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# An Investigation into the Feasibility of using Hybrid GPS/CDMA Signal Processing Techniques for one-meter Accuracy Indoor Geolocation

Nicole Brousseau and Geoffrey Colman

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# An Investigation into the Feasibility of using Hybrid GPS/CDMA Signal Processing Techniques for one-meter Accuracy Indoor Geolocation

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**Defence Research Establishment Ottawa**

Technical Memorandum

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# Abstract

This technical memorandum presents the concepts of an indoor geolocation system providing an accuracy of one meter, in real time, for the tracking of as many as twenty people. In the scenario that we are considering, the people to be geolocated are collaborating and are willing to carry special equipment. Such a system could be used, for example, to track firemen working inside a burning building. This type of application requires that the equipment carried by the people be light, portable, of a small size, very rugged, highly reliable and with low power consumption. The geolocation system, as a whole, should provide one-meter accuracy, reliable measurements and real time position updates a few times per second.

The design is inspired by a few features of both the Global Positioning System (GPS) and the IS-95 Code Division Multiple Access (CDMA) that have been modified and integrated to fulfill the requirement of indoor geolocation. The design of the main features of the system and discussions of the way these features are expected to overcome the difficulties inherent to indoor geolocation are presented. The critical issue of distinguishing between a LOS and a multipath signal has been reviewed and many techniques have been ruled out. However, a contract was issued for further studies on the possible utilization of the Doppler effect to perform that task. A proof of concept experiment that could demonstrate the feasibility of indoor geolocation to a precision approaching one meter is also proposed.

# Résumé

Ce memorandum technique présente le concept d'un système capable de déterminer, en temps réel, la position à l'intérieur d'un édifice de jusqu'à vingt personnes avec une précision d'un mètre et de les poursuivre. Les gens dont on veut établir la position collaborent et portent, à cet effet, de l'équipement spécialisé. Un tel système pourrait être utilisé, par exemple, pour poursuivre des pompiers travaillant à l'intérieur d'un édifice en feu. Ce type d'application exige que l'équipement transporté par les personnes soit léger, portable, de petite taille, très robuste, extrêmement fiable et qu'il consomme peu d'énergie. Le système devrait fournir une précision de un mètre, des mesures fiables et une mise à jour des positions quelques fois par seconde.

Le design s'inspire de quelques éléments du Global Positioning System (GPS) et du système IS-95 à Accès Multiple par Répartition de Code (AMPR) qui ont été modifiés et intégrés pour satisfaire aux exigences de la détermination de la position à l'intérieur. Ce document présente le design des principaux éléments du système et une discussion de la façon dont ces éléments pourront surmonter les difficultés inhérentes à la détermination de la position à l'intérieur d'un édifice. Plusieurs techniques pour différencier un trajet direct d'un trajet réfléchi ont été revues et éliminées. Cependant un contrat a été émis pour une étude supplémentaire sur l'utilisation possible de l'effet Doppler pour effectuer cette tâche critique. Une expérience qui pourrait valider le concept présenté pour déterminer la position à l'intérieur d'un édifice avec une précision approchant un mètre est aussi incluse.

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# Executive summary

The MCEW Group has recently been challenged to design an indoor geolocation system to provide a precision of one meter, in real time, for the tracking of as many as twenty people. In the scenario that we are considering, the people to be geolocated are collaborating and are willing to carry special equipment. Such a system could be used, for example, to track firemen working inside a burning building. This type of application requires that the equipment carried by the people be light, portable, of a small size, very rugged, highly reliable and with low power consumption. The geolocation system, as a whole, should provide one-meter accuracy, reliable measurements and real time position updates a few times per second.

The high precision geolocation of indoor co-operative mobiles is a difficult problem. The high absorption of microwaves by the structures and content of buildings and the presence of multipaths are crucial issues to deal with. The design of a signal collection and processing system capable of providing the required precision despite those difficulties is also a prime issue.

This document presents the concepts of such an indoor geolocation system, together with the design of its main features and discussions of the way these features are expected to overcome the inherent difficulties. The design is inspired by a few features of both the Global Positioning System (GPS) and the IS-95 Code Division Multiple Access (CDMA) that have been modified to fulfill the requirement of indoor geolocation. The critical issue of distinguishing between a LOS and a multipath signal has been reviewed and many techniques have been ruled out. However, a contract was issued for further studies on the possible utilization of the Doppler effect to perform that task. A proof of concept experiment that could demonstrate the feasibility of indoor geolocation to a precision approaching one meter is also proposed.

Brousseau, N and Colman, G. 2001 An Investigation into the Feasibility of using Hybrid GPS/CDMA Signal Processing Techniques for one-meter Accuracy Indoor Geolocation. DREO TM 2001-062 Defence Research Establishment Ottawa.

# Sommaire

Le groupe de la guerre électronique pour les communications mobiles (GECM) a récemment été mis au défi de produire le design d'un système capable de déterminer en temps réel, la position à l'intérieur d'un édifice de jusqu'à vingt personnes avec une précision d'un mètre et de les poursuivre. Les gens dont on veut établir la position collaborent et portent, à cet effet, de l'équipement spécialisé. Un tel système pourrait être utilisé, par exemple, pour poursuivre des pompiers travaillant à l'intérieur d'un édifice en feu. Ce type d'application exige que l'équipement transporté par les personnes soit léger, portable, de petite taille, très robuste, extrêmement fiable et qu'il consomme peu d'énergie. Le système devrait fournir une précision de un mètre, des mesures fiables et une mise à jour des positions quelques fois par seconde.

