact that transmissions from mobile phone antennae are omni-directional. In geometrically complicated terrain (due to the presence of buildings, distinct natural features, etc.), a signal originating single phone might actually find several paths due to deflection of signals about the terrain before reaching a receiving antenna. The receiver cannot initially distinguish them – they are amalgamated into a “multi-path” signal in which various versions of the same original signal are disguised, each having traveled its own journey time, and each having suffered from unique distortions of amplitude and waveform along the way. Geometric location techniques that presume the availability of “line-of-sight” signals suffer significant accuracy degradation in multi-path environments.

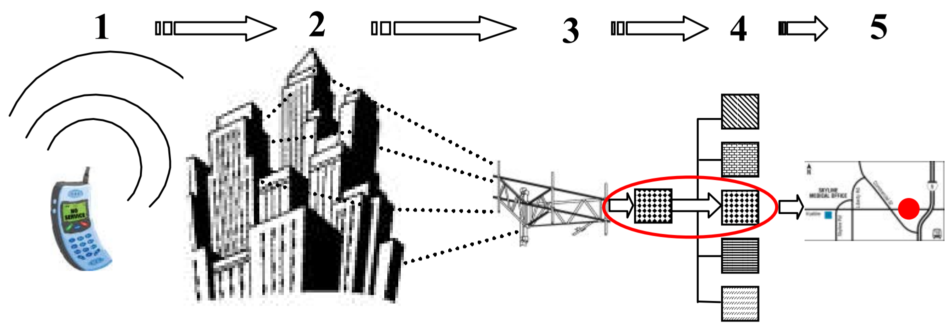
4. Multi-Path Finger Printing/ Pattern Matching

The RadioCamera™ system takes advantage of this multi-path phenomenon by using pattern recognition as its fundamental means to determine location. It identifies a signal's "signature" based on the radio frequency (RF) pattern (multi-path phase, amplitude, delay, direction, and polarization characteristics) of a cellular telephone call (Hilsenrath and Wax, 2000). In addition to this, a single base station is necessary for position estimates.

4.1 RadioCamera ™ –Multi-path/fingerprinting process

The RadioCamera™ system determines a wireless subscriber's location by measuring the distinct radio frequency (RF) patterns and multi-path characteristics of radio signals arriving at a cell site from a single caller. The RadioCamera™ identifies the unique radio frequency pattern or "signature" of the call and matches it to a similar pattern stored in its central database. Interpolation techniques are used to further refine the position estimate within the points on the calibration lattice. By continually updating the location data for multiple callers on a specified road segment, the speed at that segment of roadway maybe computed algorithmically. The RadioCamera™ network deployed for this evaluation eventually included up to 13 sites, each of which a custom USWC antenna array mounted on a tall structure, such as an existing radio tower, tall building, etc.

Figure 5 - RadioCamera™ Fingerprinting Process



The process of identifying the position of a mobile phone involves:

1. A call placed from a mobile phone emits radio signals
2. The signals bounce off of buildings and other obstacles, reaching their destination (the base station) via multiple paths.
3. At the base station, the RadioCamera™ system analyzes the unique characteristics of the signal, including its "multi-path" pattern, and compiles a "signature" pattern.
4. The signature pattern is compared to a database of previously identified locations and their corresponding signature patterns, and a match is made.
5. The matched pattern or ‘fingerprint’ identifies a unique position on the ground that may be delineated on a map.

The RadioCamera™ system does not require direct line of sight to multiple base stations to identify locations, making it highly effective in dense urban environments, where more than 70% of the wireless population currently resides. The RadioCamera™ system is also compatible with existing network infrastructure, integrating easily and requiring no modifications to the base station or subscriber handsets.

5. Anatomy of an Analog Cell Phone Call

Before going into the details of about the actual experiment, it is imperative that readers understand the concepts and operations behind making a cell phone call. Several processes goes into the making of a cellular phone call and these may affect the time it takes to make the call, the quality of the call and other important factors. The section that follows will help to familiarize the concepts of cellular telephony and will also act as the reference to other sections of this thesis, such as latency.

5.1 Overview of a Cellular Telephone System

The first step in understanding the cellular telephone system is to distinguish between the two types of cell phones, analog and digital cell phone systems. Analog cell phones transmission mode is one whose information is transmitted by converting it to a continuous variable electrical signal. With digital transmission, signals are sent as a series of pulses as prescribed amplitude and received and detected in predetermined time slots.

We will look at the cellular telephone system from an analog cellular system point of view. This is due to the fact that most of the experiments carried out on the RadioCamera™ location system described later in the thesis was done using analog phones. This was because the then USWC system only had the ability to monitor calls made from these phones. Nearing the end of the experiments, the system's capability was enhanced and as such we were able to sample a segment of the digital market as well.

The communications protocol adopted for the analog cellular phone system, and widely used in North America is the Advanced Mobile Phone System, or AMPS. In this system, voice signals are transmitted using a FM transmitter, just the way a standard two-way radio or music on a car's FM radio would operate. Digital signaling enables call setup, but call supervision functions (on hook, off hook, flash etc.) are done with various signaling tones. Subtle variations of amps exists (such as NAMPS, developed by Motorola with a narrower bandwidth channeling and low speed signaling) but the following descriptions aims to capture all the salient aspects of this protocol and is presented as if implementation were fully standardized.

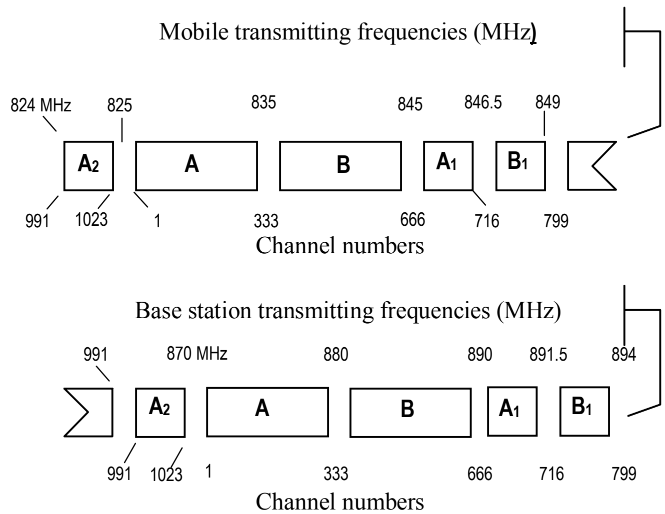
According to Farley (1984), when the analog AMPS was first introduced into the US during the early 1980s, at this time there was concern that the local landline telephone companies would have a competitive advantage in the cellular area. As a result, cities that offered cellular service were therefore required to allow a duopoly arrangement where new, non-wireline providers would be allocated a quantity of RF spectrum equal to that allotted to wireline providers. The A-Band and B-Band emerged out of this arrangement and the non-wireline carriers were given A-Band and wireline carriers got the B-Band.

The initial allocation of frequency space (1974) was a total of 40 MHz in the 800 – 900 MHz range, although an additional 10 MHz was added later to increase capacity. The frequency space was divided equally between the A- and B-Band.

Figure 6 shows a diagram of the RF spectrum from 824 MHz to 894 MHz. The blocks labeled A and B were part of the original 40 MHz allocations. The blocks labeled A_1, B_1, A_2 are a part of the later 10 MHZ additions.

Communications between a cellular phone and a base station is in full-duplex. This means that there is simultaneous transmission in both directions from cell phones and base stations through a pair of dedicated frequencies called channels. This enables one to talk and listen at the same time. The spectrum described above is divided into 1664 frequency slots each occupying a 30 KHz bandwidth. The cellular bandwidth runs from 824.04 MHz to 893.97 MHz. As depicted by the picture, the slots with the lowest frequencies are used to transmit information from the mobile to the base station and are called the reverse channels. In particular, reverse channels uses 824.04 MHz to 848.97 MHz. The higher frequency slots send information in the other direction, from base stations to mobile phones. This is known as the forward direction and these forward channels use 869.04 MHz to 893.97 MHz. With quick calculation, this amounts to 832 frequency slots or channels in either direction. Each cellular call requires a channel pair (forward and reverse). These pairings are done automatically and are separated by a guard band of 45 MHz. The guard band is used to minimize cross channel interference between the forward and reverse channels. Each band controls half, or 416 of the channel pairs.

Figure 6: Frequency of mobile and cellular base stations. A and B refer to the carrier each frequency assignment has (adapted from Farley, 1984)



Twenty-one of the 416 channel pairs controlled by each band are for the cellular system data, or to control activities which includes call setup, channel assignment, paging, messaging etc. These are usually the first channels in each cell. The other channel pairs are for voice communications, and are fittingly called the voice channels. They are paired frequencies that handle a call's traffic, whether it is voice or data, as well as signaling information about the call itself. So, between both bands, a total of 790 channels are available. This should not be used as a measure of the capacity to make simultaneous phone calls, because some cell sector allows frequency re-use in the network.

When a mobile phone is turned on, without dialing out or receiving calls, it goes through a process of registration where it monitors the forward control channels available to it from base stations and then chooses the strongest of those and locks-on to the network. This process takes only a few milliseconds. A small amount of administrative traffic takes place on these channels as well, having to do with acknowledgement of roaming status, cell number and Electronic Serial Number (ESN) and other details. This traffic, because of its time span, is not adequate at this time for mobile location purposes. If this were to change in the future this would open a whole lot of opportunities in transportation. It would have an impact on the sample size, as it would include phones in the sample that are simple turned on and not engaged in active phone calls.

When a call originates form a mobile phone (i.e., digits are dialed followed by pressing SEND or it equivalent), the intent to make a phone call is transmitted over the reverse control channel, i.e., from the mobile to the cell site. The information sent to the base station includes a request for service signal, the phone number of the mobile phone, its unique electronic serial number (ESN), and the phone number being dialed. This is transmitted on the strongest reverse control channel. Since many mobiles listen to the same control channels simultaneously, the voice traffic cannot be conducted over these channels. Assuming the system can accommodate the call, the base station through collaboration with the MTSO replies with a message indicating which pair of voice channels is open to, and should be use to, conduct the call. Additionally the message indicates which frequency of the supervisory audio tone (SAT) is used on the forward voice channel. The SAT is a continuous, high-pitched, inaudible tone that is broadcast over the voice channel as a means by which both the mobile and the base station communicate communication engagement. There a several possible frequencies of SAT[3], but the mobile is told ahead of time which frequency to use. This prevents errors in the voice channel assignment.

After the available channels are received, the cell phone locks-on to the voice channel pair (forward and reverse) as indicated by the base station, and re-transmits the appropriate SAT as an indication to the base station that it has arrived on-channel. After receiving this acknowledgement from the cell phone, the base station removes a mute and begins transmitting the same SAT over the forward voice channel. The SAT communication continues between the base station and the mobile even during the voice conversation. Since it is filtered during a call you cannot hear the SAT, but if either one of the SATs were to be deactivated for whatever reason, there is a convenient way of knowing that there is problems with a call. Mobile phones can only tune simultaneously to two channels (forward and reverse) therefore during a conversation when it use both reverse and forward channels, it does not use control channels – until the call has ended. All administrative issues between mobile and base station during a call is done via voice channels. If the mobile user hangs up, the mobile transmits a 10 KHz, signature tone (ST) to inform the base station of disengagement. There are slight differences in the process as it concerns calls that originate from the mobile phone and those which do not. However this description is sufficient to bring across point that will me made based on these references later in the thesis.

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[3] AMPS generate SAT at three different non-radio frequencies. SAT 0 is 5970 Hz, SAT 1 is 6000 Hz and SAT 2 is 6030 Hz.

5.2 Digital Cellular Protocol.

As discussed earlier, AMPS may be regarded as an analog cellular protocol, the most important implication of which is that the voice channels are FM-modulated. The implications of this include the fact that anyone with an FM receiver with the ability (meaning proper frequency range) could tune to the channels and hear conversations. Digital protocols, one the other hand, have improved features that allows for better security, in addition to the transmission of non-voice information (data) reliably, and also multiple conversations to share a channel pair simultaneously.

According to Farley (1984), the earliest and most commonly used digital cellular system in America is IS-136, colloquially known as D-AMPS or digital AMPS. It was formerly known as IS-54 and has undergone several evolutionary changes since then (including name). The system uses a multiplexing technique known as TDMA[4] or Time Division Multiple Access. No spectrum was allotted to this system; it therefore uses the same frequency as the AMPS. The difference between TDMA based I-136 and AMPS, other than the obvious analog/digital difference is the fact that TDMA based I-136 puts three calls into the same 30 KHz channel space that AMPS uses to carry one call. It does this by slicing and dicing parts of each conversation into a single data stream, each taking turn at the channel in short, synchronized burst. TDMA handles multiple and simultaneous calls by dividing

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[4] TDMA refers to a transmission technique or access technology, while IS-136 is an operating system. In the same way AMPS is an operating system using different access technology (e.g., FDMA – Frequency Division Multiple Access).

them with respect to time and not frequency. Voice traffic is digitized and portions of each call are fed into a single bit stream, one at a time.

A newer access method is code division multiple access or CDMA. The cellular operating system that utilizes this access protocol is the IS-95. This system uses a spread-spectrum technology that allows for up to 64 users per channel by assigning each user a unique orthogonal code that is incorporated into a continuous high-speed pseudonoise (PN) code. In essence, the system tags every part of multiple conversations with specific digital code. This code allows the operation system to re-assemble and jumble calls at the base station.

Current trend in cellular telephony is proving that the area of study is going digital. The AMPS analog operating system occupies a steadily decreasing share of the market, and according to market experts, will likely be obsolete soon. Hence, while many of the conclusions in this report will remain valid with digital systems, a more thorough evaluation of the performance of the system with digital protocols is recommended.

6. Mapping Projections

Whenever one discusses location estimates, for the most part, coordinates will be used to define position. Although the coordinated positions of points may be completed on the surface of a reference spheroid, it makes for much easier computation and analysis to measure Euclidean distances in a two dimensional plane. For this to be done, an orderly system of representing points on a sphere (latitude, longitude) on a plane has to be adopted – This is a map projection.

Several map projections exist. These include the Cassini Projection, Lambert Conical, Transverse and Universal Transverse Mercator (UTM) to name a few. The two most common projections used are the Transverse Mercator and the Lambert's conical orthomorphic, which are both conformal or orthomorphic projection (Allan et al. 1973). The mapping projection used for the evaluation studies was the UTM. This conformal [or orthomorphic], cylindrical mapping projection is the de facto standard for mapping in at least 60 countries, including the USA (Richardus and Adler, 1972). The advantages of cylindrical projections are that the meridians of longitude are shown as vertical lines, while parallels of latitudes are horizontal lines. Conformal mappings preserve angle measures and on these projections the scale factor at a point is independent of azimuth, so geodetic compass headings and bearings can be transferred directly to the mapping plane and map distortion is minimized because local shape is preserved.

The UTM projection is a system which divides the earth into zones, or belts. Each of these is six degrees wide beginning with the first zone at 180 degrees west longitude at its western edge (so its central meridian is at 177 degrees west longitude). The zones are numbered eastwards; a quick calculation should reveal the zone 31 as the Greenwich meridian at its western edge. These vertical strips represent how sis degrees of longitude from the earth's reference ellipsoid would appear if projected onto the inside of a cylinder then flattened.

Each zone consists of identical transverse mercator projections whose characteristics are as follows:

i. The North-South extent is 80 degrees north to 80 degrees south latitude.

ii. In the northern hemisphere the origin is on the equator at a point 500000 meters to the west of the central meridian (i.e., the false easting, F.E. is 500 000 m).

iii. In the southern hemisphere the origin is $10x10^6$ meters to the west of the central meridian.

UMD developed a software/spreadsheet based on the UTM which accepts geodetic coordinates (latitude, longitude) and automatically converts them to planar (easting, northing).

The study area examined and discussed within this thesis falls within zone 18, which covers, from 72 degrees west longitude to 78 degrees west longitude, with a central meridian of 75 degrees west longitude. The UTM zones can be further subdivided according to latitude suing zone designators, each of which represents eight degrees of latitude. The study area is within designator S (hence 18 degrees S), which covers 32 degrees north latitude to 40 degrees north latitude.

A specific mathematic model of the earth is required for map projections depending on one's location. For this exercise, the reference ellipsoid is the WGS84 ellipsoid, which corresponds to the 1983 North American Datum (NAD83). This is the most common ellipsoid used in GPS receivers.

7. Methodology

Research teams from the Universities of Virginia and Maryland conducted the experiments on the RadioCamera^{TM}. Although both teams worked closely together on the experiment, the team was effectively broken into two separate groups, responsible for macroscopic and microscopic evaluations respectively. The University of Maryland's research team was charged with the responsibility of providing microscopic evaluations of the RadioCamera^{TM} system. The purpose of the microscopic evaluation was to test the ability of the RadioCamera^{TM} system to accurately measure the position and speed of an individual mobile phone moving through traffic, while the macroscopic evaluation involved assessing whether or not the system could support macroscopic transportation management applications. To do so, the University focused on investigating (a) the sample size adequacy provided by the USWC system, and (b) the accuracy of link speed data reported by the USWC system. While the results of the macroscopic evaluations are very important for a variety of transportation applications, such as traffic forecasting, it is beyond the scope of this thesis. Portions of the microscopic assessment will be the focus of this thesis. In particular, we will use the data gathered in the studies to make determination on whether the system is suitable for vehicular tracking, by examining the position accuracy as it relates to speed and the geometric location of the vehicle.

GPS-equipped probe vehicles were used to provide a basis for comparison. Data collected from the GPS systems were used as ground truth for comparison with those collected from the USWC RadioCamera^{TM} system.

A three-pronged approach of analysis was adopted for this thesis. So, three different analyses were done on the data. The first involves a general analysis of the accuracy, the second – a dynamic analysis, and third – a spatial analysis. Each will be discussed in further details in the following sections. The final section in this chapter looks at the accuracy metrics – the measuring standard adopted for the analysis.

7.1 General Statistical Analysis

As the name suggests, the General Statistical Analysis involves an overall statistical analysis on the data. This involved collecting all relevant data, reorganizing where necessary, and processing the data – thus making statistical inferences. In this analysis, there is no direct attempt at trying to determine sources of errors that may have been introduced into the experiment. The aim is to determine how close the US Wireless's estimates were to our 'ground truth', the GPS system.

The first step in the general analysis involved sorting call records and matching these with GPS records. Although a software was developed to simultaneously log the position records and times of both the GPS and the cell phones, because both were being logged on different time lattices, in addition to the fact that the GPS was making position fixes in odd seconds in time, it was still necessary to translate call records of GPS to match those of the cell phone in time. These were small (in the magnitude of fractions of a second) translations of entire call records.

After call records were matched in time with the GPS records, the coordinates were transformed from a geodetic system to a grid system. This was done using the UTM projection and the WGS84 datum. Both the GPS coordinates and the coordinates generated for the cell phone by the RadioCamera™ were converted. The error between corresponding call records of the GPS and the cellular phones were calculated using Equation 1 below. This error represented the straight line error between the estimated position of the cellular phone and the corresponding GPS point.

Equation 1 – Error calculation (Pythagoras theorem)

$$Error = \sqrt{(N_{gps} - N_{cell})^2 + (E_{gps} - E_{cell})^2}$$

After errors were computed, various statistical operations were done on the results. These include calculating error histograms and cumulative distribution function (CDF) plots of the errors. Plots of the data points along the road were generated in Matlab for this section.

7.2 Dynamic Analysis

After the general analysis was conducted on the data, it was necessary to do a dynamic analysis. The dynamic analysis is needed for a system like this which would be operating at various speeds. The dynamic analysis was aimed at answering the question of whether or not the speed of the vehicle had any effect on the accuracy of position estimates.

The speeds were sorted into three separate ranges. First, all errors associated with the vehicle position while the vehicle was at a standstill, or when the vehicle speed was zero, were collected and analyzed. The second range was related to the speed with which the vehicle is expected to travel in an urbanized region. For the most part, this speed limit may be as much as 35 miles per hour (mph). For this reason, the second range was between 0 mph and 35 mph. A similar analysis as that of the general analysis was done on the errors.

The final range was above 35 mph. The process of gathering and sorting the data was again done. The data was analyzed using the same methods above.

7.3 Spatial Analysis

Not only is it necessary to determine if the system's errors are related to the speed of the vehicle, but it is equally important to determine if the geographic areas might affect the positioning accuracy. This is especially important for the cellular phone system, in particular the RadioCamera™, since the system's position estimates are directly linked to the geography of the region.

