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EMERGENCY RESPONSE, THE BUILT ENVIRONMENT AND GPS SIGNAL QUALITY: SIMULATION AND ANALYSIS OF URBAN CANYONS IN QUEBEC CITY

Mémoire présenté
à la Faculté des études supérieures de l'Université Laval
dans le cadre du programme de maîtrise en aménagement du territoire et développement régional
pour l'obtention du grade de Maître en aménagement du territoire et développement régional (M.ATDR)

ÉCOLE SUPÉRIEURE D'AMÉNAGEMENT DU TERRITOIRE ET DE DÉVELOPPEMENT RÉGIONAL (ÉSAD)
FACULTÉ D'AMÉNAGEMENT, D'ARCHITECTURE ET DES ARTS VISUELS
UNIVERSITE LAVAL
QUEBEC

2006

Résumé

L’objectif général de cette recherche est de synthétiser les informations disponibles sur le développement d’un système d’urgence 9-1-1 pour les téléphones cellulaires dans le contexte nord américain. L’objectif spécifique du projet est de proposer une méthodologie qui détermine les conditions moyennes d’obstruction causée par les bâtiments qui nuisent à la qualité de la réception de signal GPS. Un modèle statistique de la qualité de signal GPS basé sur une campagne de mesures de réception des signaux GPS dans les arrondissements à caractère urbain dans la Ville de Québec (Canada) est employé pour simuler l’effet d’obstruction. Ces mesures ont montré une variabilité spatiale de la qualité de signal selon les conditions locales d’obstruction des édifices sur la voûte céleste. Une augmentation du pourcentage de ciel obstrué (effet de masque) a entraîné une augmentation de la probabilité de perte de signal GPS. Des cartes continues de la probabilité de perte de signal GPS ont été créés pour des feuillets de la Base de données topographiques de Québec au 1 : 20 000 en employant la technique d’interpolation spatiale par la méthode de la distance inverse pondérée (DIP).

Abstract

The general objective of this investigation is to extract the most pertinent information currently available on developing an emergency 9-1-1 system for cellular phones in the North American context. The specific objective of this project is to propose a methodology for determining the average obstruction by buildings which affect GPS satellite signal quality. A statistical model of GPS signal quality based on a field measurement campaign in the urban districts of Quebec City (Canada) was used to simulate this phenomenon. The measurements demonstrated a spatial variation in signal quality according to the building obstruction over the local sky. An increase in the percent of obstructed sky led to an increase in the probability of losing GPS signal lock. Continuous maps of GPS signal loss probability were created for sheets of the Quebec topographic database at the 1:20,000 scale using the Inverse Distance Weighting technique of spatial interpolation (IDW).

Foreword

Part of the research conducted for this project was funded by a Canada-U.S. Fulbright student scholarship. The remaining funds were provided by grants from the Natural Sciences and Engineering Research Council of Canada and the GEOIDE Network of Centres of Excellence.

This master's thesis is a result of the support and encouragement of several individuals that have all contributed to my experience in ways that continue to inspire me. Their presence, patience and generosity have given me a genuine sense of purpose.

As a member of the Centre for Research in Regional Planning and Development (CRAD) at Laval University, under the supervision of Dr. Marius Thériault, I was immersed in a dynamic academic environment that provided constant stimulation. I greatly appreciate the opportunity to have worked with Dr. Thériault. His theoretical, methodological and technical expertise has left a lasting impression on the unique set of challenges addressed in this master's thesis.

I thank my parents for their vision and wisdom. I cannot imagine more positive role models.

I thank Amélie Bégin for sharing this new life with me. I could never have done it without you.

I thank Dr. Donald T. McGuire for urging me to pursue a Master's degree (still combing the tourist shops Don).

I thank Dr. Maureen Jameson for making my time at University at Buffalo so memorable.

I thank Dr. Alan D. MacPherson for allowing me to participate at several different capacities in the Geography Department at University at Buffalo and for helping me achieve my goals from New Orleans to Beauport.

I would also like to thank Gary Winston, Christian Gravel, François Théberge, Matthieu Roy, Benoît Carrier, Willem Fortin, Dr. Mario Carrier, Dr. Florent Joerin and Dr. Martin Lee-Gosselin.

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A-GPS	Assisted Global Positioning System
ALI	Automatic Location Identification
BTS	Base Transceiver Station
CAUCA	Centre d’appel d’urgence Chaudière-Appalaches
CDMA	Code Division Multiple Access
CRTC	Canadian Radio-television & Telecommunications Commission
CWTA	Canadian Wireless Telecommunication Association
ECGI	Enhanced Global Cell Identifier
ESRD	Emergency Services Routing Digit
FCC	Federal Communications Commission
GPS	Global Positioning System
GSM	Global System for Mobile
ILEC	Incumbent Local Exchange Carrier
LBS	Location Based Services
LMU	Location Measurement Unit
MS	Mobile Station
NMR	Network Measurement Results
PSAP	Public Safety Answering Point
QUC	Quebec Urban Community
RFI	Radio Frequency Interference
TTFF	Time to First Fix
WSP	Wireless Service Provider

1 INTRODUCTION

As of March 2005, there were over 13.5 million wireless telephone subscribers in Canada (Canadian Wireless Telecommunication Association, 2004a). With a total national population of nearly 32 million, the number of subscribers is expected to exceed 15 million by year-end 2005 (Statistics Canada, 2004, Canadian Wireless Telecommunications Association, 2004b). According to the Canadian Wireless Telecommunications Association (CWTA) approximately 50 percent of calls to 9-1-1 are dialed from a cellular telephone. Without a fixed location associated with each handset[1] verifying the geographic origin of these calls is problematic and requires real-time integration and interoperability of Geographic Information Systems (GIS)[2], advanced Location Identification Technology and telecommunication equipment.