La détermination avec une grande précision, à l'intérieur d'un édifice, de la position de mobiles coopératifs est un problème difficile. Il est crucial de trouver une façon de résoudre les problèmes liés à la présence de trajets multiples ainsi qu'à la grande absorption des micro-ondes par les édifices et leur contenu. Le design d'un système de collecte et de traitement des données capable de produire la précision requise est aussi un problème de taille.

Ce document présente le design des principaux éléments du système et une discussion de la façon dont ces éléments pourront surmonter les difficultés inhérentes à la détermination de la position à l'intérieur. Le design s'inspire de quelques éléments du Global Positioning System (GPS) et du système IS-95 à Acces Multiple par Répartition de Code (AMPR) qui ont été modifiés et intégrés pour satisfaire aux exigences de la détermination de la position à l'intérieur d'un édifice. Plusieurs techniques pour différencier un trajet direct d'un trajet réfléchi ont été revues et éliminées. Cependant un contrat a été émis pour une étude supplémentaire sur l'utilisation possible de l'effet Doppler pour effectuer cette tâche critique. Une expérience qui pourrait valider le concept présenté pour déterminer la position à l'intérieur d'un édifice avec une précision approchant un mètre est aussi incluse.

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We would like to thank Mr. Derek Elsaesser for challenging us with the problem of indoor geolocation: We really had a good time tossing ideas around.

We would also like to thanks Mr. Ronald Martin for sharing with us his immense knowledge of the world of microwaves. Not only were we immediately provided with the answers to our questions, but in less than an hour, he put on our desk copies of the key publications on the topics of interest.

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# 1. Introduction

The MCEW Group has recently been challenged to design an indoor geolocation system to provide a precision of one meter, in real time, for the tracking of as many as twenty people. In the scenario that we are considering, the people to be geolocated are collaborating and are willing to carry special equipment. Such a system could be used, for example, to track firemen working inside a burning building. This type of application requires that the equipment carried by the people be light, portable, of a small size, very rugged, highly reliable and with low power consumption. The geolocation system, as a whole, should provide one meter accuracy, reliable measurements and real time position updates a few times per second.

The high precision geolocation of indoor co-operative mobiles is a difficult problem. The high absorption of microwaves by the structures and content of buildings and the presence of multipaths are crucial issues to deal with. The design of a signal collection and processing system capable of providing the required precision despite those difficulties is also a prime issue.

This document presents the concepts of such an indoor geolocation system, together with the design of its main features and discussions of the way these features are expected to overcome the inherent difficulties. The design is inspired by a few features of both the Global Positioning System (GPS) and the IS-95 Code Division Multiple Access (CDMA) that have been modified to fulfill the requirement of indoor geolocation. A proof of concept experiment that could demonstrate the feasibility of indoor geolocation to a precision approaching one meter is also proposed.

# 2. Technology Overview

## 2.1 The Global Positioning System (GPS)

GPS is a geolocation system based on 24 satellites arranged in six orbital planes with four satellites per plane. The period of the satellite is almost 12 hours. Designed by the US Military for, among other things, the precise targeting of missiles and the tracking of assets. The constellation of satellites was completed in 1994.

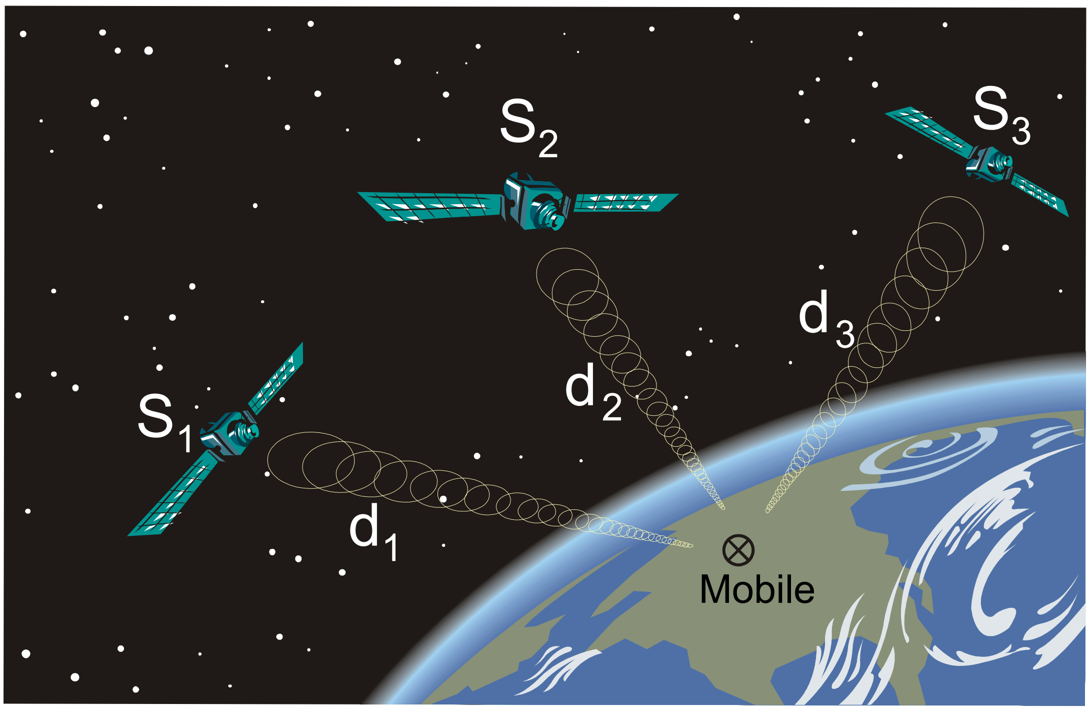


***Figure 1.*** *The GPS system.*

The GPS satellites transmit at two frequencies, L1 at 1575.42 MHz and L2 at 1227.6 MHz. Pseudo random codes are transmitted at two chip rates: The coarse acquisition C/A-codes operate at 1.023 MHz and the precision P-codes at 10.23 MHz. The L2 frequency is modulated by only one code at a time, either the C/A-code or the