The spatial analysis involved the use of ArcView GIS 3.3. This software allowed the points to be plotted onto a GIS road map of the study area. In addition to this, the software provided the ability to query data points and determine speed and errors, among other things, for the data. The revelation of other aspects of the data which were not obvious in earlier analyses stood a better chance of being accounted for herein.

First, for a geospatial analysis to be conducted, a coordinated street map of the study area, in Northern Virginia, was necessary. This is regarded as a "road shape file" in GIS terminology. Because the shape file is coordinated – meaning that the roads center lines and the map in general have coordinates associated with them it enables the generated coordinates, from the cellular phones as well as the GPS, to be superimposed over the map layer - thus giving a better pictorial representation of the data points on the road than the ones generated in the general analysis using matlab.

A script file was compiled to accept coordinates from the cell phone and GPS in a text file and convert them into a shape file. Both the shape file of the road and the shape file of the coordinates of the cellular phones, as well as the GPS, were all brought to the same projection and datum and shown on various maps. The maps were queried and trends in the error noted and discussed.

7.4 Accuracy and Accuracy Metrics

A review of previous work done with the AVL field revealed that no single performance measure or standard is available to compare the accuracy of an AVL or even a vehicle tracking system. However, according to Yim and Cayford (2000), the accuracy required for an effective vehicle tracking system is dependent on the geography of the road network where it will be deployed. In areas of greater density, with roads close together and many intersections, much greater accuracy is required for the probe to be correctly placed on its road segment Where roads are far apart with few intersections, a much lower degree of accuracy in position identification can be used and still yield correct road segment matches.

Since the use of the system is geared towards tracking vehicles in various geographic scenarios, a universal performance metric is necessary for testing of the cellular phone system. The requirements as stipulated by the FCC for E911 calls were adopted as the requirement for the testing of the RadioCamera™ system for tracking. It makes good sense that if the requirements of the FCC mandate were suitable and sufficient for locating someone who is in distress and unable to relay their own position, then it would be fitting, at least by extension, to determine the position of a vehicle.

The next section describes the probe vehicle setup, including both hardware and software. Following that, a description of the experiments themselves is provided, and then an overview of data analysis procedures is given.

7.5 Experimental Setup – Hardware

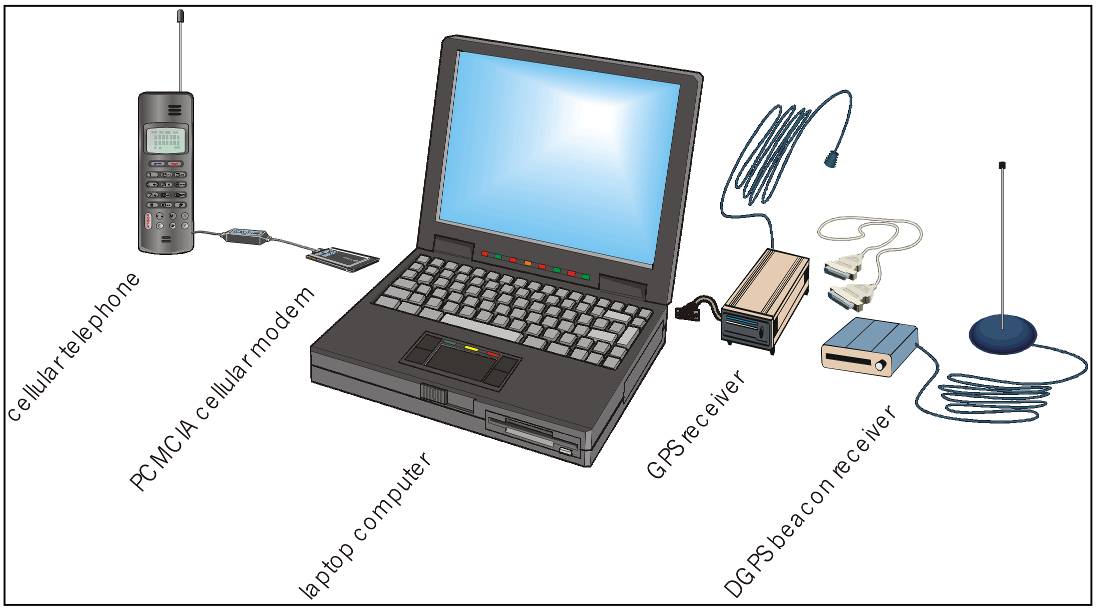
The primary vehicle that was used for the experiments was an Infiniti Q45 loaned to the research team by Nissan North America, Inc. The car is equipped with a hands-free CDMA phone for coordination purposes, CD-ROM based navigation system with GPS and inertial navigation technology, and differentially-corrected GPS equipment.

Initially the RadioCamera™ system was designed to handle only AMPS cellular phone traffic, so old single-mode analog cellular telephones were obtained, and a single-mode analog service contract was agreed upon with the Cingular Wireless network. The single-mode analog setup was important because modern dual-mode phones (AMPS plus some other digital protocol such as CDMA or TDMA) will use the analog voice channels when in analog mode, but will communicate via the control channels much the same as a digital phone. The RadioCamera™ was only monitoring control channels being used similar to that of the old AMPS phones; hence obsolete phone equipment had to be obtained.

The mobile phones used for the test were variants of the Motorola MicroTAC AMPS phone. These phones were connected to a 3Com 3CXM556 Megahertz Cellular Modem PCMCIA card installed in a laptop computer, thereby allowing software control of dialing, on/off hook, etc. No special antenna equipment was connected to the phones – they were placed in the probe vehicle on the dashboard.

Also connected to the laptop computer, via the serial port, was a SiRFstarI/LX GPS unit, augmented by a Garmin GBR 21 Differential Beacon Receiver. Figure 7 shows the arrangement of all of the hardware in the vehicle.

Figure 7 -Experimental In-vehicle Hardware Setup

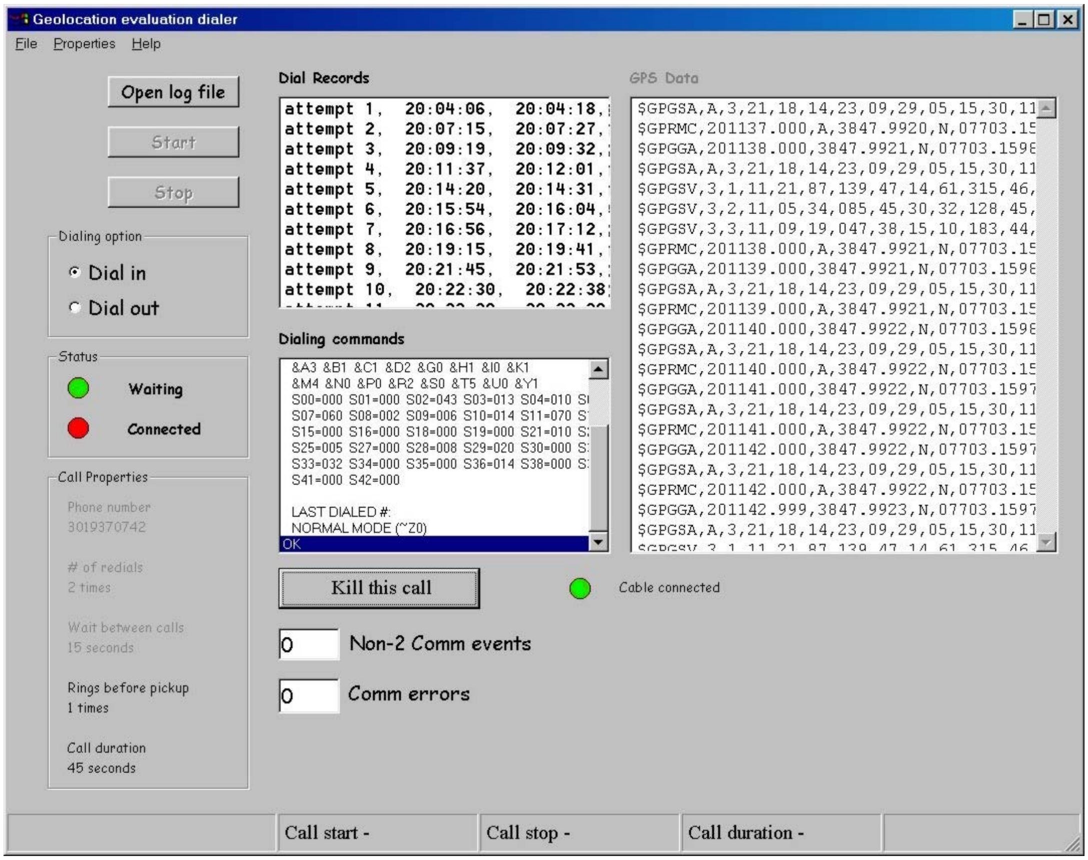


7.6 Experimental Setup - Software

A customized software was written to simultaneously control and record inputs from the cellular telephone and GPS equipment. The main purpose of the software was to log the start and end times of calls made with the cellular phone, and simultaneously recording continuous GPS location data during the times that those calls are active. The software was made to operate in two basic modes: auto-dial and auto-answer. During auto dialing, the phone in the probe vehicle initiates all of the cell phone calls, and hence their times and durations were not known a priori by USWC. Alternatively, the software could be set to auto-answer, and the phone would then simply pick up whenever its number is dialed externally. This setup was used, for example, to compare results between the UMD data rig and the USWC data rig during early stages when the bugs were still being worked out of the system. From an experimental point of view, the auto-dial mode is preferable, particularly in terms of maintaining objectivity of the probe vehicle and the experimenters. Figure 8 shows a snapshot of the Probe Vehicle Software.

The outputs produced by the software include a set of call records, which is a list of attempted calls and their associated start times and end times (each derived from the GPS clock), durations, and a note as to the success or failure of the call. The other set of output is a text file containing the GPS data stream, in standard NMEA-0183 format. Examples of both of these are shown in the windows in Figure 8.

Figure 8 - Probe Vehicle Software



8. General Analysis of Data

8.1 April 02, 2001

The data collection process for April 02, 2001 was relatively brief and resulted in 16 cellular phone calls being made from the UMD probe vehicle between 19:16:21 and 20:07:52. The results saw two of the 16 calls being located by the USWC, with a total of 10 location records. USWC data were based on a 3.5 second time lattice, and were recorded from 19:55:52 to 19:58: 43.

Figure 9 shows a map of the data collection area. The blue points represent the USWC calibration grid points, which when viewed together, offers a reasonable reproduction of the underlying infrastructure map. The green bands represent the tracks of the probe vehicle GPS used by UMD. The data collection software used by UMD was written to only capture information while there were active or on-going calls. This accounts for the gaps between the bands. The red dots represent points where successful location records were obtained by USWC. This experiment involved driving along the I-495 and I-395 in Northern Virginia.

Figure 9 - Data collection map, April 2, 2001

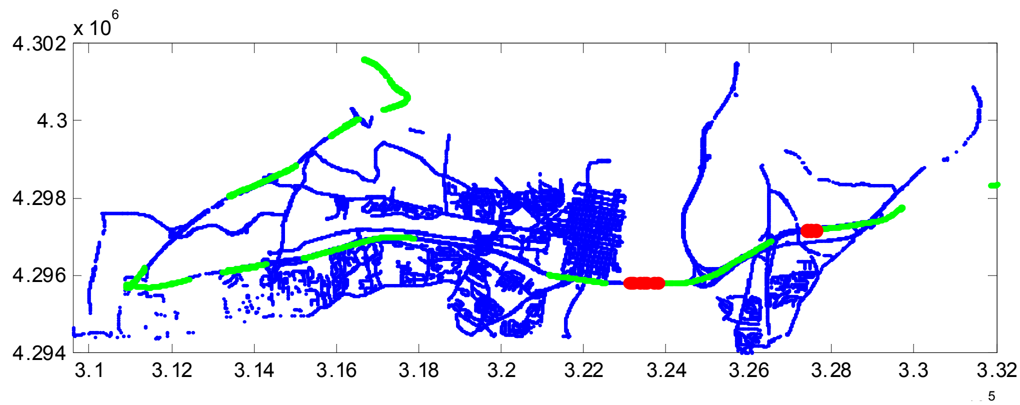


Figure 10 shows a small error histogram of the RMS position errors obtained from the data collected for this run. The cumulative distribution function for the error is shown in Figure 11. This was constructed the error histogram by summing cumulatively and then normalizing. The red and green crosshairs on the cumulative distribution function helps to pinpoint information about the 67th and 95th percentile errors respectively. The 67th percentile error was 96 meters while the 95th percentile error was 191 meters. Considering the requirements set out by the FCC, these results are quite good. However, much cannot be deduced from this sample because it was small, and further experiments were not as good.

Figure 10 - Small error histogram, April 2, 2001

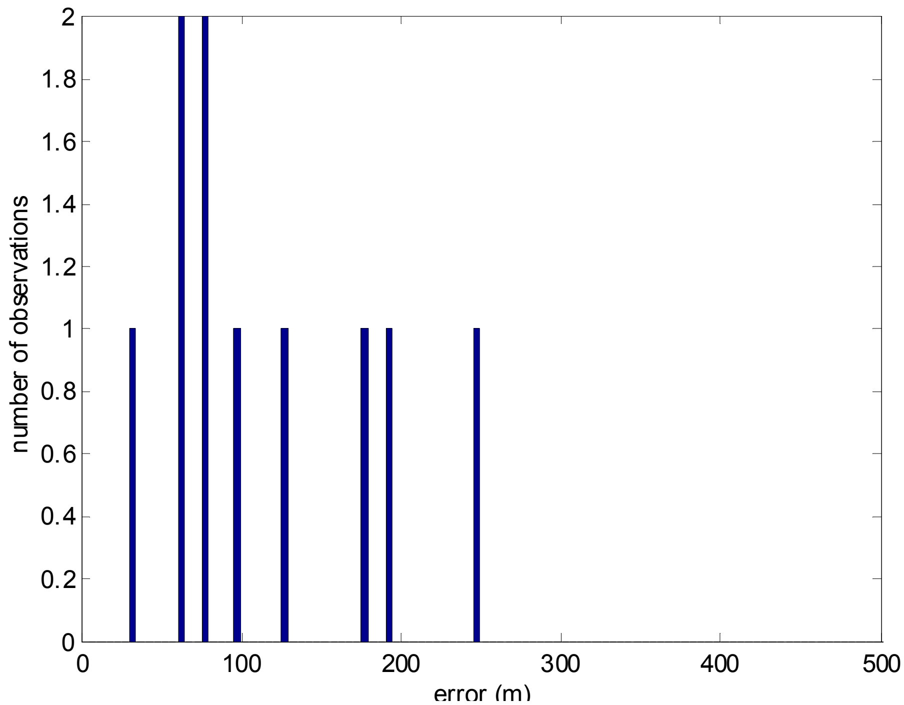
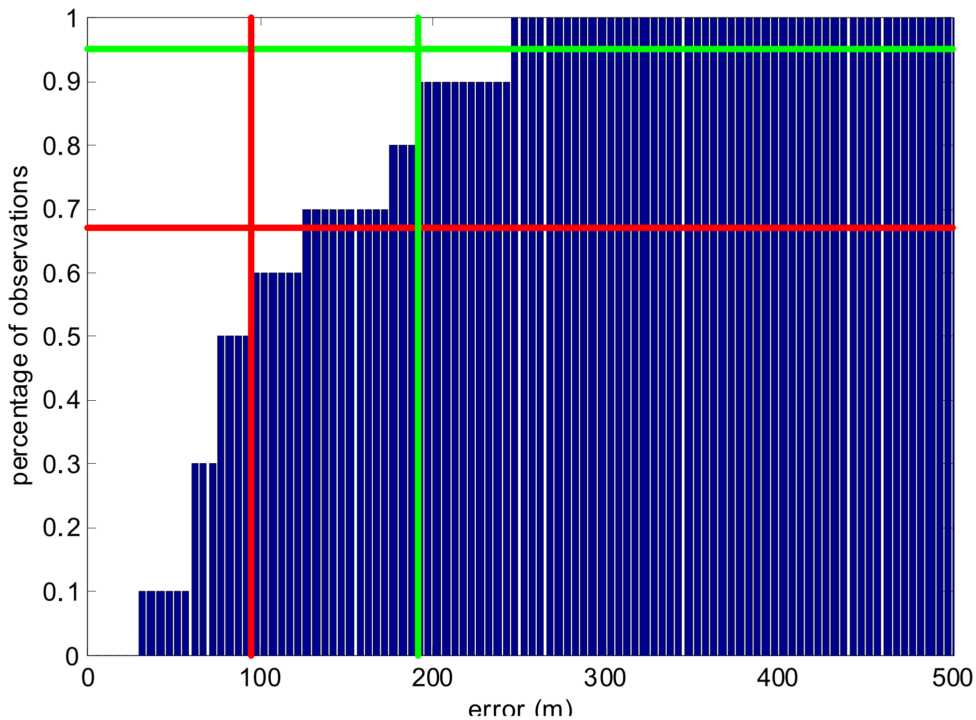


Figure 11 - Cumulative distribution of position error, April 2, 2001



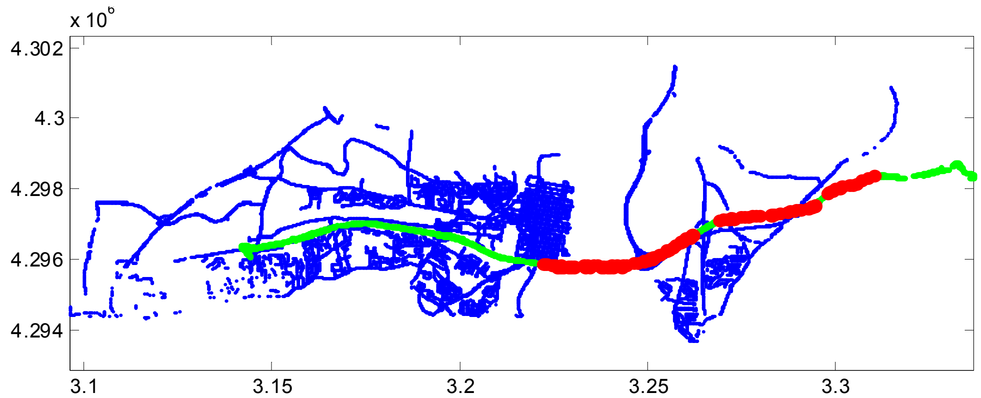
8.2 April 12 2001

On April 12, 2001, the probe vehicle surveyed the test area from time 16:51:34 to 18:00:33. During this time 92 cellular phone calls were made, however none of the calls were tracked or located because of a USWC system failure, which prevented their data from being recorded.

8.3 April 19, 2001

April 19, 2001 saw the UMD probe vehicle surveying the study area between 19:53:42 to 21:26:20. During this experiment 120 phone calls were made, of which 23 calls were recorded by USWC. The 23 calls tracked by USWC were distinguished by a total of 87 location records between 19:53:54 and 21:24:57 and were collected on a 3.5 second lattice. Figure 12 shows the data collection map representation for the run.

Figure 12 - Data collection map, April 19, 2001



Two error histograms are used to represent the results of the experiment. This was more convenient to report due to the large location errors that resulted in this experiment. Two error histograms allow a better view of the entire histogram and the ability to make distinctions about the distribution pattern within the small error range. Figure 13 and Figure 14 are the small and large error histograms respectively.