The opportunity cost associated with follow-up on these calls equates to lost life and property. Improving emergency response with new technologies in the wireless telecommunications infrastructure is a formidable task for all parties concerned. The development of a Wireless Enhanced 9-1-1 (Wireless E-911)[3] system is essential to reducing response time and advancing this aim.

The Canadian Radio-television and Telecommunications Commission (CRTC) recognizes this fact and has recently begun to intervene in this process. The CRTC decision 2003-53[4] is a step toward a more hands-on approach to creating an appropriate regulatory environment (Canadian Radio-television and Telecommunications Commission, 2003). However, no official deployment schedule has been established. As a result, 2003-53 is more of a guideline than a directive.

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[1] Handset used in this context refers to a cellular phone

[2] GIS is a system that uses a combination of hardware and software to store, manipulate, analyze and map geographic data.

[3] Wireless Enhanced 9-1-1 is the technology that relays automatic caller information sent along with the voice signal to Emergency Services Personnel

[4] CRTC decision 2003-53 states the conditions of service for wireless competitive local exchange carriers and for emergency services offered by wireless service providers in Canada

In November 2003, over 65 percent of Public Safety Answering Points (PSAP)[5] in the United States had Phase I[6] Wireless E-911 service, whereas only 18 percent of these PSAP's were receiving Phase II Automatic Location Information[7] (United States General Accounting Office, 2004). Phase I capability has been achieved in some cities in the provinces of Alberta, British Columbia, Ontario and Quebec (Canadian Wireless Telecommunications Association, 2004b). However, Phase II Automatic Location Information (ALI) is lacking throughout the country and the first national Phase II trial was scheduled to take place in Toronto during the Fall 2004 with Bell Mobility and the City of Toronto Emergency Services (Police, EMS & Fire Department) (Bell Canada Enterprises, 2003).

The designated 9-1-1 PSAP for Quebec City is among the first PSAP's in the province of Quebec to have successfully implemented Phase I capabilities of Wireless E-911 (ANNEX A). This PSAP currently serves the thirteen amalgamated municipalities until recently known as the Quebec Urban Community (QUC) (ANNEX B). According to the CRTC decision 2003-53, wireless carriers operating in areas with Phase I must continue to upgrade their network infrastructure and equipment in order to transmit Phase II ALI. Although the Quebec City PSAP currently receives both the call back number and cellular tower address, locating the wireless device and the individual who initiated the call often requires a significant amount of additional time and effort for on-site emergency personnel.

Using Phase I technologies, the positional accuracy of the location of a caller from the corresponding cellular tower varies from a radius of hundreds of meters to over several kilometers. In urban environments, where wireless service facility density is highest, more accurate location estimates are obtainable whereas the opposite is true for rural settings. Currently, not all four Wireless Service Providers (WSP) in the region deliver this

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[5] PSAP refers to the emergency call center receiving 9-1-1 calls, typically a police station or fire department

[6] Phase I requires the carrier to transmit the telephone number of the cellular phone and the address of the cellular tower that received the call signal to the appropriate PSAP

[7] Phase II Automatic Location Information refers to the carrier transmitting the latitude and longitude of the handset to the appropriate PSAP with a specific degree of location accuracy

information. Bell Mobility and Fido (Microcell) are Phase I compliant while Rogers AT&T Wireless and Telus Mobility are still in the planning stage[8].

The Phase II technological platform of this service will enable companies to pinpoint their subscriber's location, thus providing the incentive for the development of new services based on geographic location.

From a planning perspective, new developments in location based services will enhance traditional research methodologies. These new methods of inquiry will combine traditional techniques with technologies that will allow researchers to more closely monitor realistic behavior patterns of individuals (cell phone users) in terms of communication, transport and consumption. The impact these behaviors have on shaping individual and aggregate decision making could provide new insight to modify existing land-use and transportation system policies (Sustainable Transport in Europe and Links and Liaisons with America, 2005).

Studying the feasibility of the continued roll-out and development of Wireless E-911 in Quebec City could lead to a better understanding of implementation barriers and help structure operational scenarios where costs are minimized and response times are improved.

This study aims at documenting the progression toward a functional Phase II compliant 9-1-1 system. We also intend to explore the variation of positioning accuracy of conventional Global Positioning System technology within the Quebec City PSAP'S territory using a consumer-grade GPS receiver. In addition to technological feasibility we will evaluate costs associated with implementation and how these costs will be met. Finally, we consider some implications for transport and land-use planning.