P-code. The L1 frequency is modulated by the C/A code and the P-code. The power reaching the ground level is an order of –160 dBW and –166 dBW at L1 and L2 respectively. The Time Of Arrival (TOA) of the signals transmitted by at least three satellites from the GPS constellation is measured and the distance between the satellites and the mobile is calculated. The location of the mobile is then obtained by resolving the resulting set of equations [2, sec. 2.4.2]. A precise knowledge of the satellites' ephemeris is required and many corrections, such as tropospheric propagation delay, ionospheric effects and clock offsets, have to be performed. Even relativistic effects have to be compensated. The initial GPS design included a Standard Positioning Service (SPS) and a Precise Positioning Service (PPS). The SPS service provides a precision of 100m in the horizontal plane and of 156 m in the vertical plane while the PPS service provides accuracies of 22 m in the horizontal plane and of 27.7 m in the vertical plane. A Selective Availability mode (SA) was also included to deny the usage of the PPS service to unauthorized users by removing access to the P-code. In that mode the P-code is encrypted and called P(Y)-code, the L1 and L2 frequencies are subjected to encrypted dither and errors are added to the broadcast ephemeris and almanac data.

Many civilian applications, such as precision surveying, require a greater precision than what is provided by the PPS mode of GPS. Therefore, many sophisticated signal processing techniques, collectively known as Differential GPS (DGPS), have been developed to provide submeter precision for static and kinematic geolocation. GPS is now a commodity widely used by the civilian and scientific communities for demanding real time applications such as aircraft Cat. III precision approaches for blind landing where the required precision is 50cm [1]. Some commercial ventures, such as the IS-95 Code Division Multiple Access (CDMA) cellular telephone network, use GPS as a time reference and could not operate without it.

## 2.2 DGPS signal processing: Brief overview

One particular approach to the implementation of DGPS is based on two different ways to measure the distance from a few of the satellites of the constellation to a reference antenna and another antenna located on the mobile. The two types of measurement are then integrated during post processing operations.

The first measurements called the code ranges, use the correlation of reference codes with the pseudo random codes transmitted by the satellites. The equation for the pseudoranges $P_k^p$ and $P_m^p$ between receivers $k$ and $m$ and a satellite $p$ are respectively [2]:

$$P_k^p(t) = t_k^p(t) - t^p(t) + Q_k + \tau_p + \tau_k + \nu_{iono} + \delta_{tropo}$$

$$P_m^p(t) = t_m^p(t) - t^p(t) + Q_m + \tau_p + \tau_m + \nu_{iono} + \delta_{tropo}$$

where

$P$ is the receiver measured pseudorange time in seconds
$k, m$ refer to the receiver/receiver antennas phase center
$p$ is the satellite used for the measurement
$t_k^p$ or $t_m^p$ is the signal reception time as measured by the receiver clocks
$Q$ is the timing jitter due to all sources
$\tau$ is the satellite or receiver clock bias
$Y_{iono}$ is the group delay of the modulation due to the ionosphere
$\delta_{tropo}$ is the delay of the modulation due to the troposphere

The precision of the measurement is on the order of the distance traveled by the signal during the duration of one chip of the pseudo random codes. Depending on the chip rate of the codes, namely 1.023 MHz for the C/A-code or 10.23 MHz for the P-code, the precision of the measurement is 300 m or 30 m, respectively. The results of the code range measurements, although noisy, are absolute, in the sense that they do not contain any ambiguity.

The single difference $SD_{km}^p$ can be calculated by substracting the equations for $P_k^p$ and $P_m^p$ :

$$SD_{km}^p = \phi_{km}^p + Q_{km}^p + \tau_{km}$$

In a similar fashion, the single difference for the same receivers and satellite q is:

$$SD_{km}^q = \phi_{km}^q + Q_{km}^q + \tau_{km}$$

The formation of the single difference equation allows the elimination of errors due to ionospheric propagation delays. Tropospheric propagation delays will mostly cancel out if the two antennas are at similar altitude.

The difference between $SD_{km}^{p}$ and $SD_{km}^{q}$ gives the double difference equation:

$$DD_{km}^{pq} = t_{km}^{pq} + Q_{km}^{pq}$$

This last step allows the elimination of errors due to clock bias.

The second type of measurements is performed by tracking the phase of the carrier frequency of either the L1 or the L2 signal and is called the carrier-phase range. The equation for the carrier-phase ranges $\phi_k^p$ and $\phi_m^p$ between a receiver $k$ and $m$ and a satellite $p$ are respectively:

$$\Phi_k^p(t) = \phi_k^p(t) - \phi^p(t) + N_k^p + S_k + f\tau_p + f\tau_k - \beta_{iono} + \delta_{tropo}$$
$$\Phi_m^p(t) = \phi_m^p(t) - \phi^p(t) + N_m^p + S_m + f\tau_p + f\tau_m - \beta_{iono} + \delta_{tropo}$$

where:

$k$ and $m$ refer to the receiver/receiver antennas phase centers
$p$ is the satellite signal source
$\phi_p$ is the transmitted satellite signal phase as a function of time
$\phi_k^p(t)$ and $\phi_m^p(t)$ are the receiver measured satellite signal phases as a function of time
$N$ is the unknown integer number of carrier cycles from $p$ to $k$ or $p$ to $m$
$S$ is the phase noise due to all sources
$f$ f is the carrier frequency
$\tau$ is the associated satellite or receiver clock bias
$\beta_{iono}$ is the advance of the carrier cycles due to the ionosphere
$\delta_{tropo}$ is the delay of the carrier cycles due to the troposphere

Carrier phase measurements can easily achieve a precision of .01 cycle. Therefore a resolution of λ/10, where the wavelength at L1 and L2 is 37.775 cm and 48.475 cm respectively, is possible. Unfortunately, although the change in distance from the epoch of one measurement to the next is known with great precision (as long as the lock on the phase is not lost, thus producing a cycle slip) the whole number of wavelengths on the path remains ambiguous. The single and double difference equation can also be formed to eliminate errors. The single difference $SD_{km}^{p}$ can be calculated by subtracting the equations for $P_k^p$ and $P_m^p$ :

$$SD_{km}^{p} = \phi_{km}^{p} + N_{km}^{p} + S_{km}^{p} + f\tau_{km}$$

In a similar fashion, the single difference for the same receiver and satellite q is:

$$SD_{km}^{q} = \phi_{km}^{q} + N_{km}^{q} + S_{km}^{q} + f\tau_{km}$$

The formation of the single difference equations allows the elimination of errors due to ionospheric propagation delays. Tropospheric propagation delays will mostly cancel out if the two antennas are at similar altitudes. The difference between $SD_{km}^{p}$ and $SD_{km}^{q}$ gives the double difference equation:

$$DD_{km}^{pq} = \phi_{km}^{pq} + N_{km}^{pq} + S_{km}^{pq}$$

This step allows the elimination of errors due to clock bias.

At this point in the processing, a code-range DD curve (figure 2A) that is noisy but has no ambiguity and a carrier-phase range DD curve (figure 2B) that is much more precise but whose absolute location is unknown, have been generated. A Kalman filter is then used to center the carrier-phase range DD curve on the code range DD curve. The resulting curve is called the *floating solution* (figure 2C). One can notice that the shape of the floating solution curve is very similar to the carrier-phase curve except during the initialization of the Kalman filter at the very beginning. If the code range and carrier-phase range measurements were made at L1 with the 1.023 MHz chip rate C/A-code, it is expected to be precise to ±5-10λ [2, p366]. Experimental measurements made with the P-code operating at L1 or L2 at a chip rate of 10.23 MHz have produced a *floating solution* with a precision approaching one meter. These experimental measurements [1] were collected during the geolocation of landing airplanes using DGPS in conjunction with pseudolites.

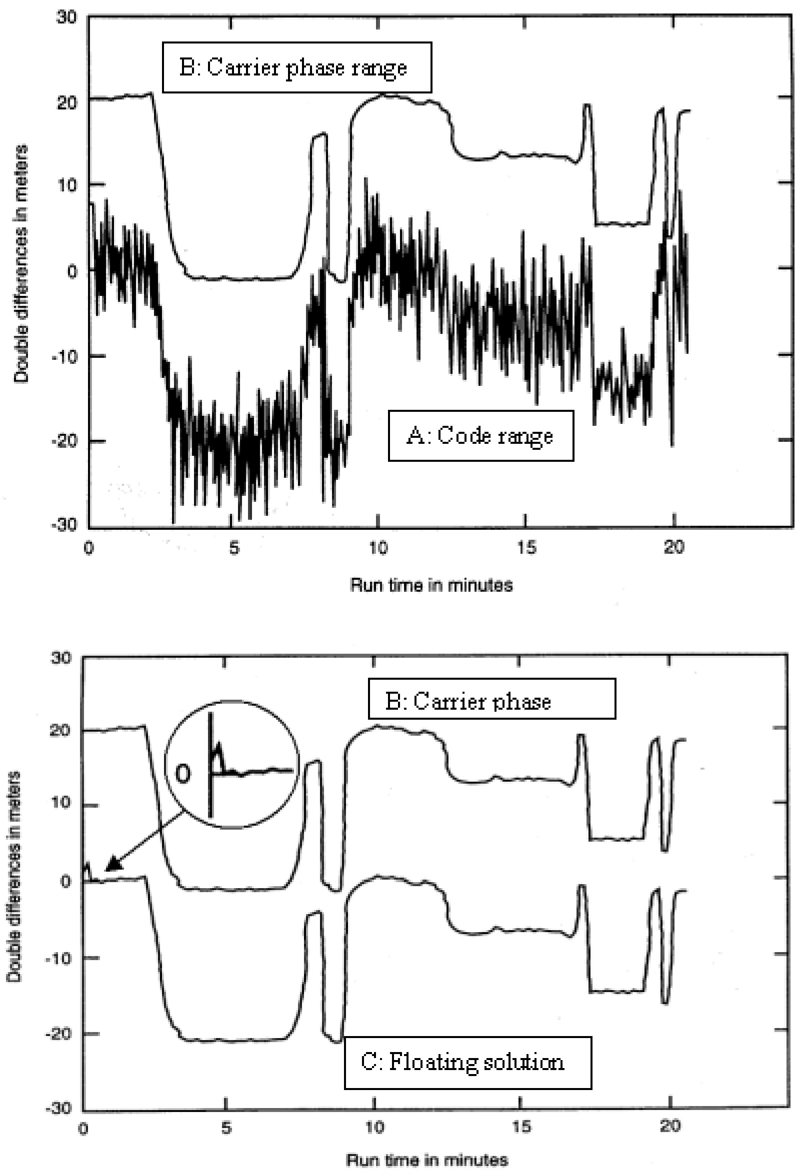


***Figure 2. The floating solution C derived from the code range A and the carrier phase range B by a Kalman filter (from 2, p366-367).***