Figure 13 - Small error histogram, April 19, 2001

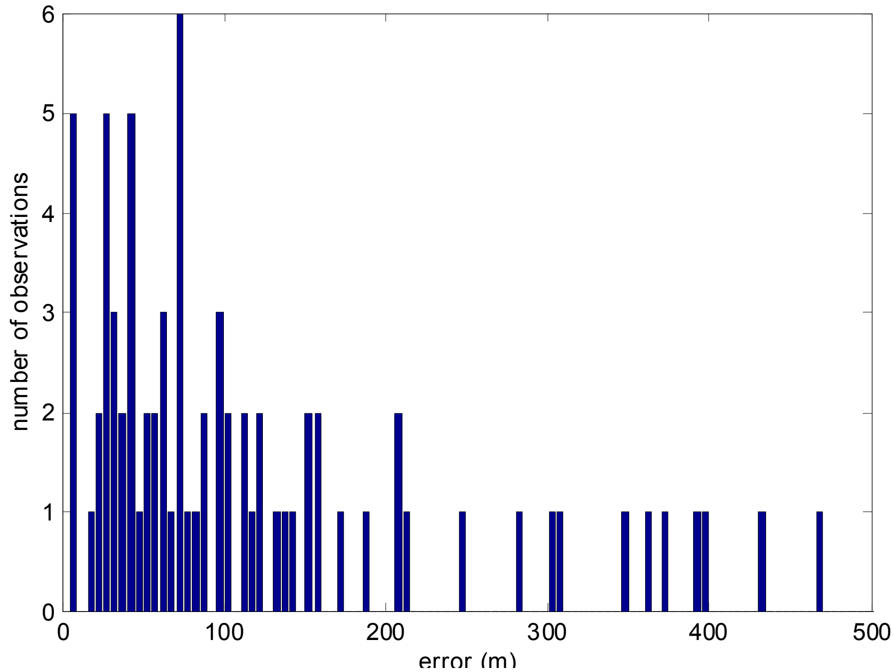


Figure 14 - Large error histogram, April 19, 2001

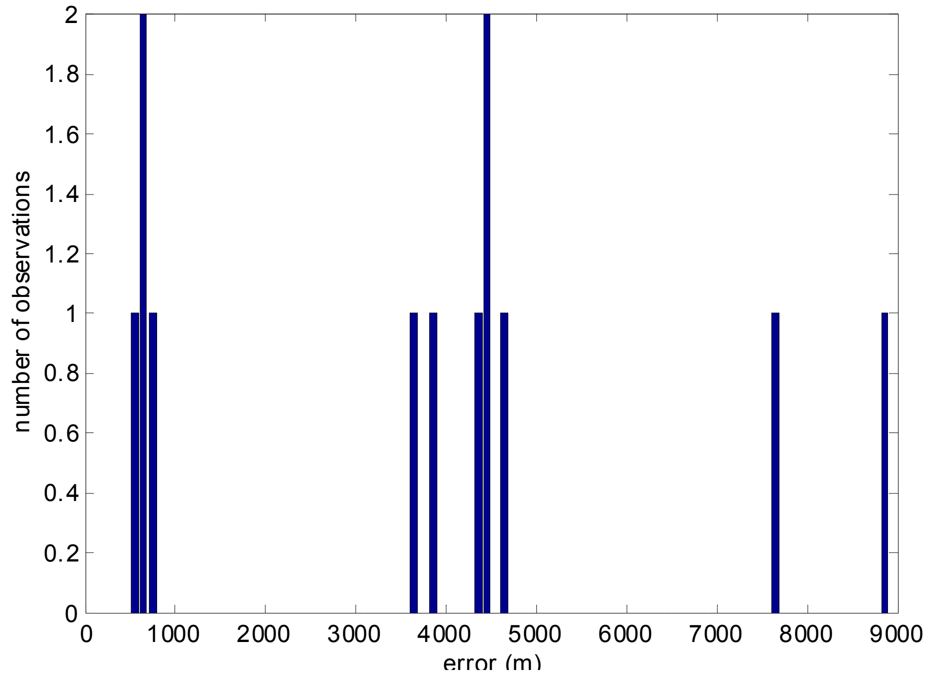
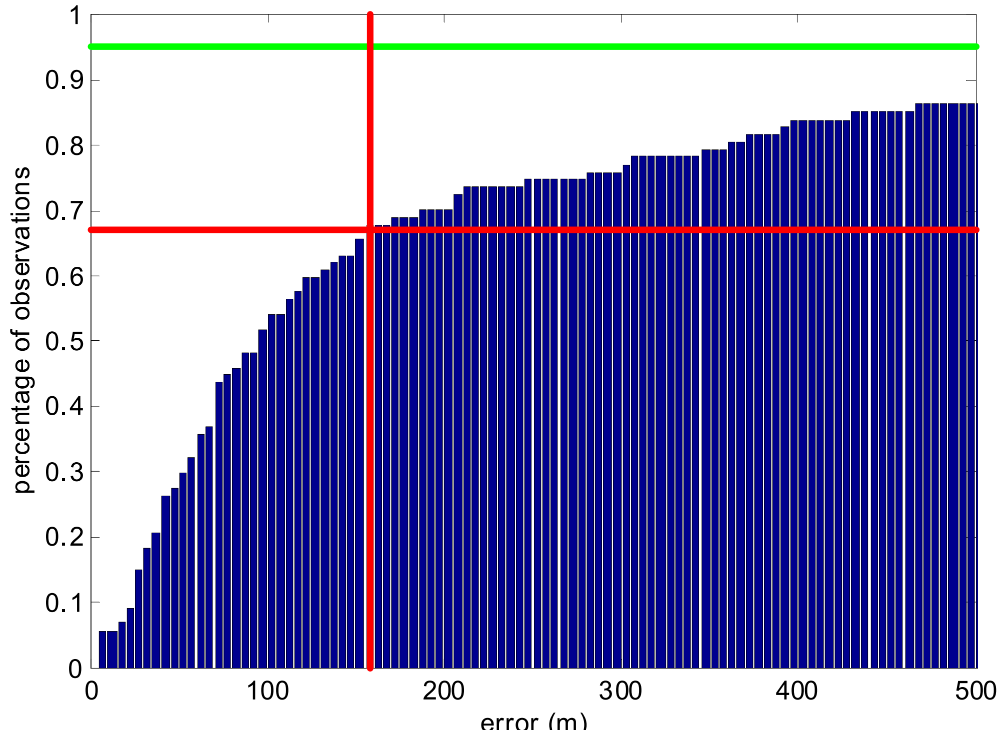


Figure 15 shows the cumulative error distribution for errors between 0 and 500 meters. The red color crosshairs again represents the 67th percentile error and for this experiment – 157 meters. The 95th percentile error is 4381 meters, which is far off the right of the figure. Both of these are not within the FCC requirements for E-911.

Figure 15 - Cumulative distribution of position error, April 19, 2001



8.4 April 26, 2001

On April 26, 2001, the probe vehicle surveyed the study area between 20:08:46 to 21:03:10, during which a total of 27 phone calls were made. USWC recorded 4 of the 27 phone calls, which amounts to 35 location records. The location records were generated between 20:15:14 and 21:00:31, on a 2.5-second lattice. Figure 16 shows the data collection map representation for this run.

Figure 16 - Data collection map, April 26, 2001

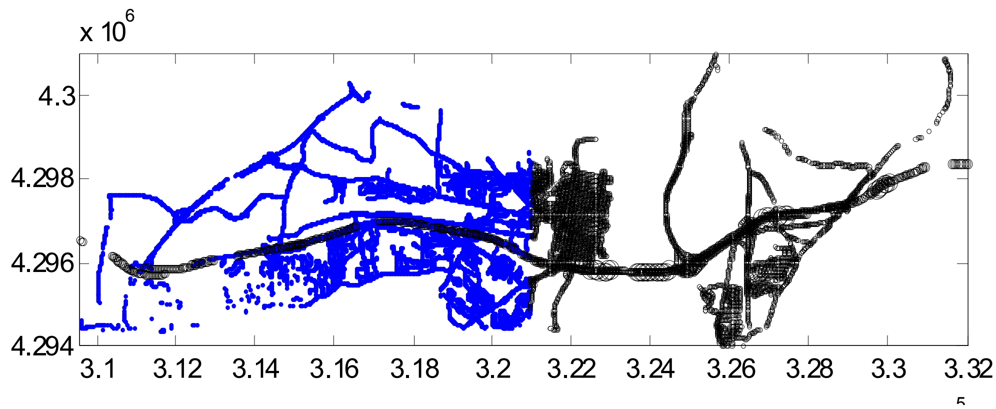


Figure 17 and Figure 18 respectively shows the small and large error histograms, while Figure 19 shows the cumulative error distribution for the entire experiment. The 67th percentile of 96 meters fell within the error range stipulated by the FCC, while the 95th percentile was 1622 which was not close to the FCC requirement.

Figure 17 - Small error histogram, April 26, 2001

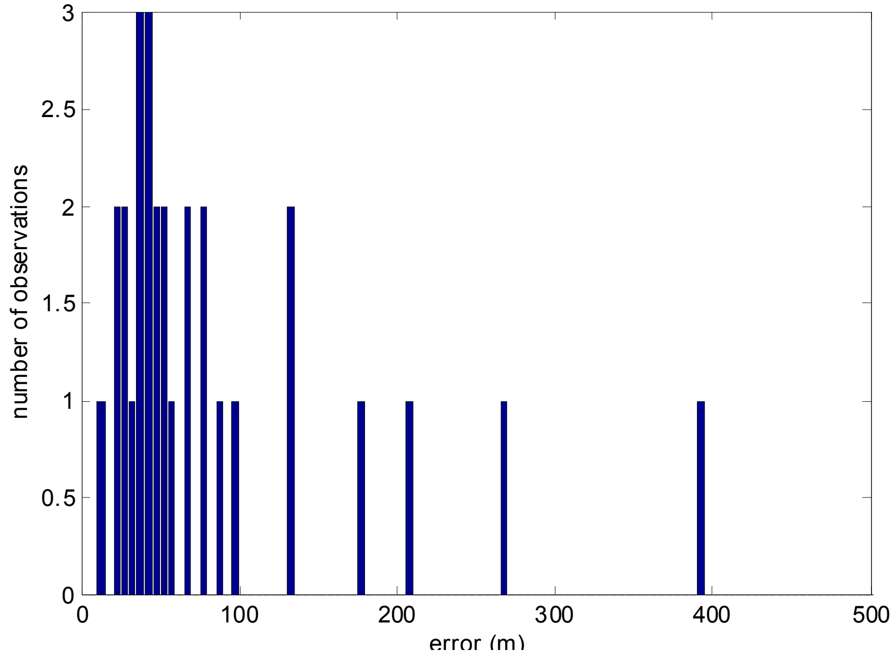


Figure 18 - Large error histogram, April 26, 2001

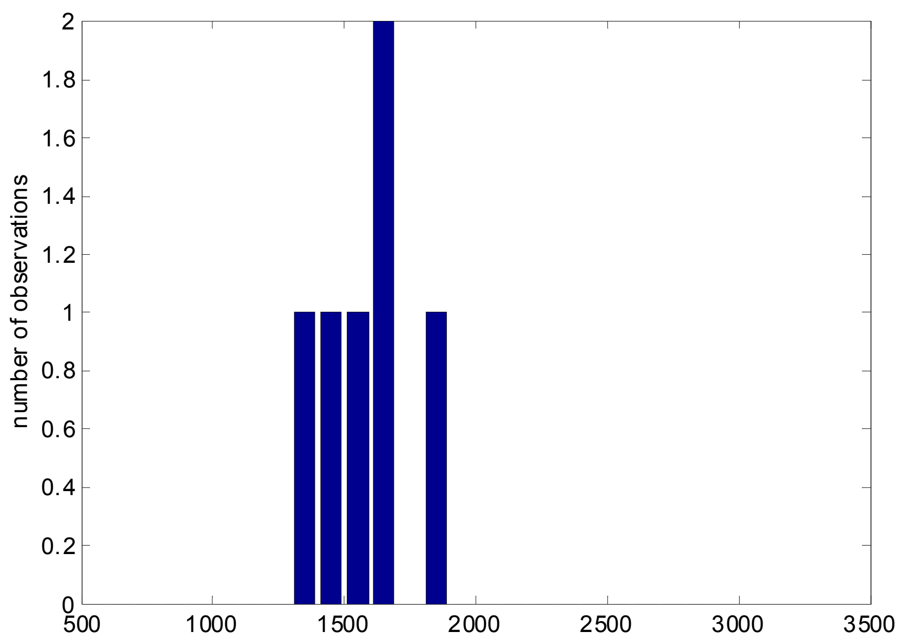
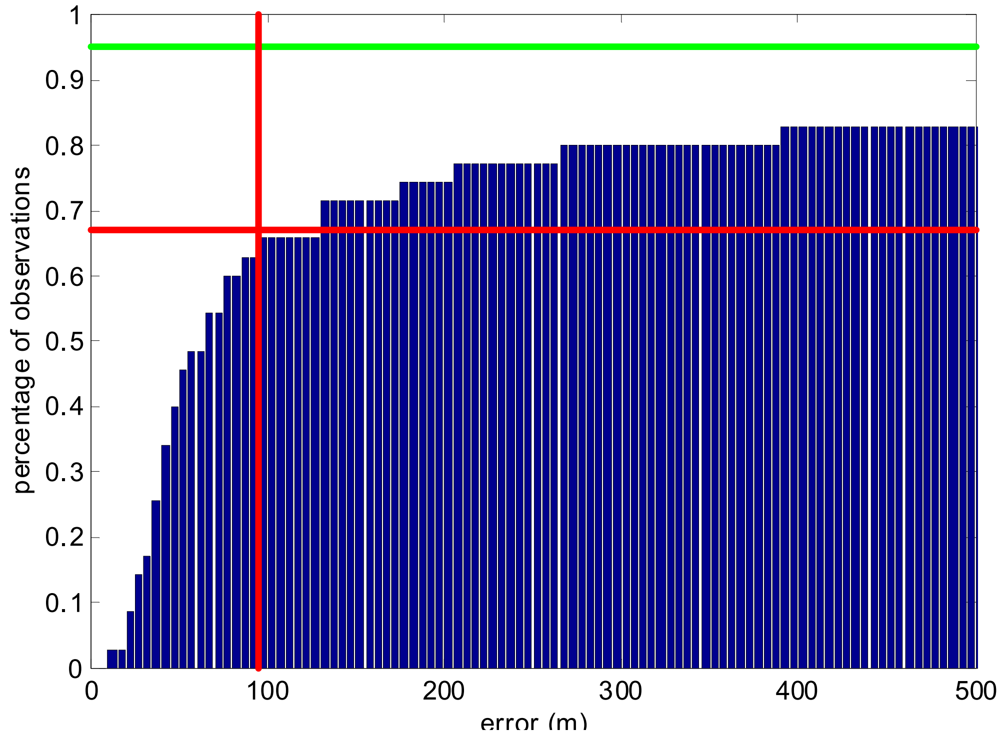


Figure 19 - Cumulative distribution of position error, April 26, 2001



8.5 August 26, 2001

On August 6, 2001, the instruments used to collect data included two AMPS cellular phones. One of these was from UMD and the other from USWC. The phones may be distinguished by the last two digits of their (scrambled) mobile ID numbers: 66 for UMD and 76 for USWC. The location accuracy results are show separately.

8.5.1 MID 66 (UMD)

The data collection process for August 06, 2001 saw 62 cellular phone calls being made from the MID 66 (of UMD) between 20:16:57 and 21:59:59. The results saw 24 of the 62 calls being located by the USWC, with a total of 138 location records. USWC data were based on a 2.5 second time lattice. Figure 20 and Figure 21 show the data collection maps with Figure 21 being a more detailed version showing a closer picture where the location records were generated.

Figure 20 - Data collection map, MID 66, August 6, 2001

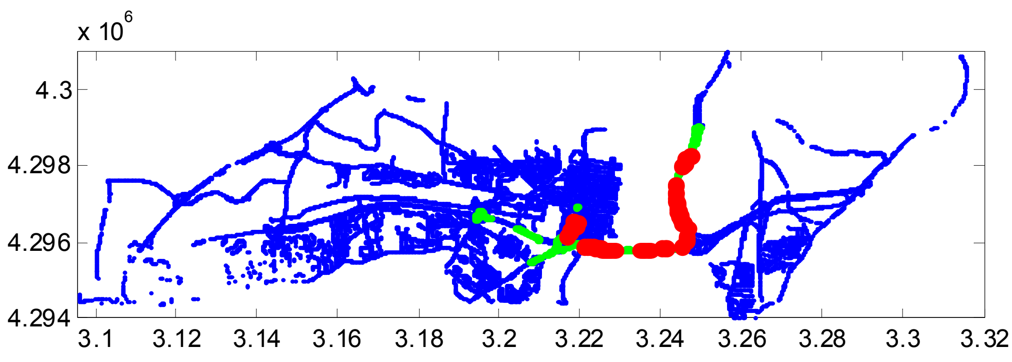
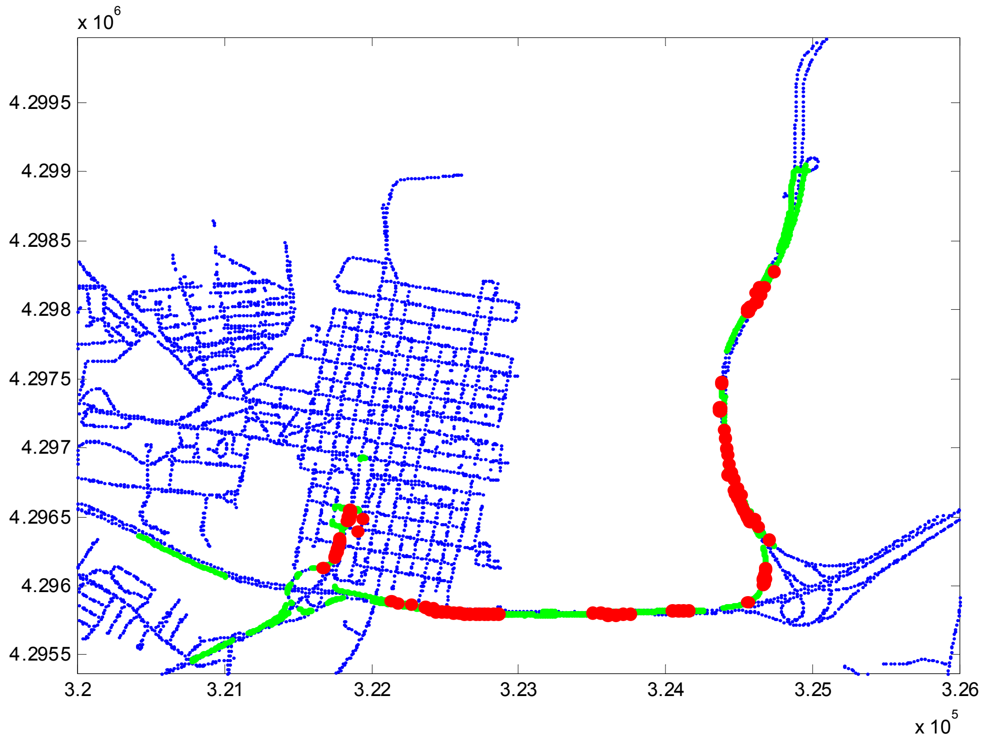


Figure 21 - Data collection map detail, MID 66, August 6, 2001



Two error histograms are used to represent the results of the experiment. This was more convenient to report due to the range of the location errors in this experiment. Figure 22 is the error histogram which spans the 0 to 600 meter range, while Figure 23 captures from the 600 meter to 4500 meter range.