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[8] This fact is based on personal communications with the director of the Public Safety Answering Point in Quebec City during an on-site evaluation in April, 2004.

2 BACKGROUND

2.1 Location Based Services New Directions

A 2001 report by Ovum Ltd projected revenues from the global Location Based Service (LBS)[9] industry in 2006 to be over 20 billion US dollars. In 2005, WSP's are still attempting to bring their mobile location services to market. Until recently, the services offered by carriers have tended to discourage usage. Subscribers have been required to initiate pay-per-use queries in mundane applications that locate ATM's, restaurants, hotels etc. from a simple geo-coded database. While relatively easy to implement, these applications have not been very successful. New applications will focus on providing personalized services that use subscriber profiles, preferences, requirements and the subscriber's immediate surroundings integrating the individual and their environment. These user characteristics will act as geographically sensitive triggers that automatically notify subscribers when personal information matches with their location. For example, an automatically triggered text message may be sent to a subscriber in the event of a traffic accident with a suggested alternative route that would allow the individual to reach a scheduled appointment destination on time. Another application may notify a user when someone with similar hobbies and interests is in close proximity. Pertinent applications of LBS for land-use planners might include real-time data collection such as real-time surveys of local residents and transportation models that use data from tracking cellular phones of individuals to identify factors in decision making.

The United States Federal Communications Commission (FCC) Rule and Order for emergency wireless calls has been the driving force for the development of Location Based Services in North America (Hjelm, 2002). Recently, similar legislation requiring WSP's to implement mobile positioning technologies for emergency service applications has also been adopted in Canada (Wireless E-911) and Europe (E112) (Canadian Radio-television and Telecommunications Commission, 2003, Europa, 2003). However, commercial applications have been at the forefront of LBS throughout the rest of the world. Asia, Japan

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[9] Location Based Services (LBS) as pertains to cellular phones are personalized requested and unsolicited services based on subscriber characteristics and geographic location

in particular, has experienced commercial success with handset-centric LBS and according to market research by ABI the combination of legislative measures and commercial availability has given impetus to a technological revitalization of the LBS industry (ABI Research, 2004).

2.1.1 Wireless E-911

There are two distinct phases for Wireless E-911 service as outlined by the United States Federal Communications Commission (FCC). In Canada, Phase I consists of requiring the wireless carrier to send the subscriber's 10-digit call back number, 10-digit Emergency Services Routing Digit (ESRD), or cell site address[10], and a voice signal over the Incumbent Local Exchange Carrier's (ILEC)[11] wireless E9-1-1 network (Canadian Radio-television and Telecommunications Commission, 2001a, 2001b, Emergency Services Working Group, 2002). Although the ways and means for adopting this emergency service differ between Canada and the United States, the CRTC is committed to harmonizing regulations with the FCC.

Phase II would require wireless carriers to provide PSAP's with Automatic Location Information (ALI). This technology can be handset-based or network-based and when implemented has often taken a hybrid form of the two. Each technology was originally assigned different penetration rates and schedules in the United States. Canada has left these decisions up to each wireless company.

Location precision requirements were later added to provide a more specific definition of Phase II accuracy standards. Handset-based solutions required pinpointing a caller's location within a 50 meter radius for 67 percent of calls and 150 meters for 95 percent of calls. For network-based solutions, 100 meter accuracy was required for 67 percent of calls and 300 meter accuracy for 95 percent of calls (FCC,2001) (ANNEX C).

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[10] A cell site refers to a geographic area where a base station equipped with one or more antennas receives and transmits radio signals to the mobile phones within its coverage area (page2, USGOA, 2004). Cell sizes vary from a radius of 100 meters to over 30 kilometers providing less than optimal location information.

[11] An Incumbent Local Exchange Carrier refers to the historic local phone service provider in a market, often a former Bell company.

2.1.2 Local Wireless Phone Service and Technologies

The four WSP's operating in the Quebec City region use different wireless standards for their networks (Table 1). Each wireless standard has a particular type of location determination technology the provider will most likely select.

Table 1. Carrier Technology

Wireless Service Provider	**Bell**	**Fido**	**Rogers AT&T**	**Telus**
Wireless Standard	CDMA	GSM	GSM	CDMA
Location Technology	A-GPS	E-OTD	E-OTD	A-GPS

(QuebecMicro, 2004)

Code Division Multiple Access (CDMA), used by both Bell Mobility and Telus, is a wireless standard that works by encoding each data signal differently to provide a specific match for the receiver. The signals are encoded and sent simultaneously allowing more than one phone and more than one base station to use the same frequency at the same time (Rappaport, 2002). The most popular location determination technology for this standard is a hybrid, handset based technology known as Assisted GPS (A-GPS) (ANNEX D). A-GPS equipped cellular phones collect GPS satellite signals and send pseudo latitude/longitude information to location servers where location is determined and transmitted to the PSAP (Qualcomm, 2004). When GPS satellite signals are unattainable the system reverts to less accurate network based location methods. These are Phase I Wireless E-911 technologies.