At this point, the data collection is finished and the only task left is the resolution of the ambiguity on the number of wavelengths. The post processing refinement that provides the ultimate precision is the resolution of the ambiguity. It leads to the *fixed solution*. Many techniques have been developed to perform that task. A possible approach is to use the successive points of the *floating solution* to find the *fixed solution*. The idea is to find all the integer numbers of λ that can be a solution for one point of the *floating solution*. Do the same for the following points of the *floating solution* and keep only the integers that are common to all the previous points until there is only one integer left. Then, if the validation of the result is successful, the ambiguity is resolved and the *fixed solution* is available. The precise knowledge of the motion of the satellites is instrumental to the successful implementation of that last step.

Limiting the size of the search space and finding techniques to speed up the process are a major concern. The development of On-The-Fly (OTF) techniques for real-time kinematic geolocation is still an active field of research where the aim is to extract the best possible precision and still have the processing done in real time. It is particularly important for applications, such as indoor geolocation and aircraft blind landing approaches, where cycle slips are expected and where fast recovery is required.

## 2.3 The IS-95 cellular system: Brief overview of relevant features

The IS-95 cellular system is based on Code Division Multiple Access technology. It is a commercial product offering good capacity and high quality voice and data communications using sophisticated signal processing techniques. We will now review some features of IS-95 that are relevant to our design of an indoor geolocation system.

One of the most interesting features of IS-95 is the way it uses a rake receiver to mitigate the effects of multipath. For example, for the forward channel, the time delays associated with the three strongest paths reaching the mobile are found by a search correlator working on the pilot signal produced by the base station. The time delay information is then passed to the three demodulating fingers of the rake receiver that process separately the independently fading signals from the three selected paths. The information produced by the three fingers is then integrated by a decision process and error correction follows. The pilot signal of IS-95 is made of two quadrature modulated maximum length sequences selected for their low cross-correlation properties. It is interesting to note that the third generation follow up to IS-95, the cdma2000 system, will use auxiliary pilots built in the same way as IS-95 but orthogonal Walsh code have been added to differentiate the various auxiliary pilots from each other.

Another interesting feature of IS-95 and of the correlation receivers for pseudorandom sequences in general, is that they produce a gain that is proportional to the number of integrated chips. For example, if the maximum length sequence produced by a 13-stage shift register is integrated for its full period of 8191 chips, a gain of 39 dB is achieved. The availability of high gain is essential for the detection of the very weak signals produced by the attenuation associated with the transmission through the features and the content of buildings.

# 3. Indoor geolocation: Proposed system

A quick review of some of the constraints and difficulties associated with indoor geolocation allows the definition of a few features of the architecture of the system. For indoor geolocation, we know that

1) *the signals used to perform the geolocation will be strongly attenuated by the structure and the content of the buildings [3, section 3.11], so the signal processing system should be able to provide a large gain in order to allow the detection of very weak signals.*

This suggests the encoding of the signals with pseudo random sequences. The receivers are then detecting the signal by performing a correlation whose duration can be adjusted, together with the characteristics of the encoding, to provide a high gain. The utilization of pseudo random sequences also allows the resolution of the multipaths up to the chip duration of the signal.

2) *the equipment carried by the people should be of light weight, of minimum complexity and power consumption and the people should not be exposed to a harmful level of microwave radiation.*

This suggests an architecture where powerful beacons are transmitting encoded signals from outside the building. In doing so, the number of signals simultaneously on the air is limited to the number of beacons required to cover the building. This makes the system fairly insensitive to the number of mobiles to be geolocated, as the addition of more mobiles does not add any extra processing load to the other mobiles. The beacons have plenty of power available from the land power lines or from generators and they can themselves be geolocated with precision with GPS. In such a scheme, the signal from each beacon will be distinguished from the other beacons by the utilization of proper encoding. Techniques such as orthogonal encoding using Walsh codes and/or the utilization of different phase offsets for each beacon are possible.