Figure 22 - Small error histogram, MID 66, August 6, 2001

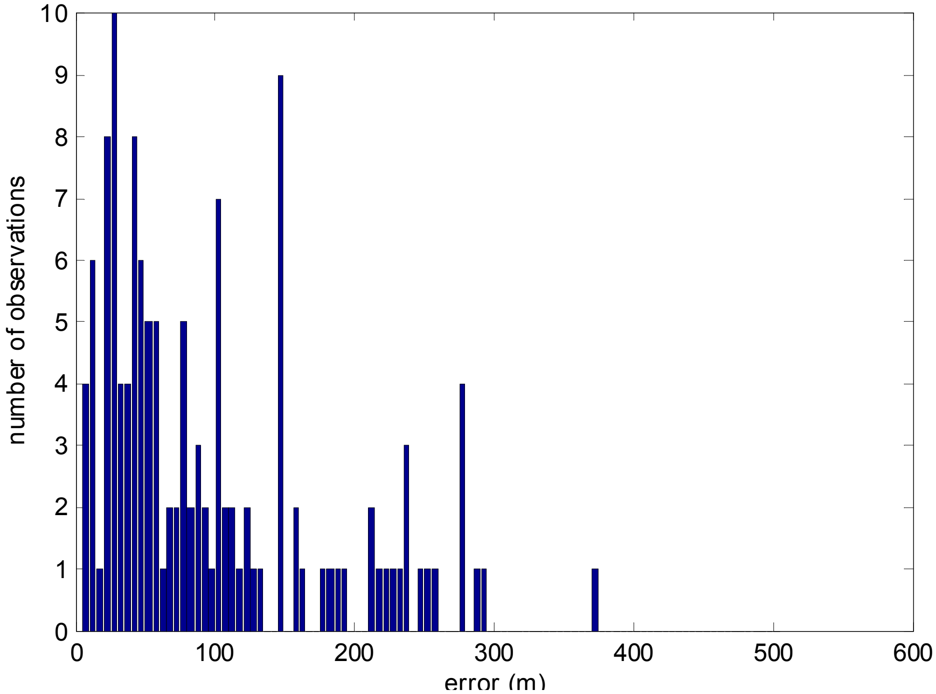


Figure 23 - Large error histogram, MID 66, August 6, 2001

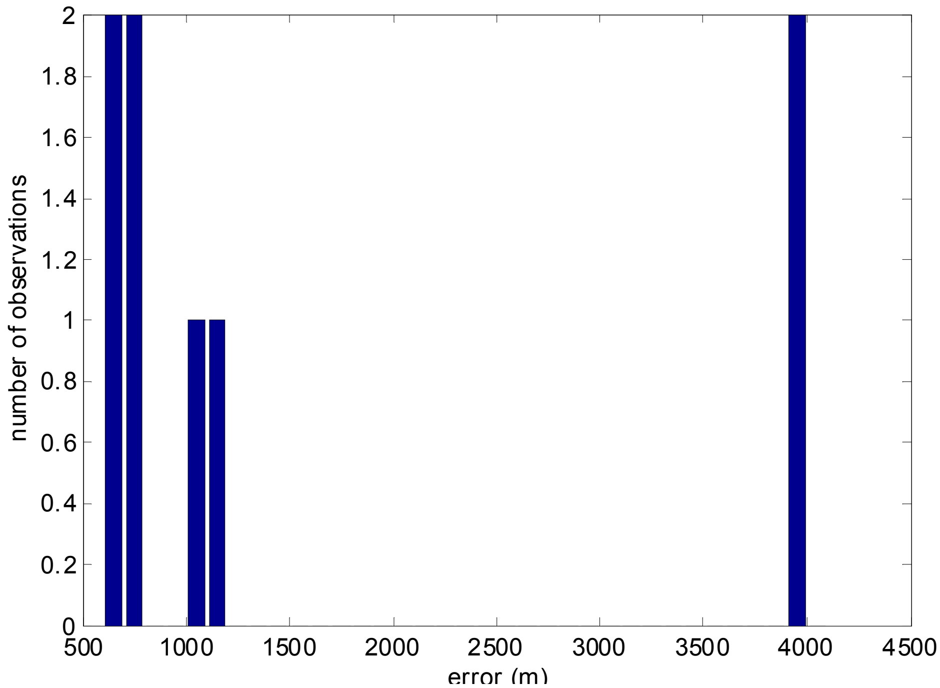
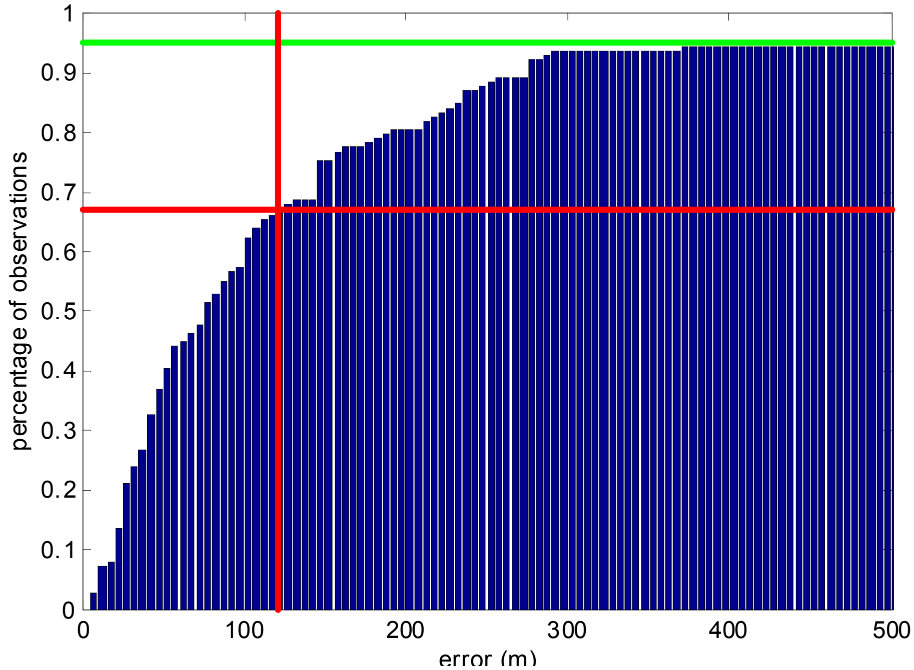


Figure 24 shows the cumulative error distribution for errors between 0 and 500 meters. The red color crosshairs again represents the 67th percentile error and for this experiment – 122 meters. The 95th percentile error is 631 meters. Both of these are not within the FCC requirements for E-911.

Figure 24 - Cumulative distribution of position error, MID 66, August 6, 2001



8.5.2 MID 76

USWC AMPS phone (MID 76) tracked 19 cellular phone calls in total, resulting in 136 location records. The call generation process was a little different for this phone. Unlike the UMD phone which originated all calls from the auto-dialing phone/GPS hardware and software package, the USWC system was set up to automatically answer calls which were continuously being made from a land-line system. Information about all of the calls being made, including the start times and end times of these calls were not provided by USWC. Only successful location records were provided. However, the location records provided by USWC for MID

76 reflected calls that were generated between 20:11:39 and 22:00:49, with a 2.5 second time lattice.

Figure 25 show the collection maps for the experiment, while Figure 26 shows a more detailed view of the areas where location records were provided.

Figure 25 - Data collection map, MID 76, August 6, 2001

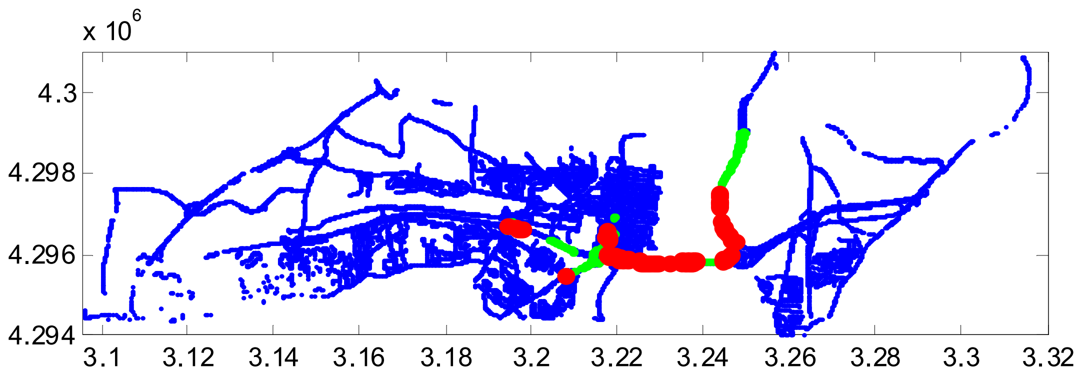


Figure 26 - Data collection map detail, MID 76, August 6, 2001

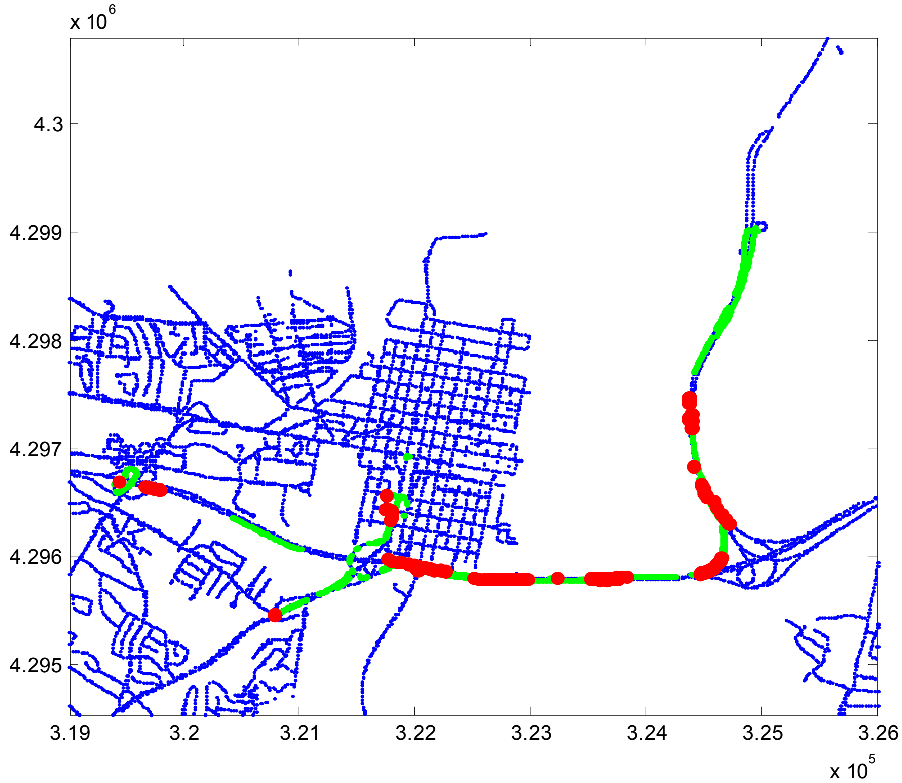
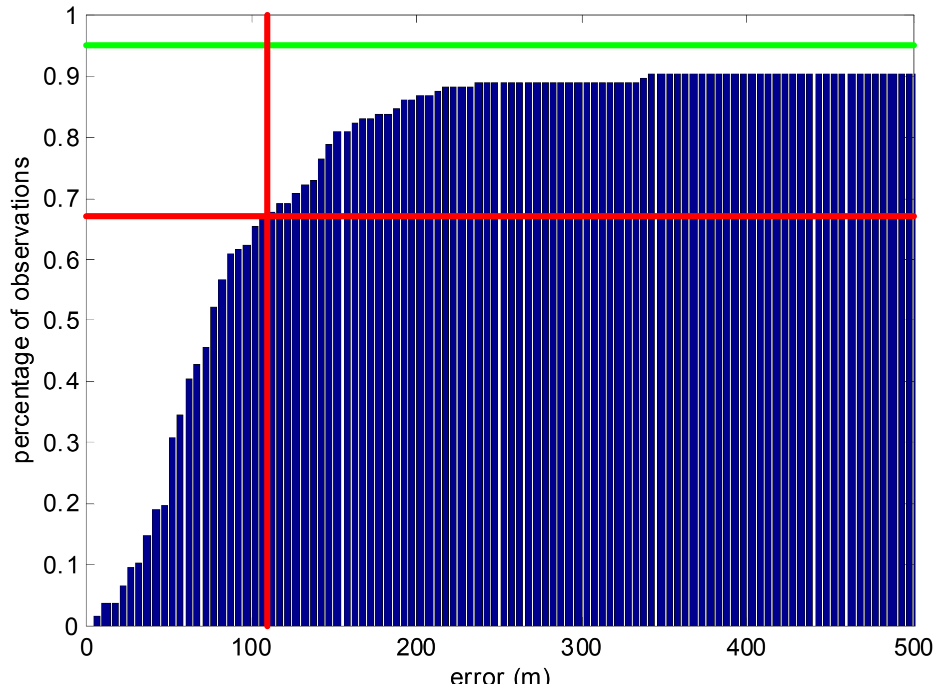


Figure 27 shows the cumulative error distribution. The 67th percentile error is 109 meters, which is slightly outside the FCC requirement and the 95th percentile error is 2800 meters – significantly out.

Figure 27 - Cumulative distribution of position error, MID 76, August 6, 2001



8.6 September 24, 2001

September 24, 2001 data collection run saw several important changes being made to the usual setup and methods in all the previous runs. This day of data collection represented the "production" version of the RadioCamera^{TM} system. Similar to the August experiment, there were two AMPS phones – one owned and operated by UMD and the other by USWC. In addition to this, a TDMA digital phone was used to in a test run to get some insights as to the systems performance with the newer digital protocol. These systems will eventually replace the AMPS systems, and so it is necessary to go through more rigorous testing of the system under digital protocols to establish its performance characteristics.

8.6.1 AMPS Data

The following section describes the results obtained from the two AMPS phones on September 24. We will look at the results of each phone separately.

8.6.1.1 USWC AMPS phone

The USWC AMPS phone received 75 phone calls within two distinct time periods. The first was from 14:08:31 to 15:04:25 and the second from 19:35:13 to 21:02:37. These 75 calls resulted in 742 location records on a 2.5 second time lattice. USWC did not provide detailed information on the actual start and end times of the attempted calls to their phone. And, as previously described, the calls were continuously generated from a land line and automatically answered by the cellular phone.

Figure 28 shows the data collection map for the USWC phone, while Figure 29 shows the relevant portions in more details. Neither figure has the plots of the GPS trajectories on the maps because USWC phone was working in conjunction with the USWC GPS and this data was not made available to UMD.

Figure 28 - Data collection map, USWC AMPS, September 24, 2001

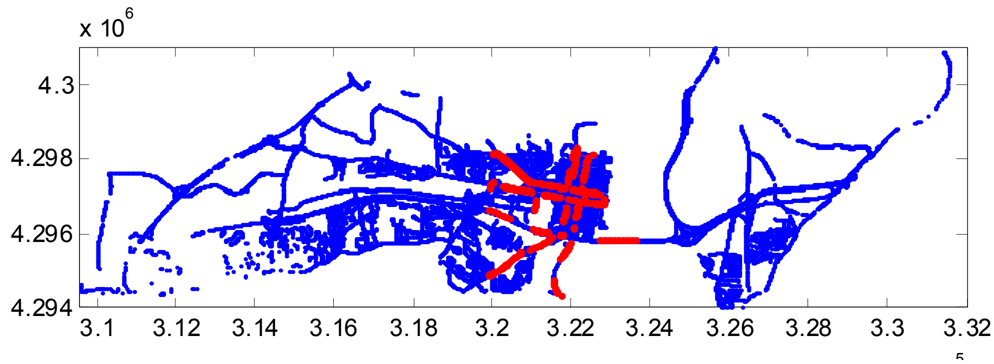
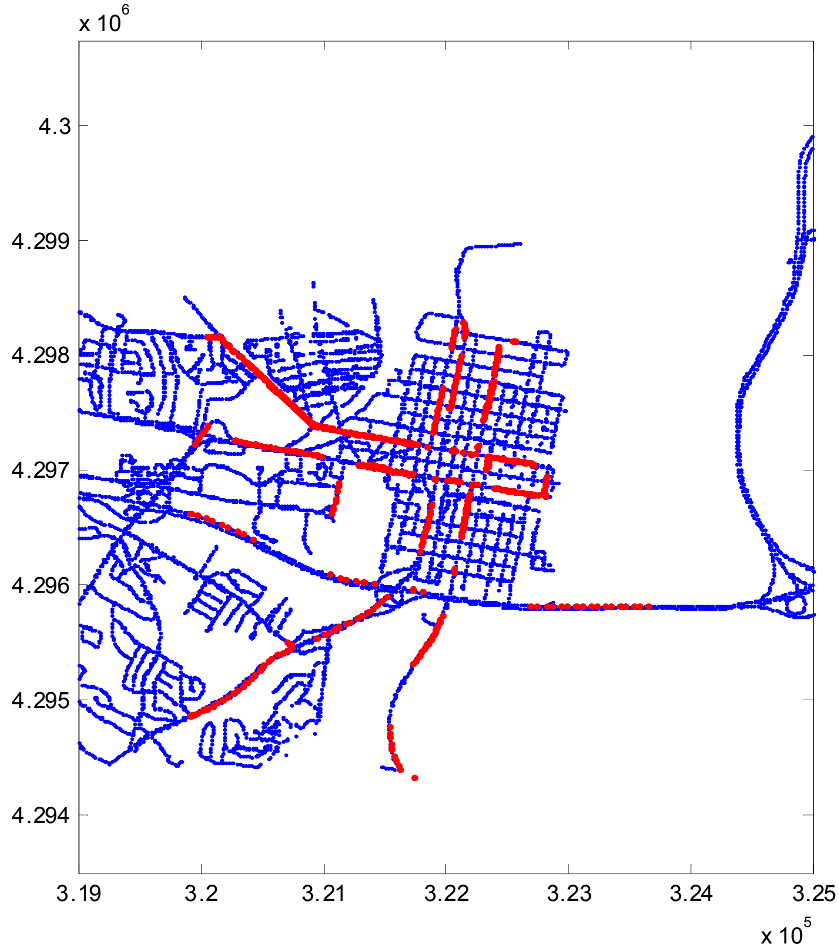


Figure 29 - Data collection map detail, USWC AMPS, September 24, 2001



The data collection run saw significant travel on the arterial streets within the city of Alexandria in Northern Virginia. This included along Route US-1, which become George Washington Parkway in the vicinity of the Ronald Reagan National Airport.

The error histogram for this run is shown in Figure 30. The very large errors that were evident in previous runs were not presenting this run; hence a single error histogram was sufficient to paint a meaningful picture of the errors. Figure 31 shows the cumulative error distribution function for this run. The 67th percentile error was 62 meters while the 95th percentile error was 132 meters. Both of these were well within the range stipulated by the FCC.

Figure 30 - Error histogram, USWC AMPS phone, September 24, 2001

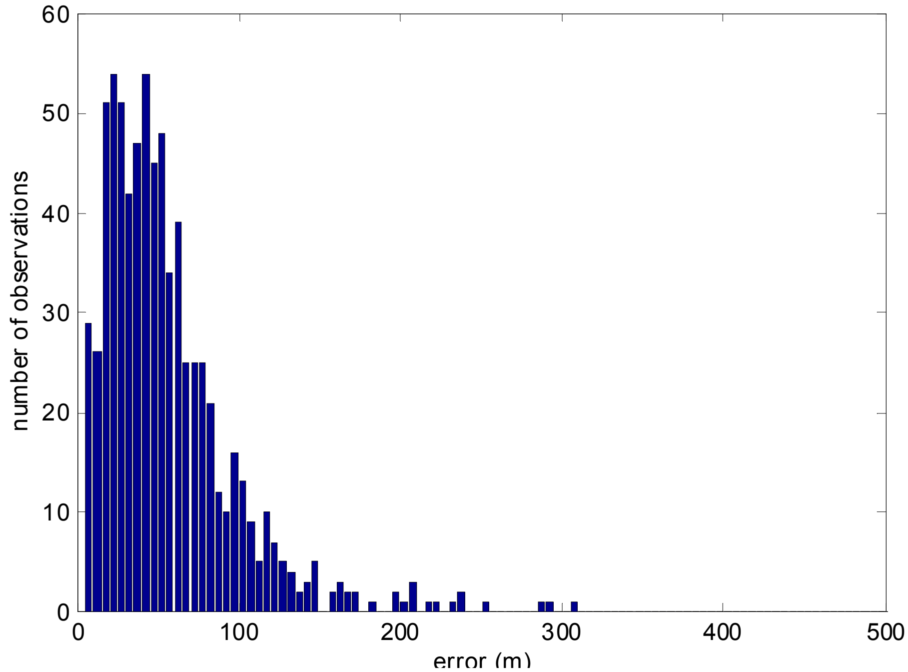
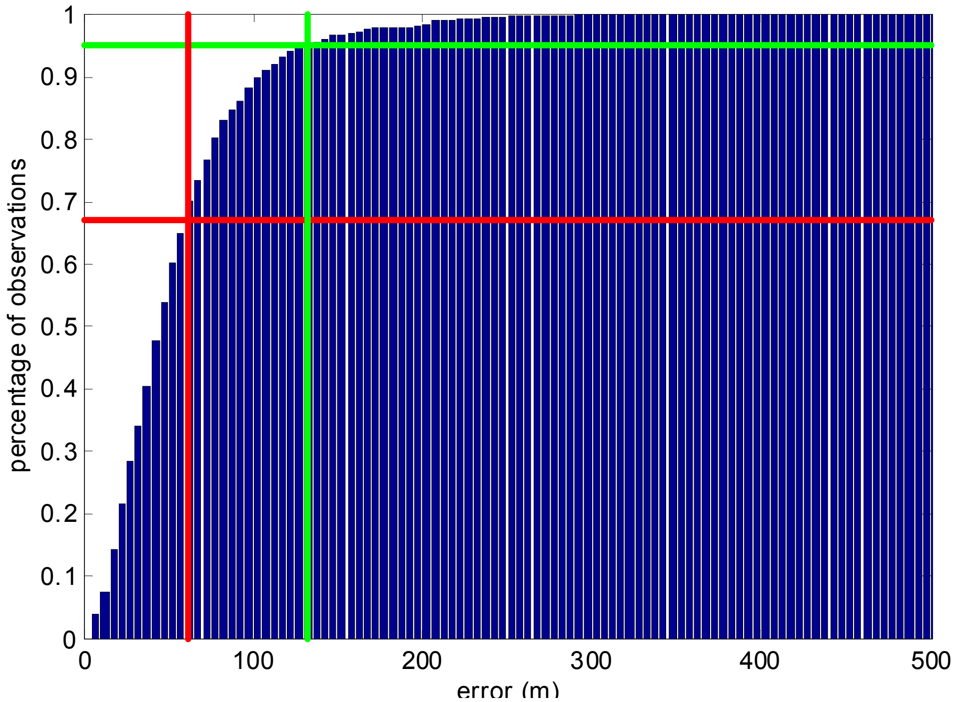


Figure 31 - Cumulative distribution of position error, USWC AMPS phone, September 24, 2001



8.6.1.2 UMD AMPS phone

The UMD phone saw operations between 17:36:24 and 19:18:33. During this experiment 61 phone calls were made, of which 27 phone calls were matched with those of USWC. The 27 calls tracked by USWC were distinguished by a total of 104 location records between 17:43:41 and 19:18:31 and were collected on a 2.5 second lattice.