Global System for Mobile (GSM) technology, used on Rogers AT&T's wireless network and Fido's entirely digital network, divides a Radio Frequency (RF) into time slots and sends compressed and digitized data down the channel in separate time slots (Rappaport, 2002). This allows multiple simultaneous data channels to be supported per channel. Enhanced Observed time Difference (E-OTD) is the standard location determination technology for GSM networks (ANNEX E). This hybrid technology also uses network and handset based information to determine location. Signals from the Base Transceiver Station (BTS)[12] are sent to two separate geographic locations. The time at

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[12] The Base Transceiver Station is the link that transmits and receives signals in a mobile communication system. This device communicates directly with the Mobile Station or cellular phone. Communication is

which the signals arrive at the mobile phone station (MS) and a fixed measurement point, known as the Location Measurement Unit (LMU)[13], are compared to estimate location (BWCS Consulting, 2004).

A-GPS and E-OTD have been implemented in several areas throughout the United States. Until now, many major technical and financial setbacks have been experienced. Both of these location determination technologies consume a considerable amount of network bandwidth and require deployment of new handheld devices and network additions in order to locate subscribers (BWCS Consulting, 2002). E-OTD has presented some of the most critical flaws failing to provide the required location accuracy of 50 meters for 67 percent of calls and 150 meters for 95 percent of calls set forth by the FCC forcing carriers to incur millions of dollars in additional network equipment and fines (Mobile Radio Technology, 2003). AT&T was charged $2.2 million, T-Mobile agreed to pay $1.35 million for Phase I and Phase II related fines and Cingular Wireless made a voluntary contribution of $100,000 to the U.S. Treasury in order to avoid further investigation into possible Phase II violations (Federal Communications Commission, 2002a, 2002b, 2003). While A-GPS has managed to deliver the required accuracy in certain environments, in other locations, particularly urban canyons[14], inside buildings, underground parking garages, subways and under dense foliage, accuracy is greatly reduced.

An alternative to these location determination technologies claiming to be the most cost-effective and accurate solution requiring no further network or handset upgrades, is Enhanced Global Cell Identifier (E-CGI) technology offered by Digital Earth Systems. The technology is a statistical software package that extracts Network Measurement Results (NMR)[15] from the network and determines location based on a wireless radio wave propagation prediction model. It is compatible with any type of wireless standard and there

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made possible via a T1 connection between the Base Station Controller which patches into the wireline telephone network.

[13] Location Measurement Units are devices used in network-based position location systems to provide timing information

[14] Urban Canyons are areas in between two or more structures, typically buildings, where satellite signals are degraded or unobtainable.

[15] Network Measurement Results are wireless signal data used by network operators for network planning, network optimization, Quality of Service and market coverage analysis. GeoMode Compares these signal data with known location information within the network to estimate location.

are three forms it may take: a network model, data model or a hybrid form. Trials of this technology have taken place in New York City and Singapore producing an average accuracy of 50 meters, results well within the FCC requirements. The system does not add any load to the network and is capable of locating all current MS subscribers in any environment unlike A-GPS and E-OTD which require new handsets. This is a very attractive option for smaller carriers despite industry trends leading to the adoption of handset based technology (Digital Earth Systems, 2004a, 2004b).

Bell Mobility and Telus Mobility are integrating GPS technology to meet the CRTC 2003-53 location identification criteria. Bell Mobility has offered some of the following GPS equipped models since 2002: Audiovox 8500 & 8600, Kyocera 3245 & 7135, LG lm250, Nokia 3586i, Samsung A460, A500, A600 & N400.

2.1.3 Assisted GPS

The Global Positioning System (GPS) was originally designed by the US Department of Defence to enhance military operations and myriad commercial, scientific and civilian applications. GPS technology uses a constellation of 24 functional satellites circling Earth nearly every 12 hours at an altitude of approximately 20,000 kilometers to provide land, sea and airborne users with accurate three dimensional position, time and velocity data (Hofmann-Wellenhof et al. 2001). These satellites are divided into six orbital planes with four satellites in each plane. The orbital planes are set at a 55 degree inclination relative to the equator.

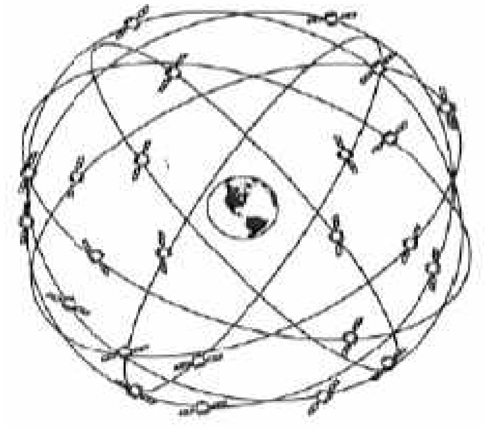

Figure 1. GPS Satellite Constellation

(Djuknic and Richton, 2001)

All of the GPS satellites use high precision clocks accurate to within 40 nanoseconds to deliver the time data used to estimate position. In order to determine two dimensional horizontal position, radio signals transmitting the pseudo-random ranging codes[16] and navigation data messages[17] from three satellites must be available to the GPS receiver. In order to calculate horizontal and vertical position, signals from four satellites must be obtained. While the satellite clocks are typically synchronized the GPS unit clock is not. The following equation is used to determine receiver coordinates.