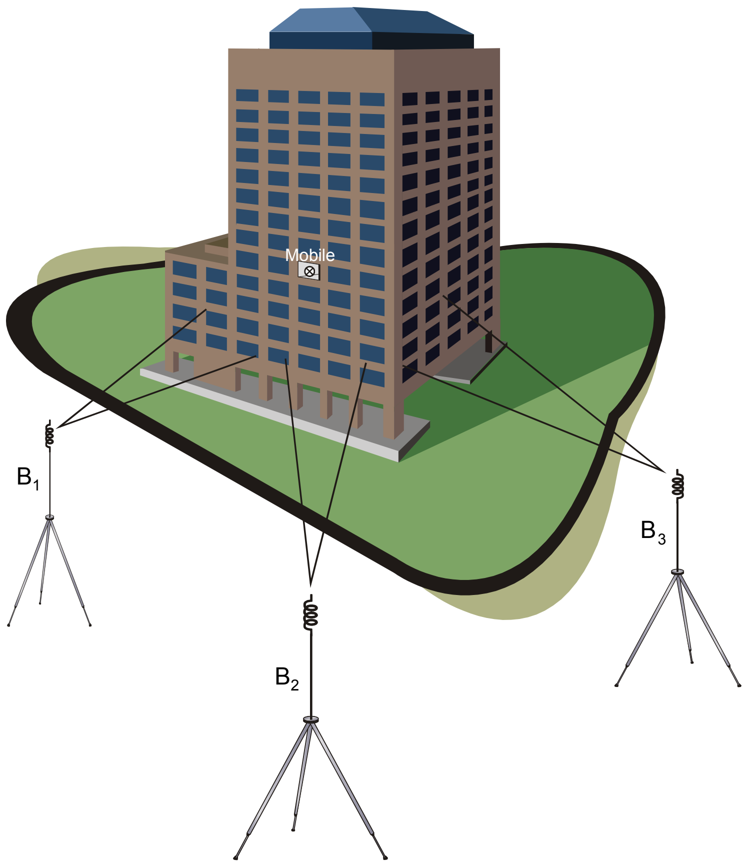


***Figure 3. Proposed architecture for indoor geolocation.***

In the proposed architecture the people carry receivers that include a search correlator used constantly to look for the first arriving signal from each detectable beacon. A bank of one-finger rake receivers operating at the time delays specified by the search correlator for each detectable beacon form the correlations between the reference signals and the signal from all the detectable beacons. The resulting Time Of Arrival (TOA) information, from the mobile relative to all detectable beacons, will be relayed back to a processing center located outside of the building by an auxiliary communication system operating independently of the geolocation system. Although the environment is expected to be difficult because of blockage, LOS is not required and a commercial cellular system could be capable of performing this function. The processing center will first determine if the TOA information for each beacon originates from LOS signals or multipaths, reject data originating from multipaths and calculate the location of each mobile by performing appropriate calculations on the remaining data set. It is to be noted, that commercial GPS receivers lock on the strongest received signal rather than on the first arriving signal. The resulting architecture is illustrated in figure 3.

3) *It would be very valuable to be able to distinguish with some test, if the TOA reading associated with the first arriving signal from a particular beacon detected by a mobile is a Line Of Sight (LOS) or a reflected signal associated with a multipath. Only a LOS signal can be relied on for the purpose of geolocation because it is impossible to know how much extra delay has been introduced in a reflected, scattered or diffracted path.*

It is important to note that the geolocation method that we are proposing will not work inside reinforced concrete structures because the reinforcing metallic bars or meshes usually have regular patterns with a period that is similar to the wavelength of the microwaves transmitted by the beacons [4]. Therefore, they act as gratings and diffract the incident microwaves.

We considered various approaches to distinguish between LOS and non LOS signals. Finding the direction of arrival of the beacon signal on the mobile could allow determining if the signal comes directly from the beacon or has been reflected. Unfortunately this would require complex high precision direction finding equipment located on the mobile and also the capability to determine the altitude of the mobile. Therefore it was discarded because of its complexity and because it obliges the users to carry too much equipment.

The fading characteristics of the first received signal cannot be used either to differenciate between a LOS and a non LOS signal. It is clearly demonstrated in Karlsson's thesis [5, p54] that the indoor fading in a LOS, an obstructed LOS and a non LOS situation can all be described by Rice distributions with a high K factor. The distributions are too similar to be distinguished reliably.

Difference in the polarization between the transmitted and the reflected signal was also considered. Although there is a change in the relative orientation of the electric field vector E and the magnetic field vector H between a reflected and a transmitted signal, the polarization of the signal does not change for reflection by a flat surface, and thus the change cannot be detected. Reflection by curved surfaces are not considered useful as they lead to highly diverging beams whose intensity become quickly undetectable.

Another approach, based on the analysis of the code range measurements taken three at a time when a few redundant beacons are detectable, is proposed as an alternative. It should be possible to find which beacons are producing consistent results and to eliminate the others from the calculations. Similar techniques have been developed for the tracking of a target by a radar.

Another method based on the measurement of the Doppler effect of the first arrived signal at the mobile from each beacon has been proposed by Dr. Wight and is presently being investigated under contract W7714-990328/001/SV.

4) *A one meter accuracy*

Designing an indoor geolocation system for a one meter accuracy, or better, is not a straightforward undertaking. The MCEW Group has previously been involved in the development of concepts for the geolocation of mobiles using the IS-95 cellular system and some simulations developed for the geolocation of IS-95 mobiles were modified and used to assess the chip rate that would be required to provide a precision of about one meter. When using direct sequence spread spectrum signals for indoor location purposes, it must be noted that the chip rate will have a direct impact on the location accuracy: The higher the chip rate, the more accurate the positioning will be. In this section we illustrate the effect of chip rate on positioning accuracy.

The CDMA IS-95A system has a chip rate of 1.2288Mcps. With signals traveling at $3 \times 10^{8} m/s$, one chip in IS-95A corresponds to 244 metres. This would not be useful in an indoor geolocation application. If the chip rate were increased to ten times that of IS-95A, one chip would correspond to 24.4 metres of propagation distance. In a simulated building measuring 100m by 100m with a height of 70m, and beacons placed in a coordinate system around the building at six relatively arbitrary positions, the error due to the signal quantization as a function of position in the building at a level 14m above the ground for a Time of Arrival (TOA) system is shown in the following Figure 4.