Figure 32 shows the data collection map representation for the run of the UMD AMPS phone and Figure 33 shows in more detail the traveled area. The green bands here represent the tracks as recorded by the UMD GPS system while the cellular phone was active. Hence visible isolated green bands imply areas where the location records were expected and should have been generated, but were not.

Figure 32 - Data collection map, UMD AMPS, September 24, 2001

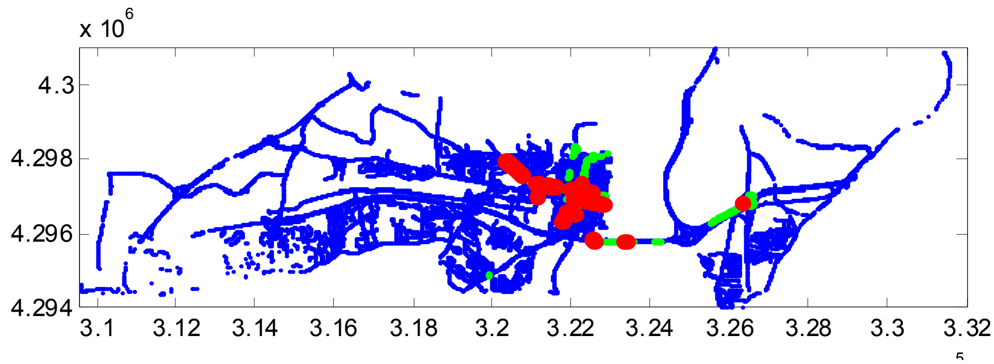


Figure 34 and Figure 35 represent the small and large error histogram of the data. Unlike USWC phone, a small amount of large errors were evident for this sample. However, from the cumulative error distribution depicted in Figure 36, the 67th percentile error was 53 meters and the 95th percentile error was 90 meters. Both of these results are substantially below the FCC requirements, so the location accuracy performance for this AMPS run was seemingly good. The overall conclusion about the accuracy performance for the AMPS data will follow in the concluding paragraphs of this chapter.

Figure 33 - Data collection map detail, UMD AMPS, September 24, 2001

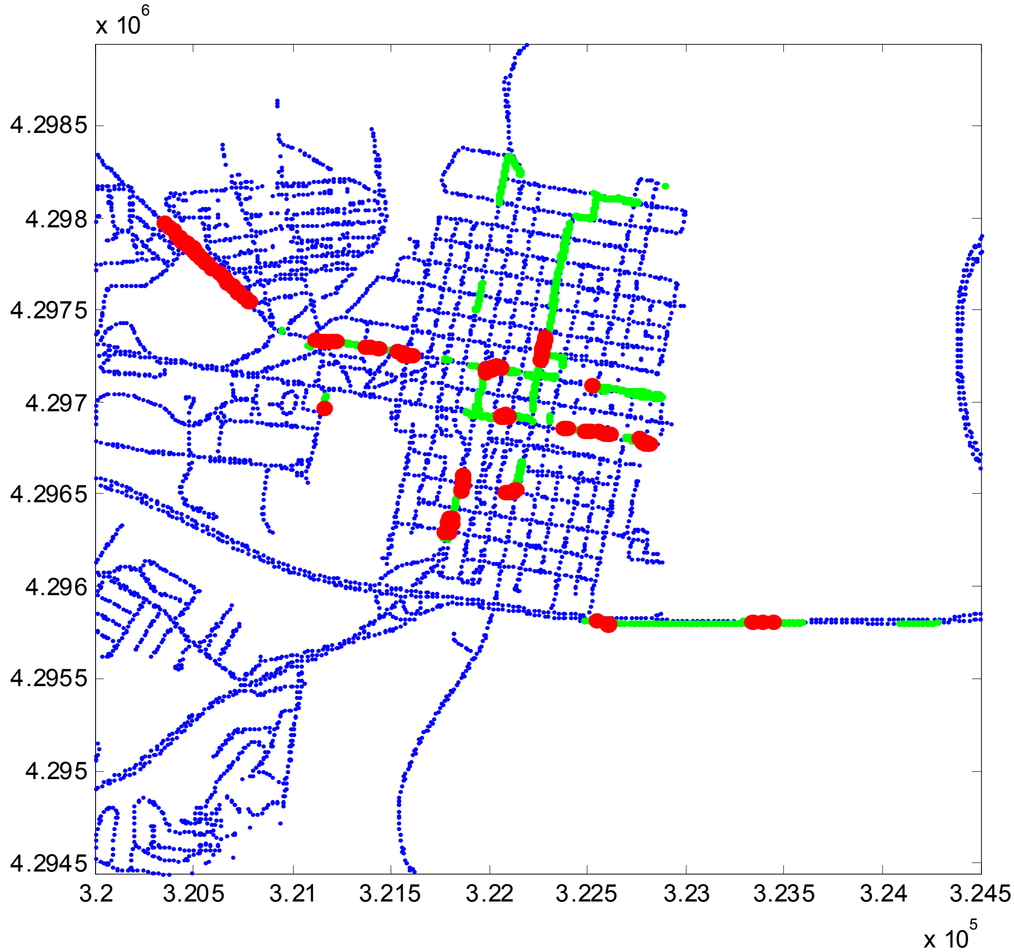


Figure 34 - Small error histogram, UMD AMPS phone, September 24, 2001

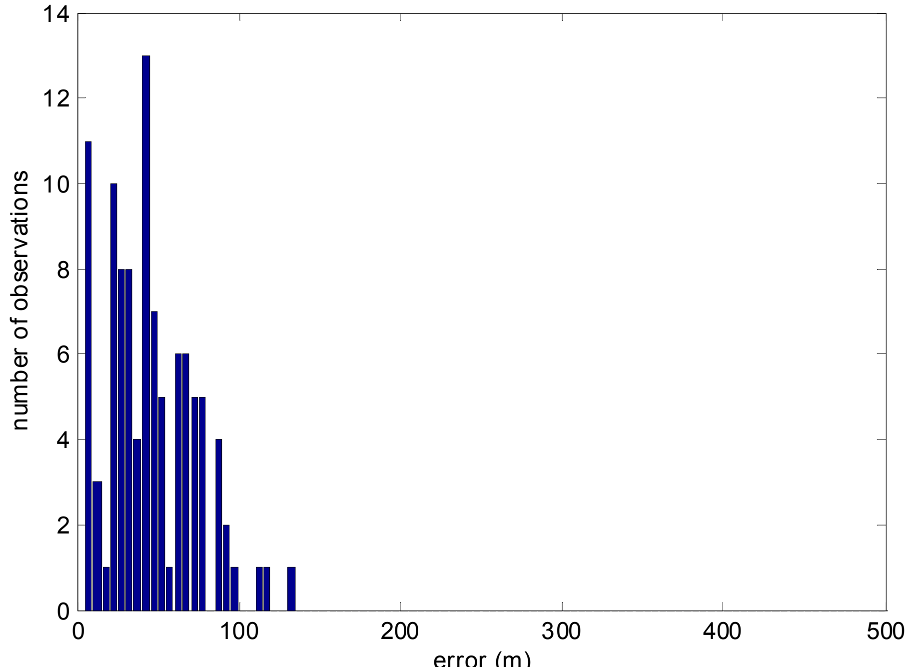


Figure 35 - Large error histogram, UMD AMPS phone, September 24, 2001

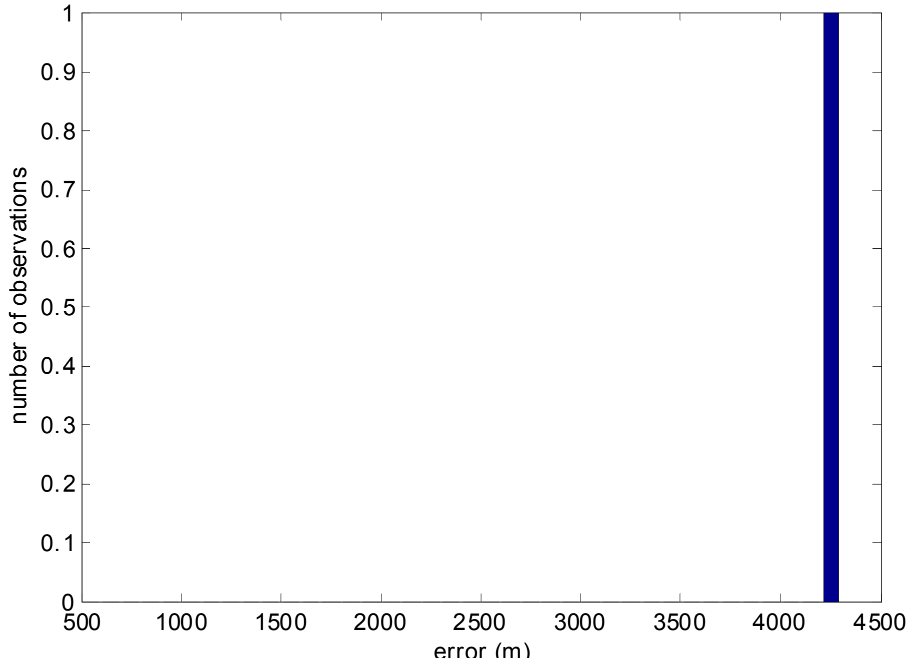
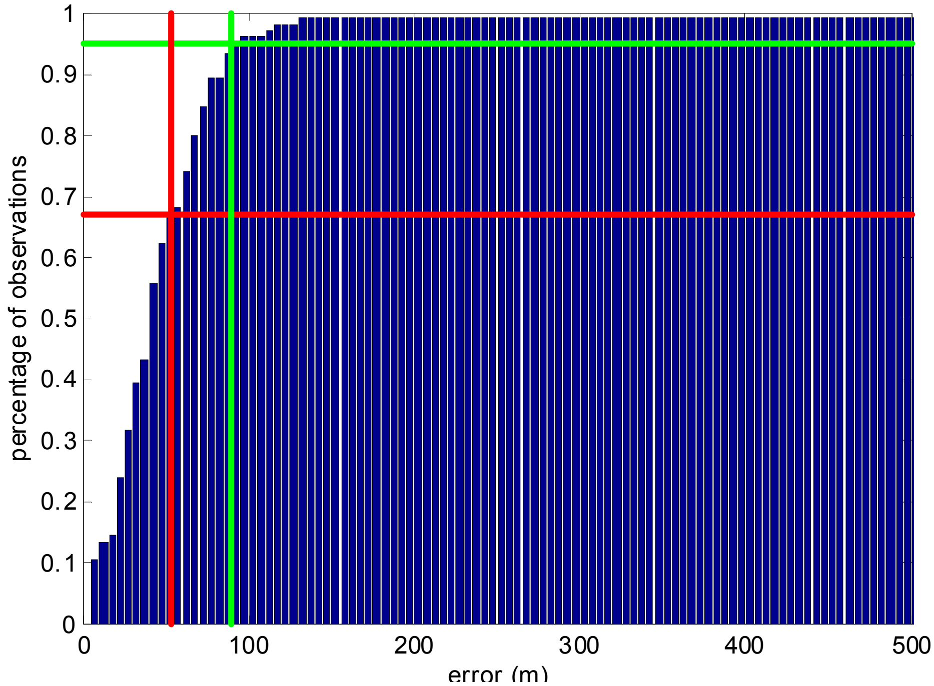


Figure 36 - Cumulative distribution of position error, UMD AMPS phone, September 24, 2001.



8.6.2 TDMA phone

This section describes the results of the test run with the digital protocol of the TDMA phone. The phone was operated by the USWC, and like the USWC AMPS phone, the results provided were limited to successful location record matches.

The USWC TDMA phone received 101 phone calls within two distinct time periods. The first was from 14:08:42 to 15:09:02 and the second from 19:35:05 to 21:04:49. These 101 calls resulted in 838 location records on a 2.5 second time lattice.

Figure 37 shows the data collection map representation for the run of the USWC TDMA phone and Figure 38 shows in more detail the traveled area.

Figure 37 - Data collection map, USWC TDMA, September 24, 2001

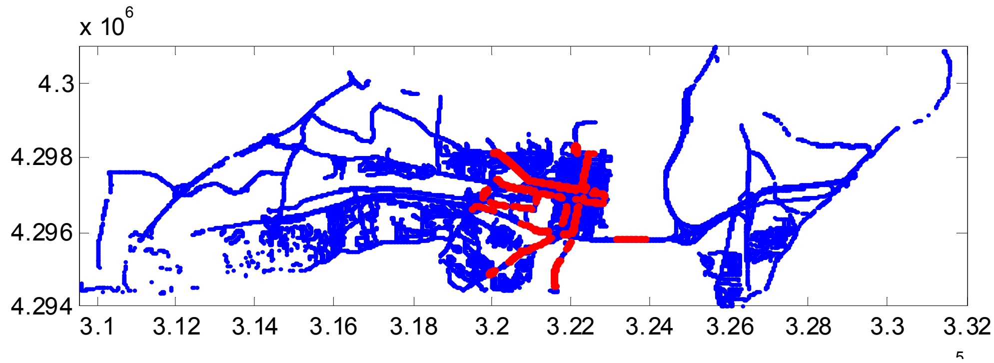


Figure 38 - Data collection map detail, USWC TDMA, September 24, 2001

Figure 39 and Figure 40 shows the small and large error histograms for the data, while Figure 41 represents the cumulative error distribution. The 67th percentile error was 78 meters and the 95th percentile error was 206 meters. Both of these results are substantially within the FCC requirements

Figure 39 - Small error histogram, TDMA data, September 24, 2001

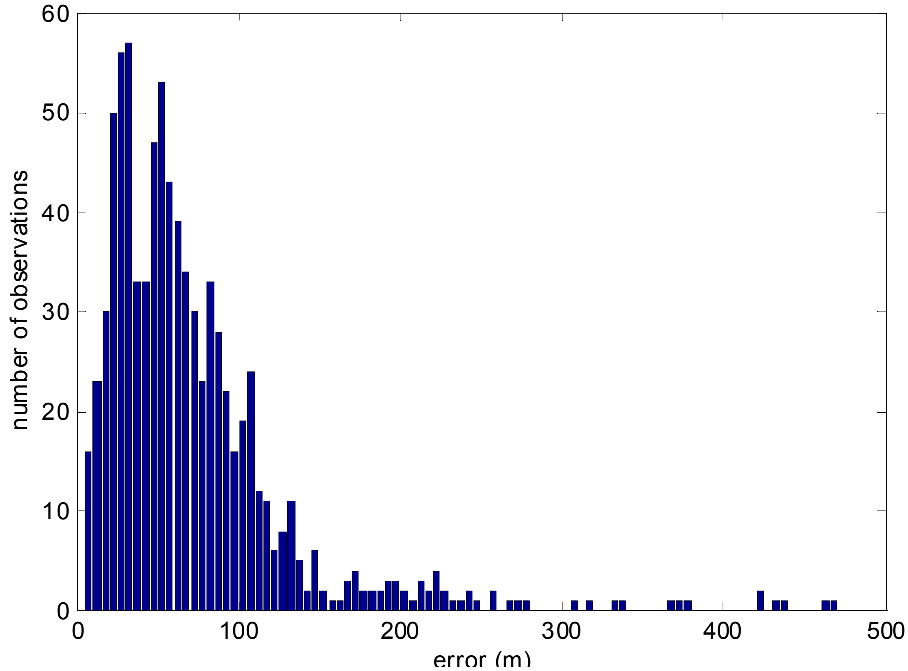


Figure 40 - Large error histogram, TDMA data, September 24, 2001

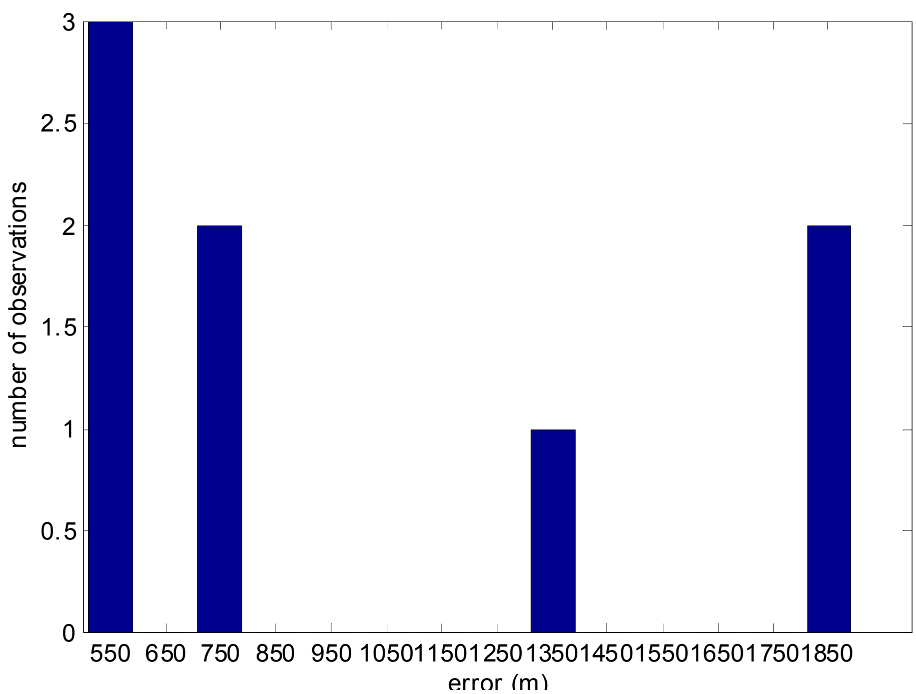
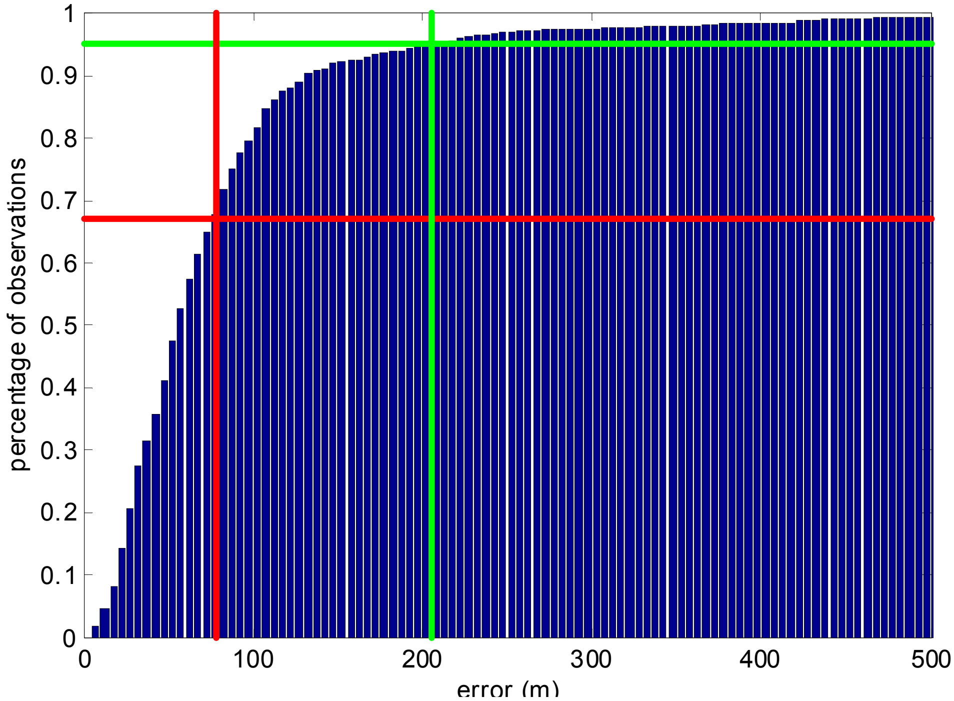


Figure 41 - Cumulative distribution of position error, TDMA data, September 24, 2001



8.7 General Analysis summary and discussion

The general analysis was carried out on several days of data. Table 5 gives a summary of the data for each day and the result of the analysis done.