Equation 1. Time Differential

$$Pj = \sqrt{(Xj - Xu)^2 + (Yj - Yu)^2 + (Zj - Zu)^2 + Ctu}$$

Pj is the measured range

(*Xu, Yu, Zu*) is the user coordinate

tu is the speed of light

(Djuknic and Richton, 2001)

GPS receivers use the ranging codes to measure the transit time (i.e. propagation) of the signals and determine the range between each satellite and the receiver. The navigation data message allows the receiver to calculate the position of the satellites at the time the signal

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[16] Pseudo random ranging codes enable GPS receivers to calculate distance

[17] Navigation data messages contain satellite position data

was transmitted. The receiver then calculates distance measurements to establish its location in relation to the captured satellites (United States Department of Defense, 1996).

Conventional GPS units typically require up to a several minutes to gain a “cold” position fix[18]. This is usually immediately after a GPS receiver unit has been activated and produces a surge in energy consumption. This is referred to as Time to First Fix (TTFF)[19].

Unlike conventional GPS, assisted GPS uses stationary reference GPS receivers placed at A-GPS servers which are connected to the wireless network to aid in locating the mobile handset (Djuknik 2001). The reference GPS receivers have a view of the same satellites as the handsets would under a clear line-of-sight[20] situation. The network sends this satellite information obtained from reference receivers to the handset. The partial GPS receiver in the handset uses this information to increase sensitivity when detecting GPS signals from visible satellites. This aids the handset in reducing TTFF to 1-10 seconds which is significantly lower than conventional GPS receivers. For emergency and commercial applications a TTFF under 60 seconds is essential to providing quality service. This signal data is then sent over the network to a central location server where position calculations are performed to obtain location coordinates.

This communication among devices and servers requires additional bandwidth. Although A-GPS is considered by many as the best location technology, there is a weak case for its use in commercial applications. In these instances multiple handsets requiring constant position updates would lead to excessive network congestion which is already a serious problem for WSP’s (Digital Earth Systems, 2004b).

GPS was created for open sky environments, where clear line-of-sight propagation conditions exist without obstructions which interfere with location estimate accuracy. The presence of physical obstructions between satellites and receivers interferes with satellite signal[21] acquisition producing location errors. These signal interferences are often referred

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[18] A cold position fix is a position taken without any information about the GPS constellation’s state.

[19] Time to First Fix (TTFF) is the time it takes the receiver to acquire signal lock with one satellite and extract correct time

[20] Line-of-sight in this case is the direct radio signal path from the satellite to the GPS receiver

[21] Satellite signals are microwave signals that cannot penetrate objects.

to in the literature as multipath errors, shadowing, fading or masking effects (Boulton et al., 2003; Deshpande, 2004; Karunanayake et al., 2004, 2005; Klukas et al., 2003; Kuusniemi et al., 2004; Lachapelle et al., 2003).

However, the increased availability of satellites used for positioning by 2010 will likely lead to more accurate location estimation in challenging environments. This will be made possible by the 30 additional satellites being launched for the European Union's Galileo project. These satellites will be both compatible and interoperable with GPS satellites thus enhancing satellite availability (Kuusniemi, Lachapelle, 2004).

2.1.4 Other Sources of GPS Errors

As described in *The Global Positioning System: Theory and Applications* by Parkinson and Spilker (1996), GPS errors can be classified by six different categories: ephemeris data, satellite clock, ionosphere, troposphere, multipath, receiver. Ephemeris errors occur when an incorrect satellite location is transmitted to the GPS receiver. Satellite clock errors deal with errors in the rubidium clock in the satellite vehicle and result in average location error of 1-2 meters for a 12 hour period. Ionosphere errors are caused by free electrons which delay the satellite signal. Troposphere errors are a combination of variations in temperature, pressure, and humidity that alter the speed of light of radio waves. Multipath errors are caused by objects that reflect or refract satellite signals creating a delay in nanoseconds to reaching the receiver and a location error of up to several kilometers. Receiver errors are caused by the unit itself and are affected by the ratio of the number of channels to the number of satellites tracked.

2.2 9-1-1 History and Assets in Quebec City

Prior to 1994, residents of the Quebec City Region were required to dial the desired emergency response service number directly. When 9-1-1 became recognized as the official emergency number in the province of Quebec, individual municipalities started to operate their own 9-1-1 call centers. This was an expensive endeavor and to promote a more efficient system five alternatives were proposed. Each municipality has the following choices for providing primary response 9-1-1 service (Federation of Quebec Municipalities, 2000):

1) Contracting a not-for-profit 9-1-1 call center known as Centre d’appels d’urgence Chaudière-Appalaches (CAUCA)

2) Requesting service from a peripheral municipality already operating a call center

3) Operating a secondary response center at an emergency service headquarters

4) Contracting a security company

5) Contracting a telephone company to handle emergency calls

Wireline customers and wireless subscribers in the Quebec City region are taxed for access to 9-1-1 service. These funds are used for a number of operational and fixed costs incurred by the carriers and the primary Public Safety Answering Point.