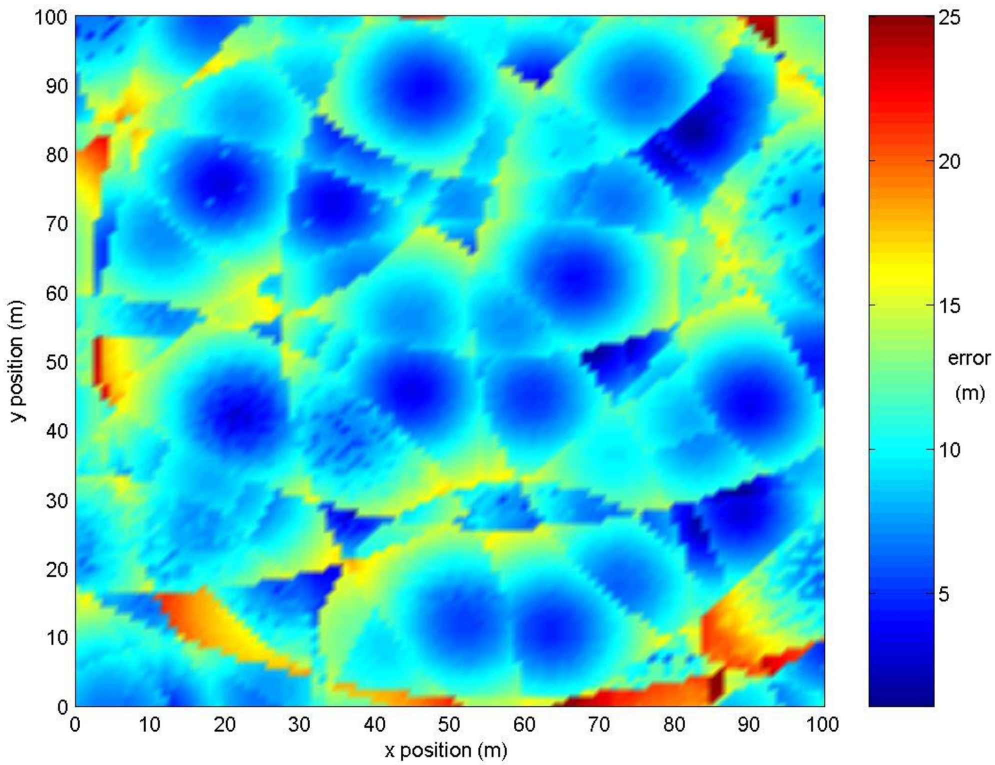


***Figure 4.*** *Accuracy of a TOA system with a chip rate of 1.2288 Mcps.*

As can be seen from this figure, the error on a reading will be a function of the mobile user's position within the building with dark blue areas representing an error of less than 5 metres and dark red areas representing an error of 20 metres or more. The average position error in this system is 9.8m for the specific geometry of beacons used in the simulation.

If the chip rate is again increased to 100 times that of the IS-95A system (i.e. 122.88Mcps) the error is illustrated on Figure 5:

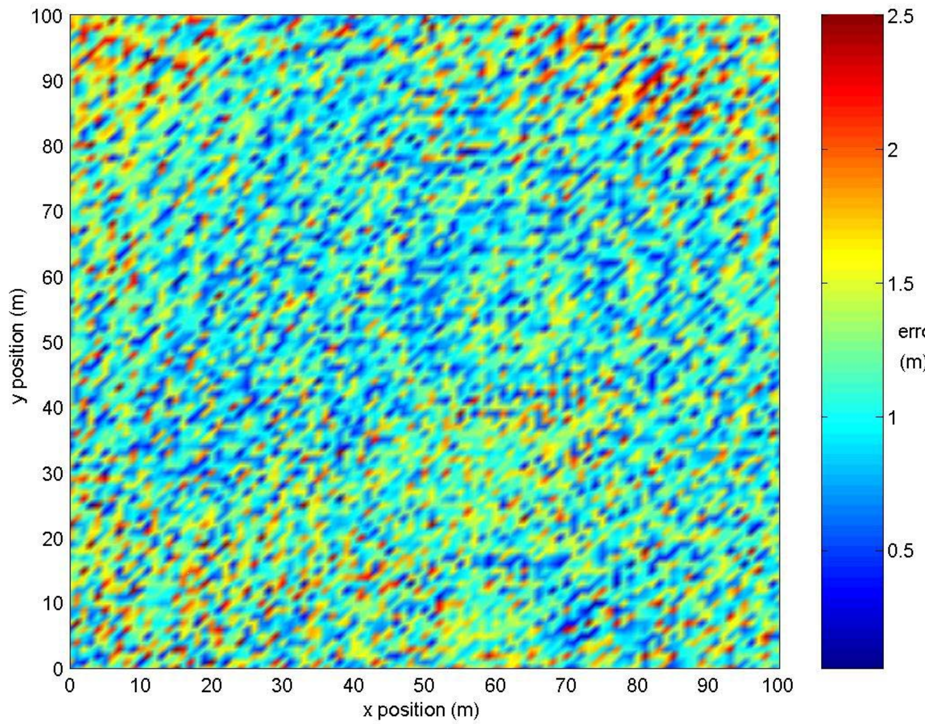


***Figure 5.*** *Accuracy of a TOA system with a chip rate of 122.88 Mcps*

This has an average error of 1.13m. This exercise could be extended to the case where the chip rate were 1000 time that of CDMA IS-95A and the error due to quantization would continue to decrease. At this point, however it is important to note that a 1GHz bandwidth system will be very difficult to develop and could provide interference to other systems using the band. Also, with an increased chip rate, chances are that the system will need to operate in a higher band. One of the goals of an indoor geolocation system will be to operate it in as low a band as possible to minimize interaction with the building materials. More sophisticated techniques were considered where a few modified DGPS signal processing techniques are integrated into the system.