To the extent that "sufficiently accurate" can be construed to mean compliance with the accuracy requirements of the Federal Communications Commission (FCC) for Extended-911 service, the USWC system tested under this evaluation has the potential to satisfy that criterion. For example, Figure 36 shows the cumulative error histogram for data collected on September 24, 2001, from an analog cellular phone.

This data set includes 104 location records, for which the 67th percentile error was 53 meters, and the 95th percentile error was 90 meters. Both of these are well within FCC guidelines. The mean error was 86 meters, but the maximum error was 4219 meters. Thus, when the system is accurate it is very accurate, but it can also make significant mistakes. If this is a problem with calibration in certain areas of the map, then efforts need to be made to ensure that the area of interest is sufficiently saturated with calibration data, and that a program is in place to evaluate and monitor the quality of the calibration database on a recurrent basis.

Table 5 - General Data summary[5]

	4/2 AMPS	4/19 AMPS	4/26 AMPS	8/6 AMPS1	8/6 AMPS2	9/24 AMPS1	9/24 AMPS2	9/24 TDMA
calls made	16	120	27	62	62		61	
start time	19:16:21	19:53:42	20:08:46	20:16:57	21:16:57	2 periods	17:36:24	2 period
end time	20:07:52	21:26:20	21:03:10	21:59:59	22:59:59	2 periods	19:18:33	2 period
calls recorded	2	23	4	24	19	75	27	101
start time	19:55:52	19:53:54	20:15:14	-	20:11:39	-	17:43:41	-
end time	19:58:43	21:24:57	21:00:31	-	22:00:49	-	19:18:31	-
% call recorded	12.50%	19.17%	14.81%	38.71%	30.65%	-	44.26%	-
location records	10	87	35	138	136	742	104	838
67th percentile	96 m	157 m	96m	122 m	109 m	62 m	53 m	78 m
- within FCC req.	yes	no	yes	no	no	yes	yes	yes
95th percentile	191 m	4381 m	1622 m	631 m	2800 m	132 m	90 m	208 m
-within FCC req.	yes	no	no	no	no	yes	yes	yes

[5] AMPS1 refers to USWC AMPS telephone, while AMPS2 is the UMD AMPS phone

On that same day, data were collected from a digital phone also. While the evaluation was not originally intended to consider digital protocols, they started to become available towards the end of the project, and hence some data were collected. Figure 41 shows the cumulative error plot from the digital data, consisting of 838 location records. The 67th percentile error for this data was 78 meters, while the 95th percentile error was 206 meters. This appears not to be a better result than the analog data provided on the same day; however, there is not enough evidence to make this point convincingly. The analog data from September 24 were the last data collected over many months of system trials; hence there were many opportunities to improve that part of the system. The digital data came from a much earlier part of the respective rollout. Further, the digital data represent a much larger number of location records. This suggests that there are significantly fewer missed location records with the digital data.

9. Dynamic Analysis of Data

In this section we will attempt to answer the question of, if and how, the speed of the probe vehicle affects the accuracy of the location estimates. Selected data acquired from the collection periods between April and September 2001 was used for this analysis. In particular, the TDMA and AMPS data of September 24 was chosen because, as mentioned earlier, they represented the "production" version of the RadioCamera^{TM} system and the data, when compared to those collected on earlier dates, was more complete with respect to the volume of calls and location records. In addition to this, several enhancements were made to the system as a result of earlier experimental findings.

Data from the position accuracy analysis (section xx) was carried over into the speed analysis. The errors in the position estimates were compared to the speed deduced from the data collection effort and inferences were drawn about the comparison. The speeds were calculated between location records by 'inverting' between coordinate pairs to determine the distance traveled between successive call records and subsequently dividing by the 2.5 second time lattice. This gave a good estimate of the instantaneous speed of the probe vehicle.

The bearing was also calculated between successive location records. This helped in the analysis of the data because it helped to verify the authenticity of the coordinates. For example, given the geography of the area and the route that was traversed during the experiments, if the data reflected a 180 degrees change in direction within the 2.5 second time lattice between location records, then one might question the accuracy of that location record.

9.1 Analysis of TDMA data (09/24/2001)

Figure 42 below shows the plot of speeds obtained and the corresponding error in the position estimate for the TDMA data. Figure 43 gives a closer look at the graph with focus on the smaller errors (i.e., position error between 0 and 400m).

Figure 42 - Speed vs. position accuracy (0m to 800m)

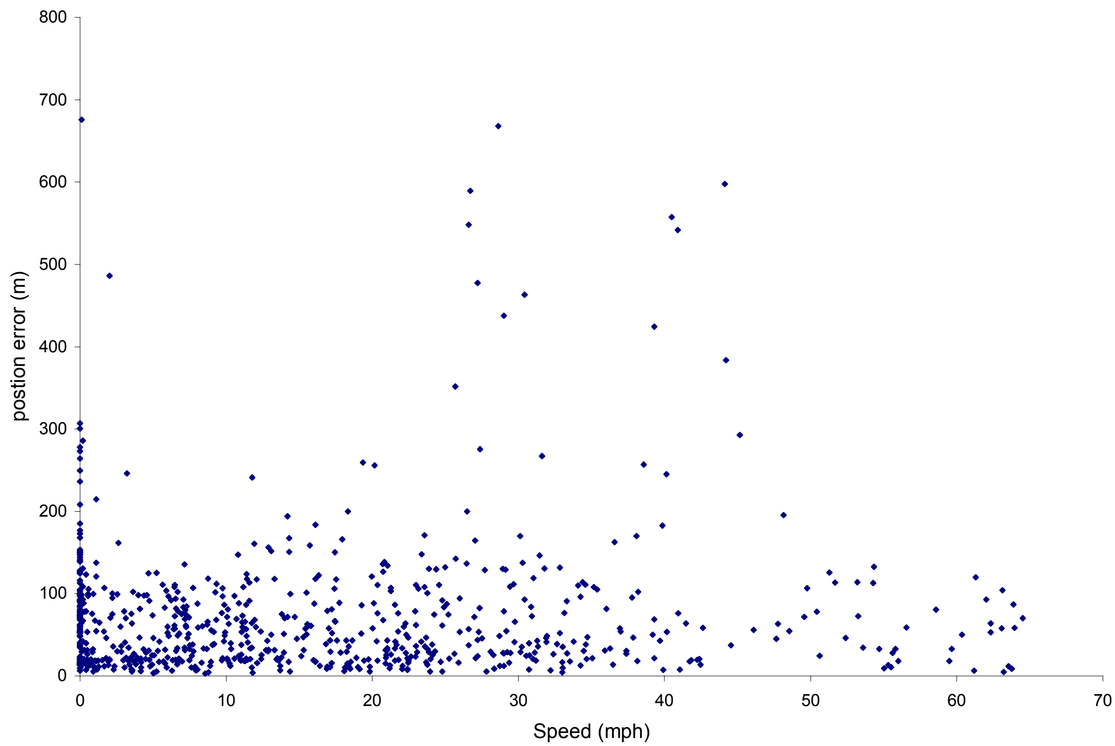
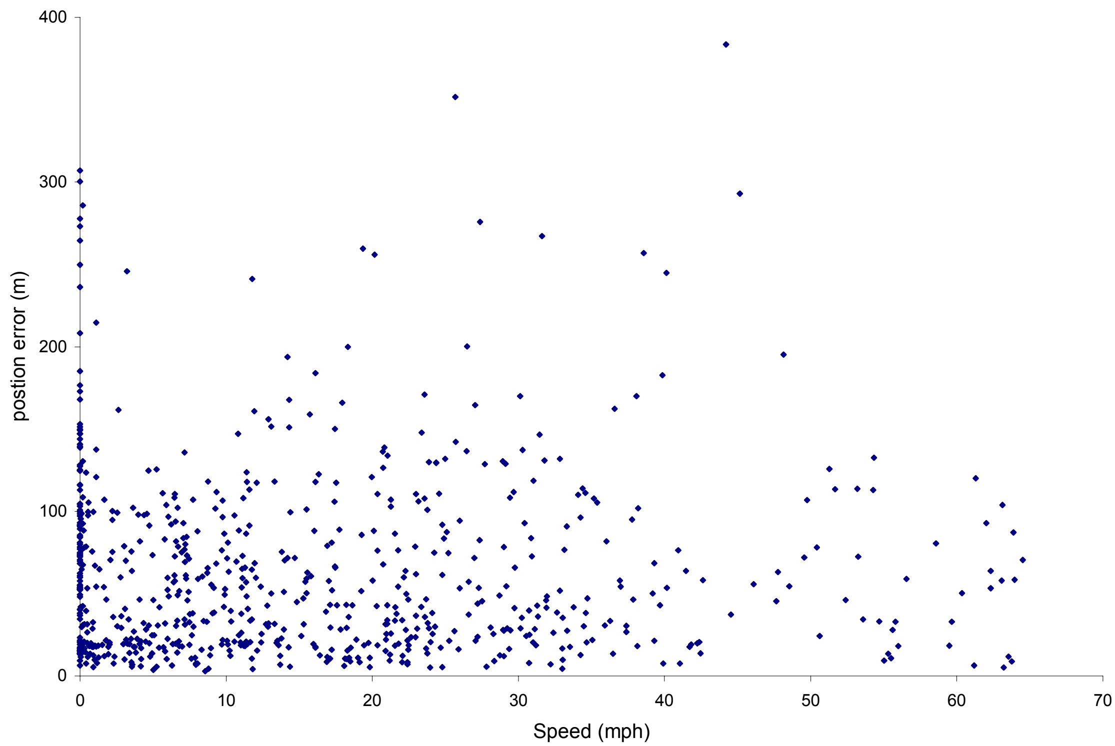


Figure 43 - Speed vs. Position error (0m to 400m)



From the appearance of the plots and the correlation result of -0.0165 (relatively close to zero) between both variables, it seems that there is no evident relationship between speed of the probe vehicle and the position accuracies obtained.

However, it very useful to look at the errors generated over various speed range. To do this we extracted the errors generated while the speed was (1) zero, (2) between 0 and 35 mph, and (3) over 35 mph.

Noteworthy was the fact that over 90 location records were obtained when the probe vehicle's speed was zero. The error histogram of the position errors for the call records with corresponding speeds being zero is showed in Figure 44. The graph is positively skewed, suggesting that the smaller errors were more frequent than larger ones. The cumulative distribution function is shown in Figure 45.

Figure 44 -Error Histogram with speed = 0

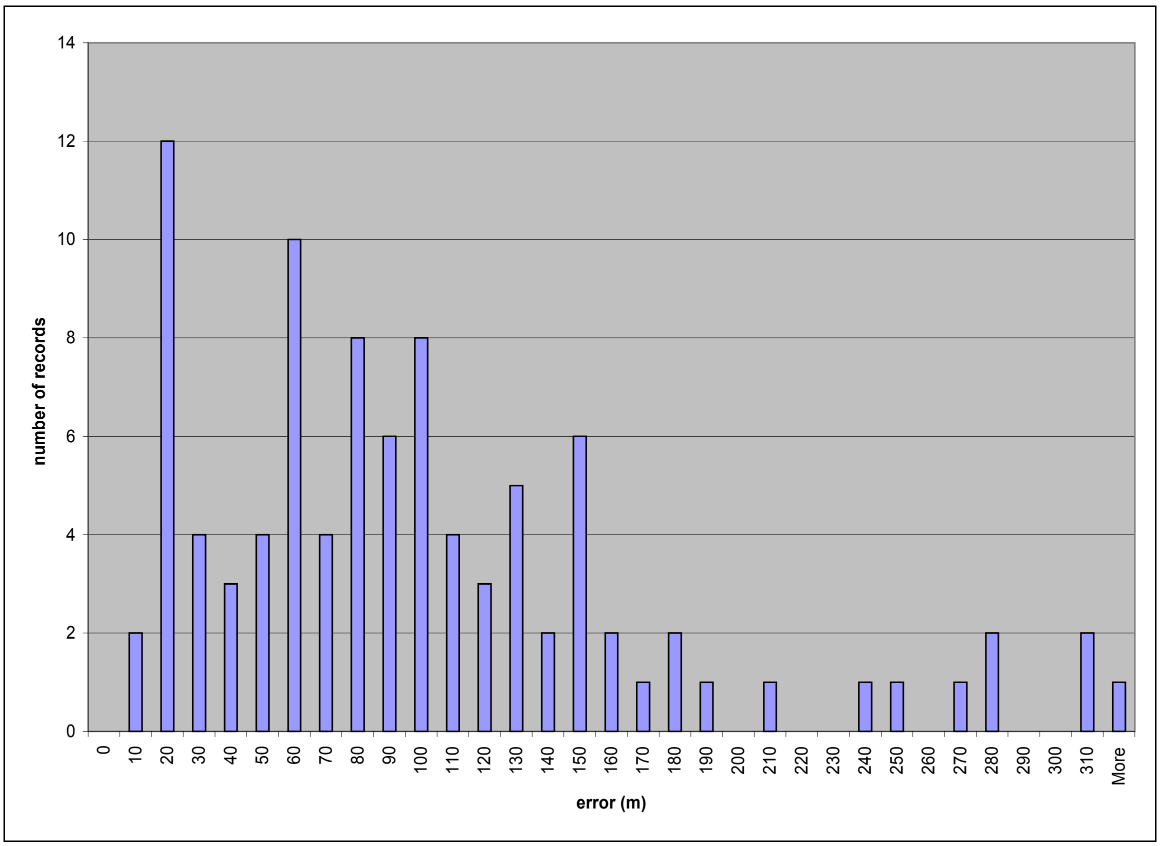
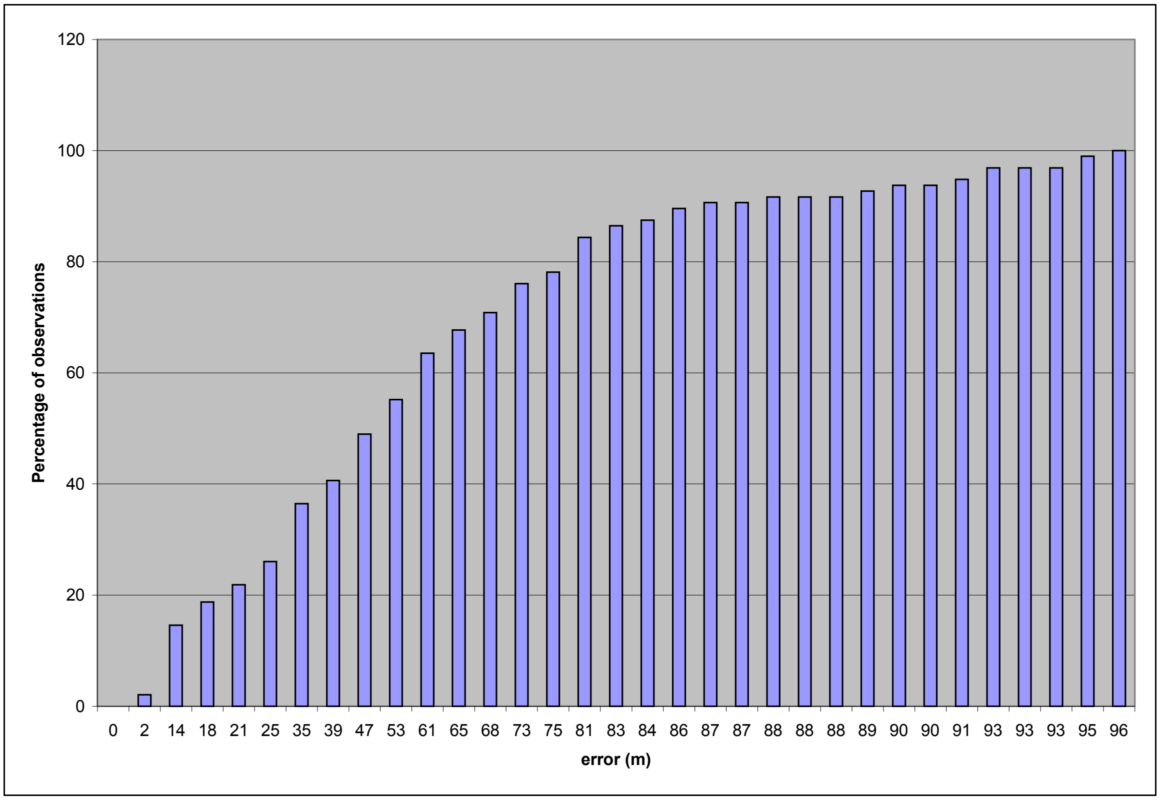


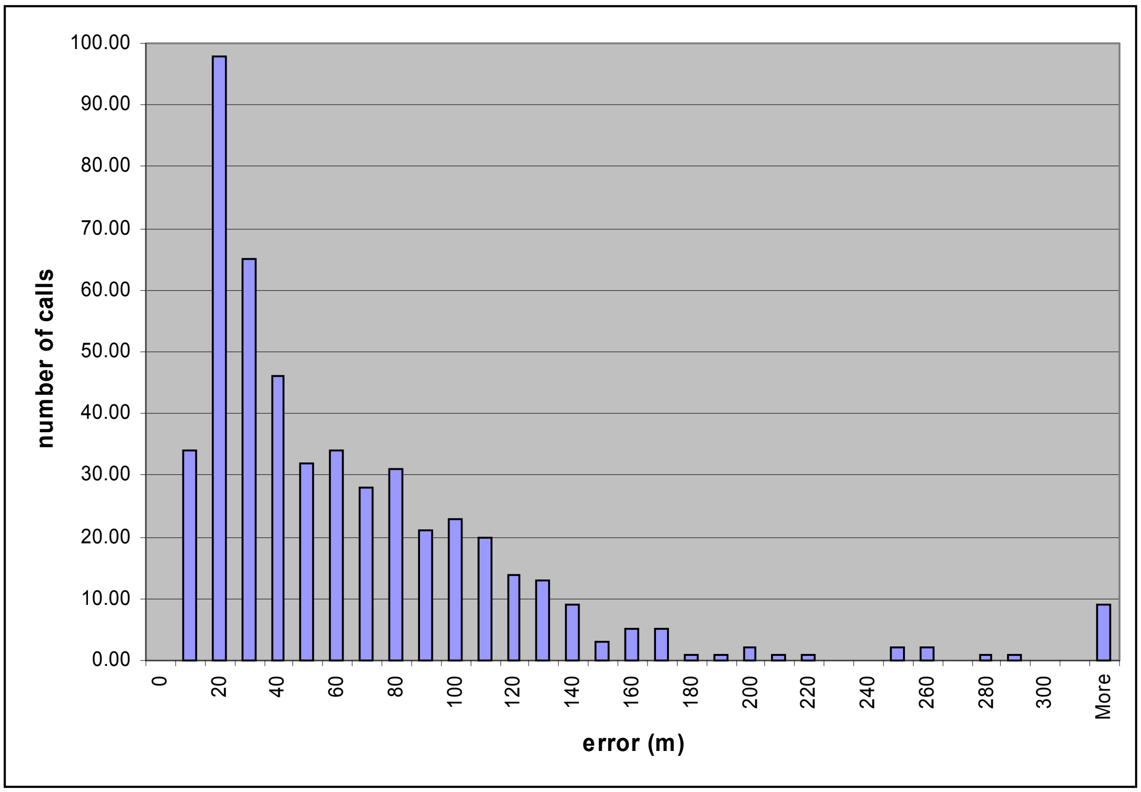
Figure 45 - Cumulative Distribution function (Speed = 0 mph)



The mean error when the speed was 0 mph or when the probe vehicle was at a standstill was calculated to be approximately 116.2 meters. The 67th percentile error for this sample was 104.50 meters and the 95th percentile error was 266.57 meters. While the first is outside the FCC stipulations, the second is in.