The 9-1-1 system dispatches emergency assistance for both wireline and wireless emergency calls. Wireless calls require more sophisticated telecommunication equipment. This equipment is more technologically advanced and incurs additional costs.

Given that the equipment used must be compatible with both wireline and wireless technology, one might assume that cost-sharing for new equipment exists. In this case, taxes from wireline and wireless customers would be pooled together for necessary expenses. Taking a more in depth look at these taxes will help define the current situation.

Comparing the collection and distribution of wireline and wireless 9-1-1 access fees may allow us to gain insight on how these levies are spent. This will also aid in identifying differences between the two taxes and suggesting alternatives to financing system upgrades.

Table 2 identifies the distribution of monthly fees for each wireline customer for supporting 9-1-1 service. For each wireline customer 32 cents per month goes toward maintaining 9-1-1 infrastructure and 47 cents per month goes to either the Federation of Quebec Municipalities or the Union of Quebec Municipalities that redistributes these funds to their respective municipalities.

If the municipality in question operates their own PSAP or receives service from a neighboring municipality's PSAP, these funds are handled by the Federation of Quebec Municipalities. The funds for municipalities that contract third parties to provide this service are managed by the Union of Quebec Municipalities. Having only one primary PSAP to finance with fees from the residents of the thirteen amalgamated municipalities of the former Quebec Urban Community is much more cost-effective than funding a PSAP for each one individually.

Table 2. Monthly 9-1-1 Wireline Fees

Monthly Fee	.32	.47
Maintenance	.32	
Phone Companies		.06
Union of Quebec Municipalities		.01
Municipality		.40

(Federation of Quebec Municipalities, 2004)

Although all but one of the wireless service providers collect a 25 cents per month fee of which approximately 17 cents goes toward maintaining Bell's Public Emergency Reporting Service 9-1-1 platform (Bell Canada 9-1-1 PERS), no municipal fee is charged to run the first respondent PSAP. From 1 July, 2004, Rogers Wireless will be collecting 50 cents per month in order to defray the costs incurred from E-911 upgrades.

Many public officials are under the impression that maximum rates have been established for each province by the CRTC and that requiring WSP's to collect a municipal fee is out of their jurisdiction. However, article 244.8 of the Fiscal Municipal Law of Quebec (*Loi sur la fiscalité municipale de Québec*, Chapter F-2.1, section III.1) states :

> *La municipalité peut conclure avec l'exploitant d'une entreprise de télécommunication une entente en vertu de laquelle l'exploitant perçoit au nom de la municipalité tout ou partie d'un montant payable en vertu de la présente section et destiné au financement de tout ou partie des biens, des services ou des activités relatifs à un « centre d'urgence 9-1-1(...) »*

Therefore, each municipality has the authority to request the wireless carriers operating in their area to collect a municipal 9-1-1 fee from their subscribers to finance their 9-1-1 service. If each of the 13 municipalities were to collect the same municipal 9-1-1 fee associated with wireline service for wireless, a significant means of cost-recovery for new installations and service would be created.

The annual budget for the Quebec City PSAP is nearly 3 million dollars, over ninety percent of which is spent on wages (Table 3). Although the figures for the 2004 PSAP budget seem to have been sufficient, there will be significant additional expenses when readying the center for Phase II capabilities and finding alternative means of financing these upgrades is necessary.

Table 3. Quebec City PSAP Budget for 2004

Expense	**Budget**
Salaries and Wages	2,924,863.00 $
Other Service Related Fees	125,000.00 $
Technical Service Fees	7,000.00 $
Goods Purchased	8,304.00 $
Maintenance Replacements	10,000.00 $
Total:	3,075,167.00 $

(Quebec City Department of Finance, 2004)

The multifaceted challenge of bringing accurate and affordable Phase II compliant location determination technology to Quebec City has only recently begun. The technological and financial feasibility will largely dictate the quality of emergency and commercial service rendered to Quebec City residents.

This will also provide new research and development opportunities for numerous regional public and private organizations that could harness these new capabilities and services to further advance their interests.

2.3 Related Research on Signal Quality

The relationship between GPS satellite signal quality and degraded signal environments has been studied extensively by several research teams. Kuusniemi *et al.* (2003) have proposed epoch-by-epoch least squares estimation for detecting and removing erroneous GPS signal observations using High Sensitivity GPS receivers in such environments. Klukas *et al.* (2003) concluded that the Urban Three-state Fade model developed by Akturan and Vogel (1997) provided a sufficient means of modeling outdoor GPS signal fading. Boulton *et al.* (2003) attempted to create models to verify multipath impairments in mobile phones equipped with A-GPS in the laboratory to avoid costly field testing. Their results reveal that the modeling accuracy of the variation of fading and multipath did not correspond well to field data. Lachapelle *et al.* (2003) explored performance enhancements of High Sensitivity GPS technology in these degraded signal environments. The improved measurement they observed is due to tracking ability of weak signals relative to conventional GPS. However, interference when using weaker signals introduced large measurement errors.