Improving the precision of the system can be done by adding the tracking of the carrier phase to the range measurements made with the pseudo random sequences transmitted by the beacons (that we call code-range). This allows the measurement of the mobile movement in terms of the number of wavelengths of the microwave radiation used to perform the measurements. Carrier tracking (or carrier-phase range) is performed by the mobile for each of the detectable beacon signals.

From that point, the signal processing follows the methodology used for DGPS that is briefly outlined in section 3.0 and described in detail in [2, sec. 8,3]. In our case, the satellites are replaced by beacons that are very similar to the pseudolites used in conjunction with DGPS for the precise geolocation of airplanes during precision landing maneuvers [1]. The double differences are formed for the code and the carrier-phase measurements and lead, after the application of a Kalman filter, to a *floating solution* where the carrier-phase double differences have been centered on the code double differences. Actual measurements made with the P-code operating at L1 or L2 at a chip rate of 10.23 MHz have produced a *floating solution* with a precision approaching one meter during the geolocation of landing airplanes using DGPS in conjunction with pseudolites [1].

At that point, the data collection is finished and the only operation left to do is the resolution of the ambiguity on the number of wavelengths to obtain the *fixed solution*. The ambiguity resolution has decreased the maximum error in the position for the aircraft landing experiment cited above to 9 cm [1].

Moving the beacons in a known, periodic pattern is likely to assist in the fast resolution of the ambiguity and that supplementary feature does not involve any addition to the receivers located on the mobiles. The velocity of that motion should be compatible with the integration time used by the receivers of the mobiles to build up a gain that is sufficient to detect very weak signals.

Other techniques such as simultaneous carrier phase tracking at both L1 and L2 have been used for this purpose, but it would imply that the people would have to carry more equipment.

## **3.1** Proof-of-concept experiment

Modified GPS equipment could be used to perform a proof-of-concept experiment. It is suggested to use a P-code operating with a chip rate of 10.23 MHz to build a high power beacon that will be similar to the pseudolites used in [1]. Only one mobile will participate to the experiment and a search correlator will be added to the normal GPS receiver of the mobile to find the first arriving signal from the beacon and the receiver will have to correlate the reference code with the beacon signals at the time delay found by the search correlator. For the proof-of-concept experiment, the mobile receiver could then be moved in steps around in the building. The signals from all the detectable beacons could be processed one after another while the mobile is at a fixed location. Doing so also makes it possible to use the same P-code for all the beacons as they don't have to be transmitting at the same time. However, the antennas used to transmit the beacons should be at exactly the same location for each of the positions of the mobile. Measurements of the code range and the carrier-phase range should be performed at each location, for all the detectable beacons, the DD equations formed for both the code range and the carrier-phase range and the *floating solution* should be calculated with a Kalman filter. This should provide a step-by-step tracking capability with a precision of just over one meter as obtained with the *floating solution* of the aircraft landing experiment previously mentioned [1]. An improved accuray could be obtained later by resolving the ambiguity. It could also be a good opportunity to try techniques to differentiate LOS signals from multipaths.

Extreme care should be taken during this experiment not to interfere with the normal operation of GPS. It is suggested to use a different frequency band and to make sure that there is no leakage of signals into the GPS bands. The normal GPS receivers will require a few more modifications. The filtering in the front end and the down conversion process will have to be altered to accommodate the new band of operation.

## 4. Conclusion

The concept of an indoor geolocation system whose purpose is to provide an accuracy of one meter, in real time, for the tracking of as many as twenty people was presented. The design integrates several features of both the Global Positioning System (GPS) and the IS-95 Code Division Multiple Access (CDMA) that have been modified to fulfill the requirement of indoor geolocation. The design of the main features of the system and discussions of the way these features are expected to overcome the difficulties inherent to indoor geolocation are presented. The critical issue of distinguishing between a LOS and a multipath signal has been reviewed and many techniques have been ruled out. However, further studies on a promising new technique using the Doppler effect will take place under contract.

A proof of concept experiment that could demonstrate the feasibility of indoor geolocation to a precision approaching one meter was also proposed.

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# List of symbols/abbreviations/acronyms/initialisms

| | |
|---|---|
| CDMA | Code Division Multiple Access |
| DD | Double Difference |
| DGPS | Differential Global Positioning System |
| DND | Department of National Defence |
| GPS | Global Positioning System |
| LOS | Line Of Sight |
| MCEW | Mobile Communications Electronic Warfare |
| OTF | On The Fly |
| TOA | Time Of Arrival |

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This technical memorandum presents the concepts of an indoor geolocation system providing an accuracy of one meter, in real time, for the tracking of as many as twenty people. In the scenario that we are considering, the people to be geolocated are collaborating and are willing to carry special equipment. Such a system could be used, for example, to track firemen working inside a burning building. This type of application requires that the equipment carried by the people be light, portable, of a small size, very rugged, highly reliable and with low power consumption. The geolocation system, as a whole, should provide one-meter accuracy, reliable measurements and real time position updates a few times per second.

The design is inspired by a few features of both the Global Positioning System (GPS) and the IS-95 Code Division Multiple Access (CDMA) that have been modified and integrated to fulfill the requirement of indoor geolocation. The design of the main features of the system and discussions of the way these features are expected to overcome the difficulties inherent to indoor geolocation are presented. The critical issue of distinguishing between a LOS and a multipath signal has been reviewed and many techniques have been ruled out. However, a contract was issued for further studies on the possible utilization of the Doppler effect to perform that task. A proof of concept experiment that could demonstrate the feasibility of indoor geolocation to a precision approaching one meter is also proposed.

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CDMA
GPS
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