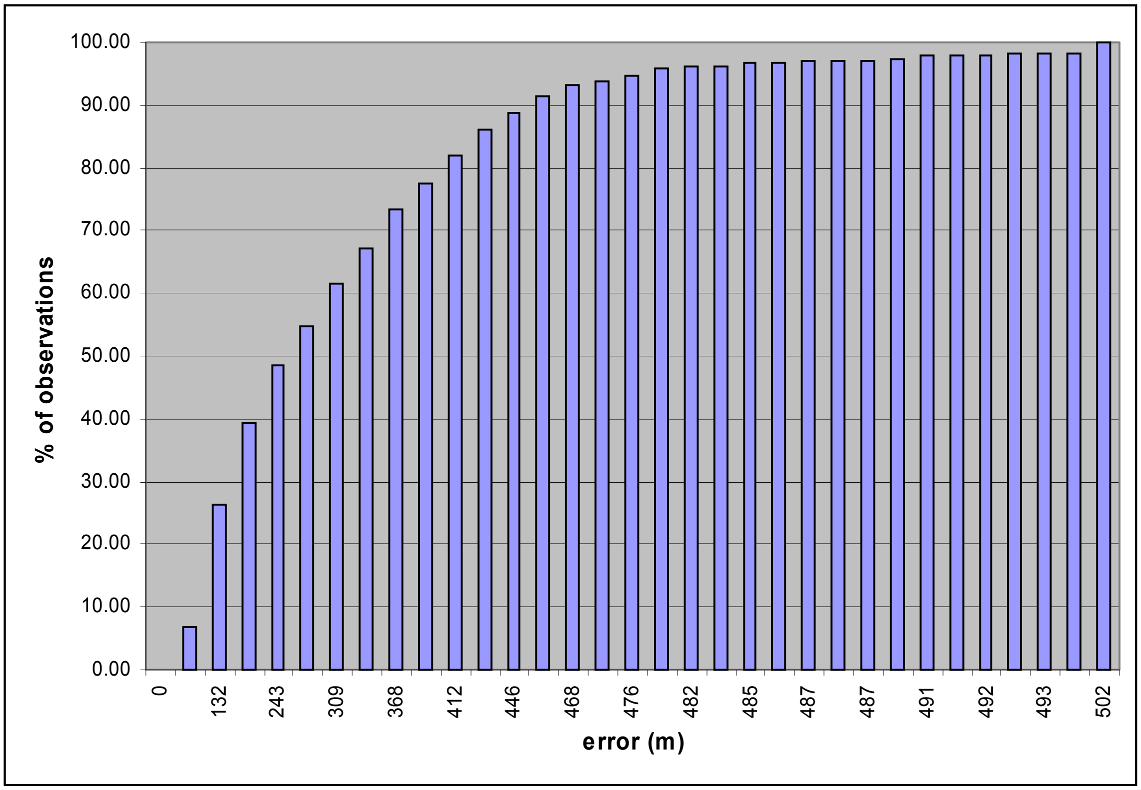
The position errors as it relates to the probe vehicle traveling at speeds between 0 and 35 mph were also observed. Figure 46 below shows the histogram of the position error for vehicles traveling between 0 and 35 mph. Figure 47 is the corresponding CDF. A total of 502 call records were collected with the speed of the vehicle between 0 and 35 mph. This amounts to more than 50% of the call records collected for the TDMA data. This volume of call record was expected because a majority of the roads were city streets with speed limits within this range. The mean error in the position estimates for this speed range was approximately 68 meters, with a standard error in the mean being 5.5 meters.

Figure 46 - Error Histogram with speed between (0 and 35 mph)



This error histogram again was asymmetric and positively skewed. Only a few calls had error greater than 160 meters. The 67th percentile for the error was 69.37 meters, while the 95^{th} percentile error was 160.72 meters. Both results were encouraging because they were well within the FCC requirements.

Figure 47 - CDF of errors (speed between 0 and 35 mph)



A total of 132 location records were generated while the speed was above 35 mph. Figure 48 and Figure 49 represents the histogram and Cumulative distribution function for errors generated while traveling at this speed. The histogram was again positively skewed with smaller errors occurring more frequently. The mean error was approximately 84.03 meters. The 67th and 95th percentile error was 77.67 meters and 278.69 meters respectively. Both of these were within the FCC requirements.

Figure 48 - Error Histogram with speed above 35 mph

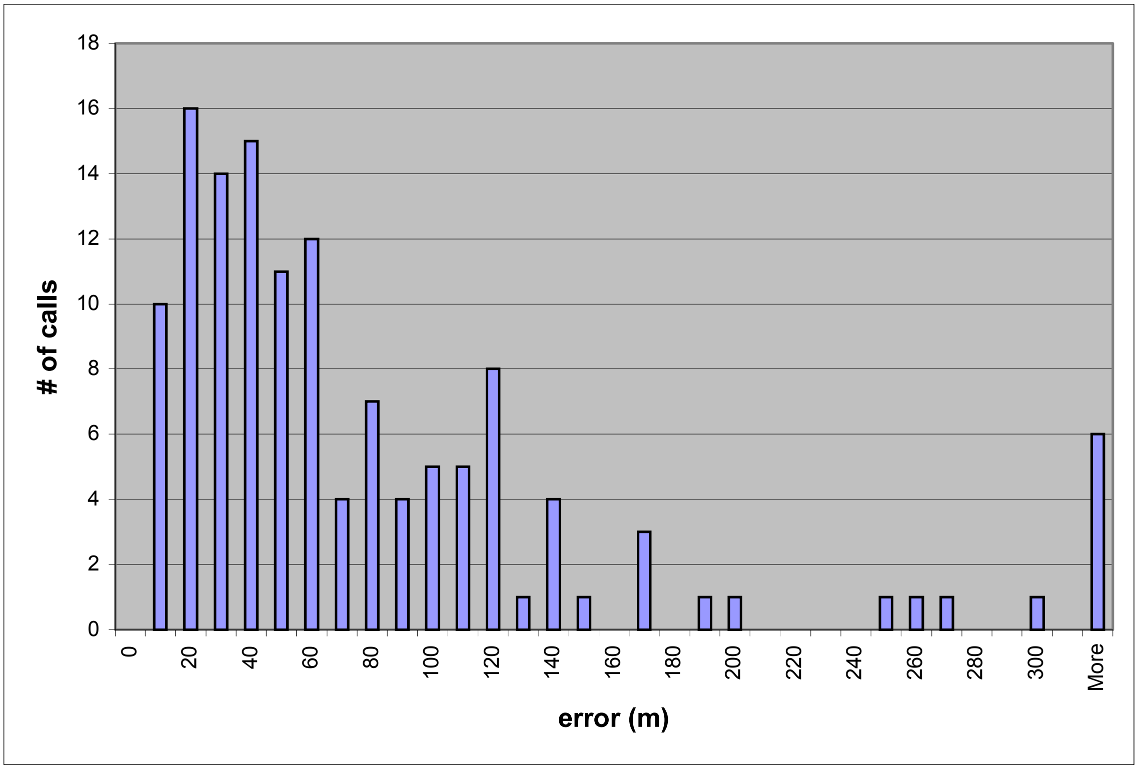
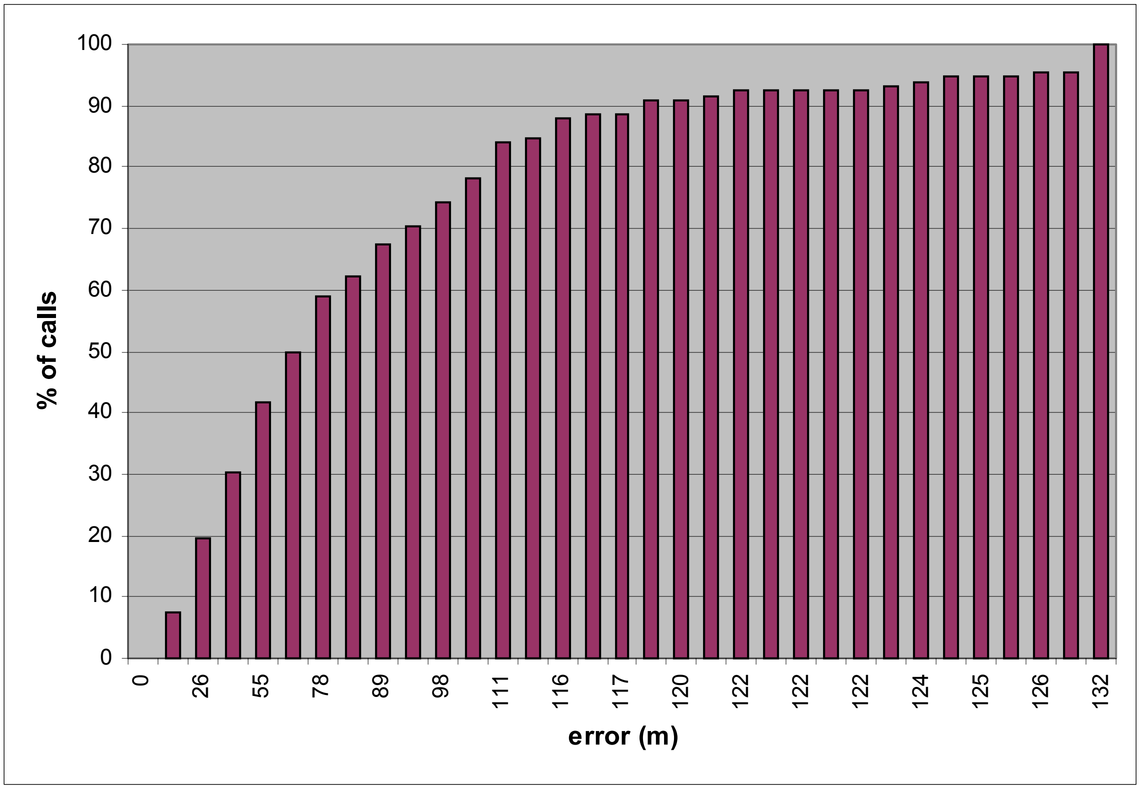


Figure 49 -CDF or errors (above 35 mph)



9.2 Summary of Dynamic Analysis

The speed analysis involved looking at the accuracies while the vehicle traveled at different speed ranges: 0 mph (or standing), between 0 and 35 mph – the expected speed within an urban setting, and over 35 mph. Table 6 summarizes the data and the results.

It is obvious again that the RadioCamera™ system has the potential to obtain accuracies stipulated by the FCC. However, it is also clear that there are instances where the system is unable to get results that fall with the FCC requirements.

Table 6 - Speed analysis summary

Speed	67th percentile	95th percentile	Mean
0 mph	104.5 m	266.57 m	116.2 m
between 0 and 35 mph	69.37 m	160.72 m	68 m
above 35 mph	77.67 m	278.69 m	84.03 m

Figure 42 and Figure 43 gives strong indication that there is little or no correlation between accuracies and the speed the vehicle travels. In fact, while the vehicle assumed a stationary position the errors in the position estimation did not fall within the acceptable range for the FCC. This result is not very revealing. One might be lead to believe that the performance of the system that is not moving should be significantly better than if it was moving. However, the RadioCamera™ system is believe to work better if it was moving because of its Kalman filter, a recursive algorithm, which allows predicted estimates of the position to be made based on previous estimates. What this means is that if the vehicle remains at a position with an initial position that is in error, then chances are the system will not be able to correct itself. This will be looked at in further details later.

While traveling at the speed expected for urban areas (0 and 35 mph), the RadioCamera™ showed that it was more than capable of getting the results the FCC required. Additionally, for the above 35 mph speed range, the system was favorable for the 67th percentile, but was way off for the 95th percentile.

10. Geo-Spatial Analysis

With evidence indicating no correlation between speed and accuracy, it is necessary to do a spatial analysis to determine if the geography of the area or instrumental errors are factors. As explained in earlier chapters, various location systems have positioning error biases that are based on the geographic location. For example, significant reduction in accuracy of GPS position estimates may result in locations with a high concentration of high-rised buildings and other obstructions that can cause a blockage of the GPS antenna. In this chapter, the focus lies on determining whether or not geographic location affects the accuracy with which the RadioCamera™ system makes estimates of the 'true position'.

Geographic information system (GIS) was primarily used in the spatial analysis. GIS enables you to model and analyze geographic data to identify relationships and trends that would not otherwise be apparent in the previous analyses.

For this particular analysis, ArcView GIS 3.3 was the software chosen for a couple of reasons. First, for a geospatial analysis to be conducted, a coordinated street map of the study area, in Northern Virginia, was necessary. This would enable coordinates that were derived from the RadioCamera™ system to be overlaid unto street maps. Such maps of Virginia were available from the GIS-Cartography section of Virginia Department of Transportation (VDOT), and were compatible with AcrView 3.3.

The second reason lies in the functionality of ArcView. ArcView makes it easy to create maps and add your own data to them. It allows one to see patterns you could not see before, revealing hidden trends and distributions, and gaining new insights. In addition to this, the software has a projection utility that is appropriate for the data and analysis for the data. The projection utility supports an extensive array of projections as well as datum conversions which are very vital for the proper overlaying of points on the map.   The ability to write executable scripts to automate many processes is also a key element in ArcView.

10.1 Method of analysis

Since the objective of this analysis is to find spatial patterns in the accuracy of the data, one simple way of doing this involves representing the coordinate data on a map. To ascertain the accuracy of the map and likewise the GPS system being used both the GPS data and the road map were superimposed on a single map. This was necessary because both and the street map provided by VDOT and the coordinates from the GPS system were used as 'ground truth', for spatial and statistical analyses, respectively. However, before this was done, it was necessary to project both pieces of data to a single projection, and likewise datum. Both the GIS road maps and Geodetic coordinates (latitude and longitude) obtained from the RadioCamera™ system were projected using the Universal Transverse Mercator (UTM) projection and the North American Datum of 1983 (NAD83).

After the geodetic coordinates were projected to UTM using the excel worksheet (discussed earlier), they were then converted to a shape file[6] using the GPS2shape.ave script in ArcView. This script was executed using the avenue compiler in ArcView and allowed the coordinate pairs to be plotted as points. After this plot was achieved, the data was then projected using the UTM and NAD83 datum.

The ArcView road map was also projected from the original Lambert Conformal Conical projection to the UTM and NAD83 datum. This was done using the projection utility of ArcView GIS. Figure 50 shows the map of part of Northing Virginia, produced using ArcView GIS. The points represent the tracks of the probe vehicle.

From Figure 50, it becomes obvious that the GIS road map and the coordinates obtained from the GPS are well-matched. This is a good indication that both data sources are fairly accurate and may be used as ground truth. The GIS-Cartography section of Virginia Department of Transportation (VDOT) indicated that the accuracy of the road map is with 6 to 12 feet range. The GPs system, as indicated, is capable of results with accuracy 15 ft and less. The center lines of the roads are represented on the maps – A close observation of Figure 50 will reveal that the GPS points lies on either side of the center lines, depending on the direction of travel. This is another good indication of the accuracy of both data sources.

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[6] ArcView native spatial data format

Figure 50 – Map of Part of Northern Virginia Showing Probe vehicle tracks as recorded by GPS

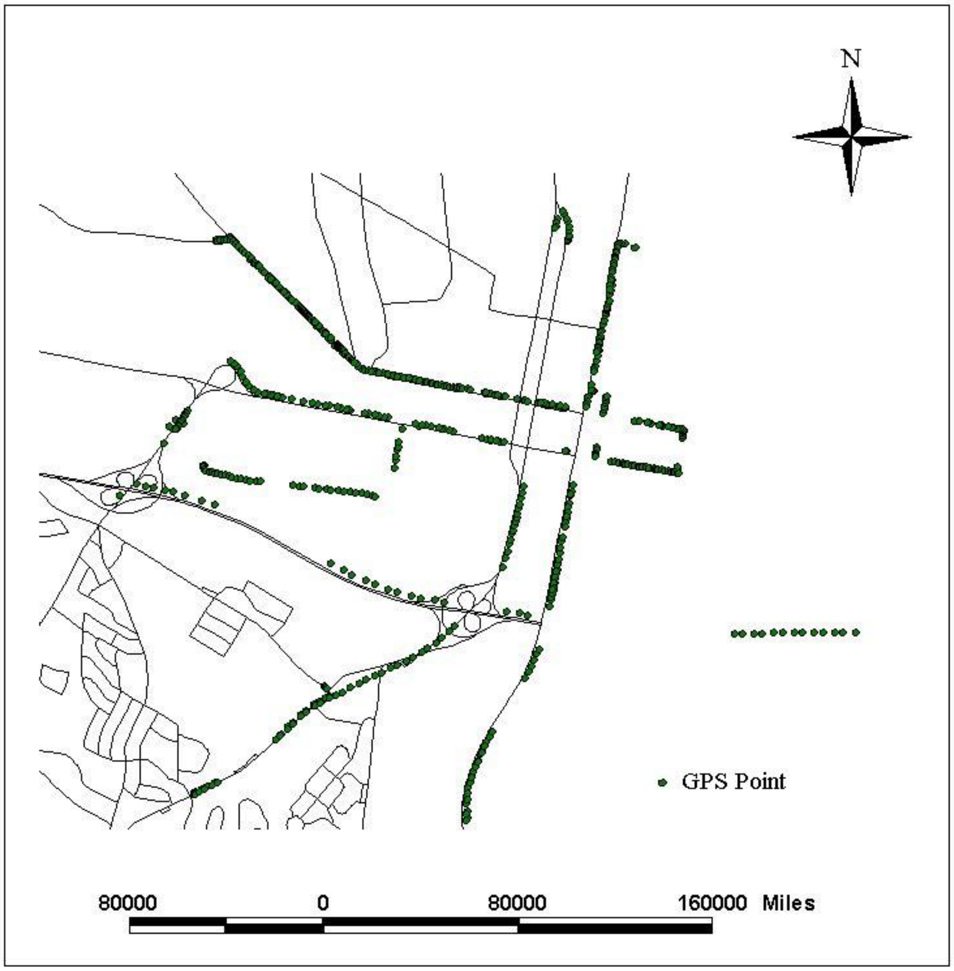


Figure 51 shows a map of part of Northern Virginia with data points of GPS and TDMA coordinates plotted unto it, while Figure 52 shows the same with GPS and AMPS data of September 24, 2001. Both figures have areas where data points are seemingly clustered. This is the combined effect of continuous errors in estimates of probe vehicles position by the RadioCamera™ system, in addition to the probe vehicle traversing the roadway several times during the experiment.

Figure 51 - Map of part of Northern Virginia - showing GPS and TDMA coordinates of 09/24/2001

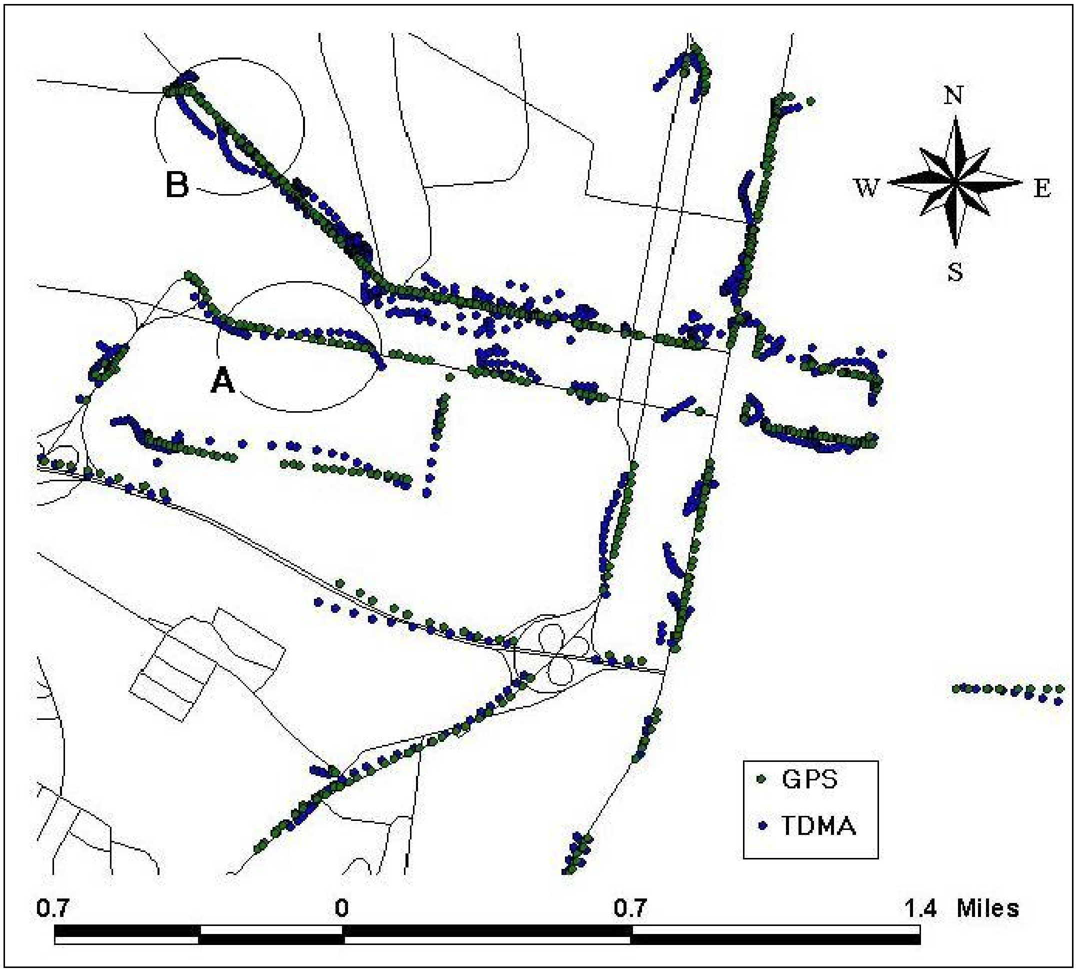


Figure 51 and Figure 52 also reveal several distinct patterns of the data – for both TDMA and AMPS. The circled regions, A and B on both figures, point towards areas where the both the TDMA and the AMPS records have produce coordinates that forms a curved path, which is in stark contrast to that of the road network and the path of travel indicated by the GPS.