These studies have largely focused on improving GPS accuracy in degraded signal environments. They have not identified the percentage of a given administrative area affected by these environments or the varying degree of expected accuracy according to building dimensions and relative location.

3 PROJECT JUSTIFICATION

- From an urban planning perspective, we are interested in questions related to the quality of public safety regarding the massive usage of wireless technologies
- An all-encompassing document which explores the multifaceted developments in wireless 9-1-1 service in a local and national context is currently unavailable.
- The project aims at updating the estimation of current technological capabilities using GPS in urban areas.
- There is a definite need to study the effect of the density of the built environment and the urban landscape on the reliability and accuracy of location determination using GPS.

- This will allow us to identify problem areas when using GPS technology in the urban districts of Quebec City.
- Several recent studies at the Centre for Research in Regional Planning and Development at Laval University have incorporated GPS technology. A functional model of GPS signal quality in the urban environments of Quebec City could aid these groups in planning around difficult signal reception areas.

4 RESEARCH QUESTIONS

There is a definite relationship between GPS signal quality and the Quebec City urban environment. Quantifying this relationship and uncovering the primary building attributes affecting the signals is the motivation behind this investigation. This study is an analysis of four related questions:

1) Does the probability of losing satellite reception increase as the percent of obstructed sky increases?

2) By how much does the probability of losing satellite reception change when the percent of obstructed sky increases or decreases?

3) Does the proportion of obstructed sky affect the average number of available GPS satellites in the line-of-sight?

4) If the percent of obstructed sky does affect the number of GPS satellites at what percent of obstructed sky does the critical minimum number of satellites to determine location drop below three?

These questions cannot be answered with certainty. However, identifying strategies to analyze these questions and determine to what extent building obstacle characteristics locally influence GPS signal quality may aid in identifying priority zones within Quebec City that would be susceptible to degraded location information.

5 HYPOTHESES

Our study addressed the research questions in the previous section with the following research hypotheses:

1) GPS satellite signals are not equally available throughout the urban landscape, creating spatial variation in signal reception and the number of satellites used for obtaining a position

2) The spatial variability in the building obstructions' height, width and location relative to the observation point affects the quality of GPS signal reception and the accuracy of the positioning

3) There is a statistically significant negative effect on satellite signal reception quality with increasing proportions of obstructed sky

4) Modeling the effects of obstructed sky is an efficient means of assessing the likelihood of losing GPS signal lock in an urban environment

6 GENERAL AND SPECIFIC OBJECTIVES

6.1 General Objectives

There are three general objectives for this master's thesis:

1) To document the development of a Wireless E-911 system in the Quebec City region by synthesizing the available knowledge of federal, provincial and municipal policies, cost recovery mechanisms, technological feasibility and barriers to implementation

2) Combining a GIS and GPS field measurements, propose a new methodology for estimating GPS reception quality using readily available large scale digital topographic maps

3) Contribute to the development of surveys for monitoring transportation patterns and consumer behavior of the Quebec City population using real-time GPS receivers

6.2 Specific Objectives

The specific objectives related to these general objectives are:

1) Create a geostatistic database to model the effect of building obstacles (obstructed sky) on GPS signal reception quality for the Quebec Topographic Data Base digital files 21L14-101 and 21L14-102 at the 1:20 000 scale

2) Identify problematic areas that local emergency dispatch personnel should be aware of when receiving automatic location information from carriers using A-GPS technology

3) Spatially assess potential repercussions that GPS signal loss could have on the efficiency of local emergency dispatch

7 METHODOLOGY

7.1 The Overall Modeling Strategy

The simulation of estimated probability of GPS satellite signal lock loss in urban environments was performed using a geographic information system in MapInfo software. A brief description of the main steps required to accomplish this goal follows:

1) Observe GPS signal quality and record field measurements of obstructed sky

2) Create a statistical model that takes into account the measured obstacles

3) Create an index using these statistical models

4) Apply the model in urban areas

5) Stratify the study area according to distance and building height using buffer zones around the building objects

6) Create a cartographic representation of average GPS signal lock loss using the inverse squared distance weighting interpolation method

The modeling procedure diagram in Figure 2 illustrates the order in which the data was processed and the software used to execute the individual tasks. A more in depth description of these tasks is given in the following sections.