Figure 52-Map of part of Northern Virginia - showing GPS and AMPS coordinates of 09/24/2001

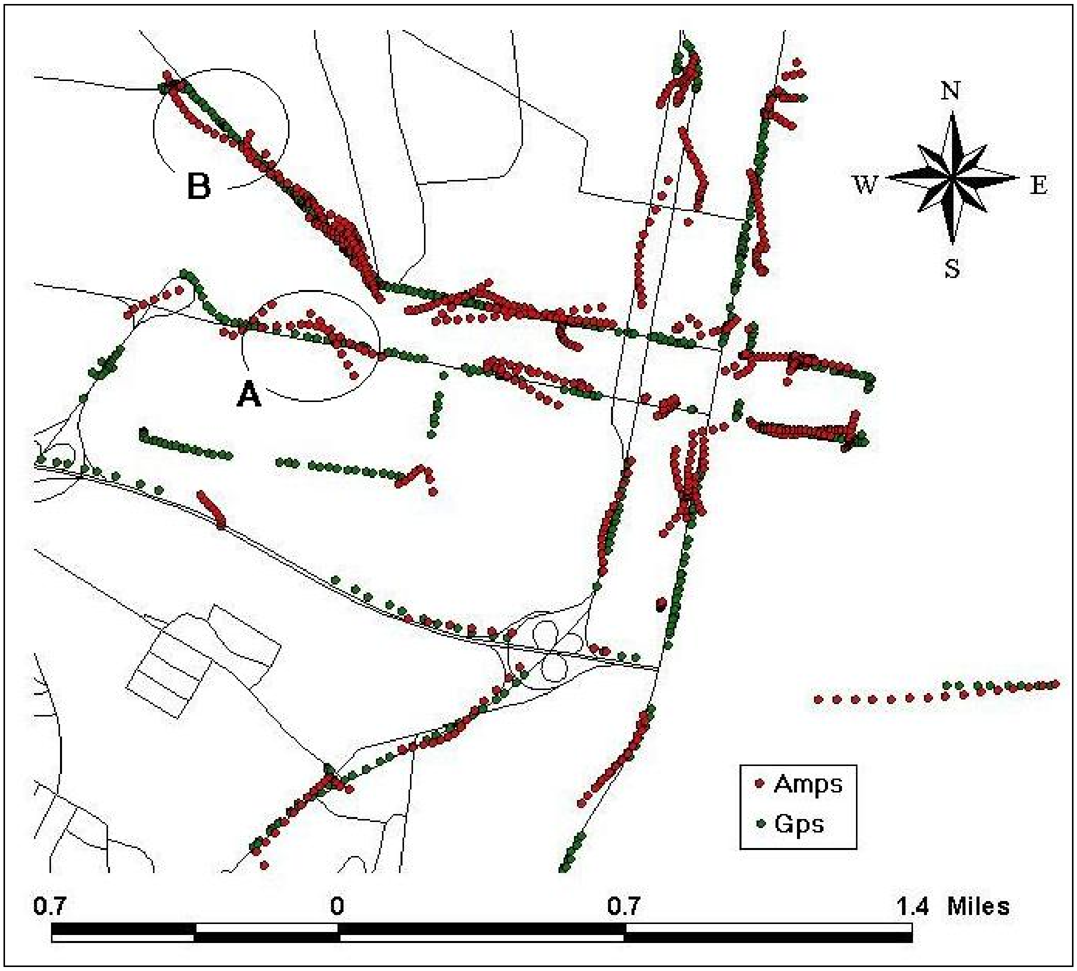
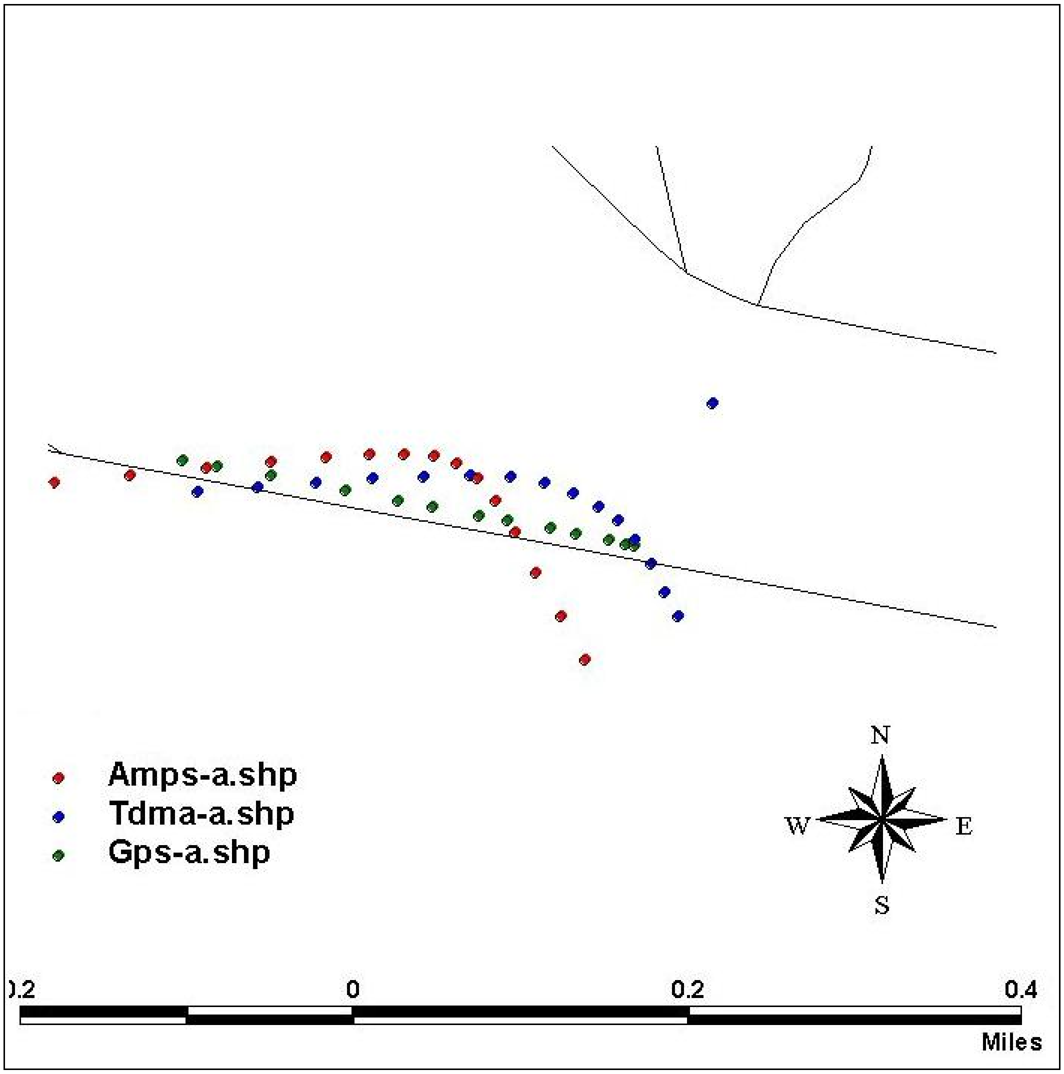


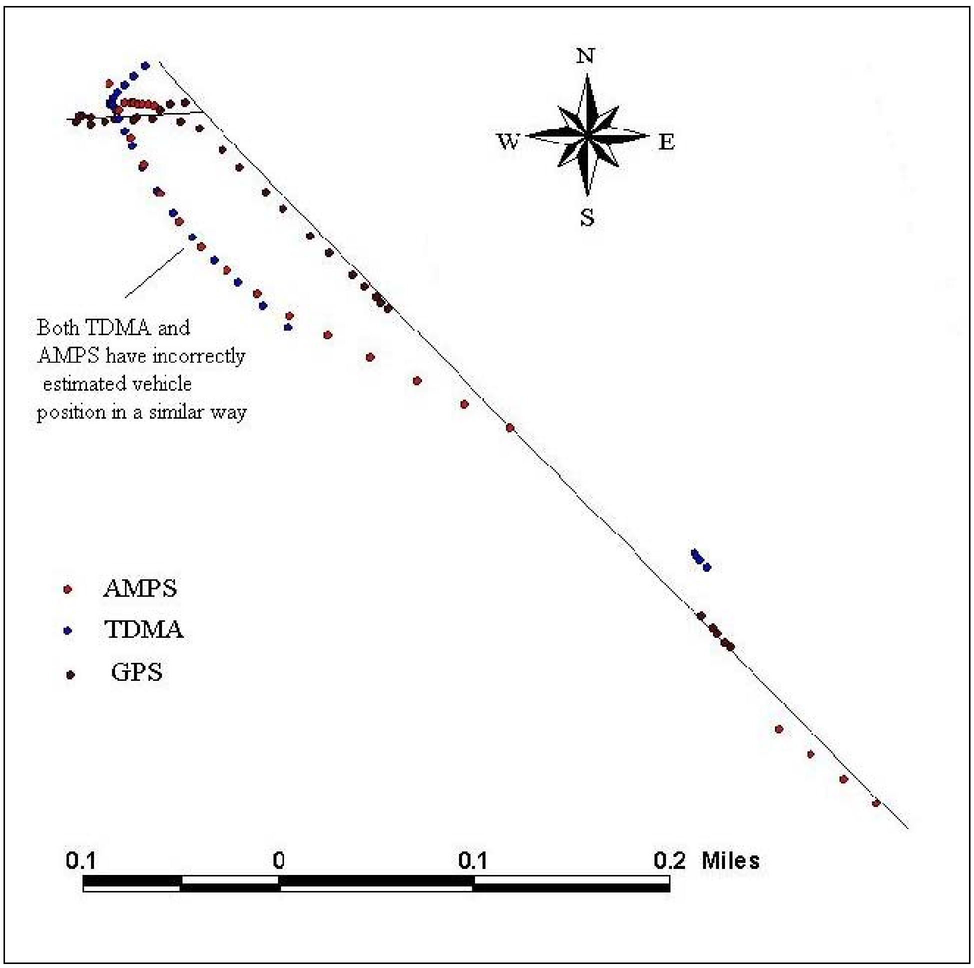
Figure 53 shows a more detailed picture of region A. While the GPS follows the pattern of the roadway, both the TDMA and AMPS estimates follow curved paths. A statistical analysis of the points was done for this region. A different approach was used to determine if there was a bias in the estimates of the position. The northing and easting of GPS were compared to the northing and easting (respectively) of both the TDMA data and the AMPS data. The error in the northing and easting for both sets of data was tested for correlation. It was found that the correlation in the northing error between the TDMA –GPS and AMPS-GPS was 0.22781458, while the correlation in the easting error between the TDMA –GPS and AMPS-GPS was 0.672179309. This shows some correlation between the errors of the TDMA data and the errors of the AMPS data, and suggests that there might be errors in the data base of the RadioCamera^{TM} system.

Figure 53 - Region A - Showing path of TDMA and AMPS vs. GPS



Additionally, Figure 54 gives a more detailed look at encircled region B. It can be seen that both the TDMA and the AMPS replicated similar paths, which are seemingly incorrect if the roadway is being considered. While the GPS follows the path which is in alignment with the roadway. Furthermore, after a data query was done on the points, it was also revealed that the path of the TDMA and that of the AMPS, were apparently at different times, and direction of travel in each case was different. The TDMA position estimates were made when the vehicle was heading in a northeasterly direction, while the AMPS data was collected when the vehicle was headed in a southeasterly direction – and along the same path. This is good indication that there might be a systematic error or problem with the RadioCameraTM, because both estimates were made at different times and in two different phone systems.

Figure 54 - Region B - Showing path of TDMA and AMPS vs GPS



Although the RadioCamera^{TM} system uses to its advantage the multi-path of radio waves, this might also be the problem in this spatial analysis. Although it is not very evident from the map, the area being studied is not one which has a lot of high-rised buildings and other obstacles that may promote a 'multi-path' travel of radio waves. According to Yim (2003), the technology works well if muti-path variations are high; if multi-path variations are low, it doesn't work. Further statistical study of the data for region B could not be done because, although the points overlapped in location, they were not corresponding in time.

10.2Kalman Filter

One possible explanation of degraded performance as indicated by the curved paths along a relatively linear roadway is data filtering (Figure 51 and Figure 52). A data filter is a software algorithm that attempts to filter out or correct data that are judged to be in error (Franklin et al., 1994). The well known Kalman filter is used with the RadioCamera^{TM} to help to predict the position of vehicle. In simplest terms, the Kalman filter considers the most recent computed positions to estimate where the next position should fall. If the new point does not fall where expected, the algorithm would assume that it is in error and adjust or scale the new location accordingly. This completes a three step process of defining the vehicle position: prediction - the computation of the expected position of the vehicle at some subsequent time, t_k based on the last measurement, t_{k-1}; filtering – the process of computing the vehicle's position in real-time (observation at time, t_k and position estimates required at time t_k; and smoothing - the estimation of where the vehicle was at say time, t_k once all measurement are post processed to time t_{k+1} (Drane and Rizos, 1998)

While the use of data filtering is necessary to reduce errors in vehicle tracking, if the algorithm used is not fitting for the kinematic model then error might be introduced. One simple example to show where a filter effects become especially evident is when a moving receiver (or transmitter as the case may be) makes an abrupt turn (Figure 55). The filter expects the receiver to be continuing on the original path and applies "corrections" to the first several points after the turn. Depending on the nature of the data filter, it may take many data points for the algorithm to settle to the desired path once again.

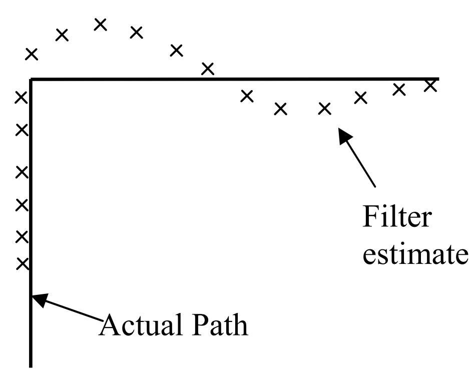


Figure 55 - Effects of filtering

Kalman filters are very dependent on the data fed into them. Essentially, they are governed by the Garbage-In-Garbage-Out (GIGO) rule, which means that if there is an error in the assumption regarding the model or if the input data is questionable, the position results could be highly biased (Drane and Rizos, 1998).

This dependency of the Kalman filter on accurate data can be detrimental to the RadioCamera™ system. Because the system is very susceptible to changes in the landscape, this could also seriously affect the operation of the filter used to predict position. If the database is in error, then all estimates of position based on this database error could be way off.

11. Summary and Conclusion

In this thesis the objective was to determine the suitability of the positioning capabilities of the cellular phone for tracking vehicle, or vehicular fleet. In so doing, the accuracy assessment scheme used in this thesis may be mirrored as an effective method of evaluation for future emergence or continued work on these location systems.

Three separate analyses were done on the data. First, a general test of the accuracy was employed. This involved determining the accuracy of the coordinates produced by the RadioCamera™ – all things being equal. Factors such as speed and location, which are looked at in later chapters, were not considered in this analysis. Several days of data were looked at in this section. Error histograms, cumulative distribution functions, as well as correlation coefficients were calculated and plotted to determine the trend in the position estimates. The results of the general analysis showed that the RadioCamera™ has the potential to obtain 'sufficient' accuracy for the FCC requirement and, by extension, vehicular tracking. However it also indicated that the system had inaccuracies well outside the range of the FCC requirements. At times, the system had errors of above 4000m. This means that the when the system is on point, it is on point – but when it is inaccurate – it can be by a very large amount

The second analysis took into consideration the speed with which the probe vehicle was traveling at the time of the position estimate. The speed was broken down into, more or less, three ranges: 1) when the vehicle was in a stationary position

– the speed was zero; 2) when the vehicle was traveling between 0 and 35 miles per hour, and 3) when the vehicle traveled at speeds greater than 35 miles per hour. Various error histograms and cumulative distribution functions for range specific speeds were plotted and correlation analysis done. The errors in position estimates were analyzed in these ranges and no correlation was evident between the speed of the vehicle and the errors generated for position estimates.

The third analysis was aimed at identifying, through spatial means, some of the sources of errors in the earlier general analysis. Two likely sources of errors were identified and discussed. First, from the maps and the plot of the points through GIS, it is believed that the database of the RadioCamera™ system might be in error. This deduction was made as a result of the deviation of the TDMA and AMPS points from the 'ground truth', in this case - the GPS and the road map.

A second probable source of error identified after spatial studies of the GIS generated maps was the Kalman filter used by the RadioCamera™ system. Incorrect calibration of the filter, in addition to possible errors in the database is believed to have caused the many curved paths taken by the TDMA and AMPS data points. This is in contrast to the fairly linear roadways.

Concluding from the analysis, the RadioCamera™ shows good potential for vehicle tracking and may be regarded as a feasible solution. As tested, the system was able (at times) to achieve the FCC requirements (used as the metrics in this case), but was unable to do this with a level of consistency, which would deem it outright ready. Instrumental errors, such as the database or filter might be the areas to look at if the system were to be improved to a level fitting for vehicular tracking.

The process of analysis used to arrive at this sequitur could be used to analyze other systems of this nature. The process involves doing a general analysis of the errors in the position estimates to determine trends in the data and an overall ‘goodness’ of the data. If this analysis proves that the accuracy was, without doubt, acceptable and within range, and requires no further improvement, then the other analysis might not be necessary. If however it is found that the accuracy is questionable, as was the case of the RadioCamera™ system evaluated in this thesis, it stands as good reasoning to do both a dynamic analysis, as well as a spatial analysis.

In the dynamic analysis, one would look do statistical analysis on the data to determine if there is any relationship between the errors generated and range-specific speeds. Different speed ranges may be specified depending on the speed variation of the probe vehicle and/or the likely speed range that the system will be deployed and operated.

The third analysis is the spatial analysis. The importance of this analysis is evident in this thesis, as it allows information, which is not otherwise covert in other analysis to be revealed. In the spatial analysis, one would look for patterns in the errors, and note areas where errors are most frequent and the reason for these errors. In particular, one should look for areas where the coverage of the system may be limited, in addition to areas where the system calibration may be at fault.

11.1 Further work

One area of further work that is beyond the scope of this thesis and worth looking into is the data filtering aspect. It is very likely that a combination of an erroneous database and the configuration of the Kalman filter used for the RadioCamera™ position predictions may have been the cause for the smooth wave-like patterns depicted in the TDMA and AMPS data. A test of the database would first be necessary, as it is a known fact that the output from Kalman filters is input dependent. The input in this case would be points predicted by the RadioCamera™ itself, which, according to the results of our analysis, is not consistent.

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