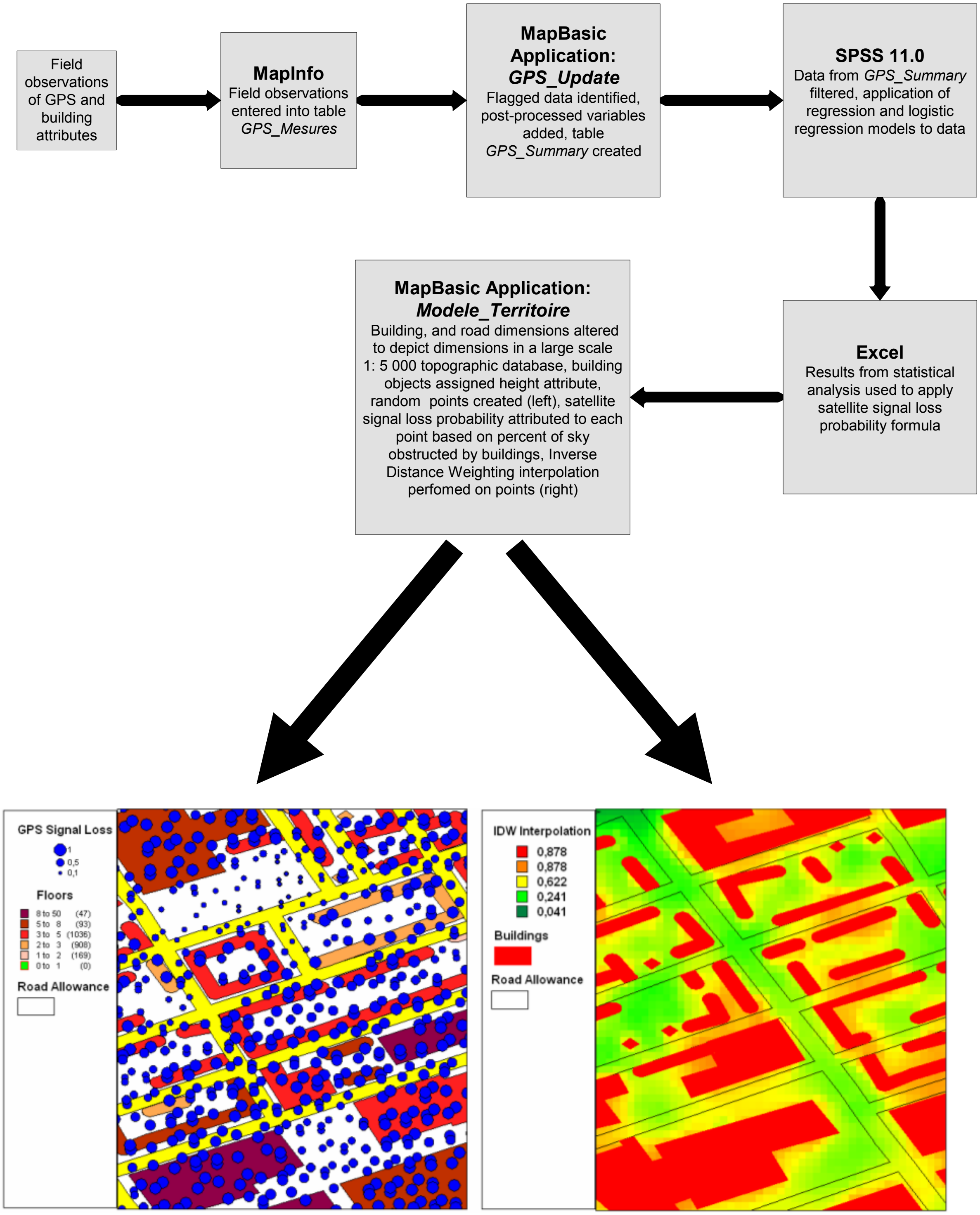

Figure 2. Modeling Procedure

7.2 Materials and Equipment

For this study, GPS signal quality data was collected by observing satellite signal presence, the number of satellites received and measuring the magnitude of obstructions (building height and width) with a GPS receiver, laser distance meter mounted on a level tripod and a compass with raised azimuth dial (Figure 3).

The receiver was a 12 channel, hand held Garmin GPS 76 with a built-in Quad Helix antenna operating at L1 (1.57542 GHz). By default the receiver mask angle[22] is set at 5 degrees above the horizon. The receiver's LCD screen indicated when the receiver had lost satellite reception and displayed the satellites being used for location determination and their relative signal strength.

The laser distance meter was a Leica Disto Classic 5 accurate to +- 3 mm/100 m with a built in level, and ¼" camera thread. The laser provided an accurate and immediate means of determining distance to buildings. However, the laser was not visible during daylight hours, even with red filter laser glasses, unless in dark shadowed areas. This required the vast majority of measurements to be taken at night (during winter in Quebec, from 5 pm to 3 am).

Distances greater than 40 meters at vertical angles above 80 degrees were rarely possible to measure. This is primarily due to the fact that the obstruction's vertical surface did not reflect the laser beam back to the point of origin which is how it determines distance.

The tripod was a Manfrotto 190QCB with a 325RC ball head (rotates 360 degrees and allows 90 degree inclination) and locking handle to control each axis movement. This head was fitted with a locking quick-release camera plate for additional laser stability. In order to take an accurate reading the mounted laser had to be completely locked into place allowing no movement.

A soft GPS pouch was attached to the center of the tripod where the GPS was placed during the laser and compass measurements.

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[22] Mask Angle- Signals from satellites must be above this threshold (degrees above the horizon, usually 5 to 10) to be used for location determination.

The Silva compass used had a split-sight mirror, geared declination and raised azimuth dial. The declination was set at 15.5 degrees for all measurements. This was a close approximation as current large scale topographic maps indicating declination for individual urban areas were not available. The delicate nature of this instrument required bare hand operation.

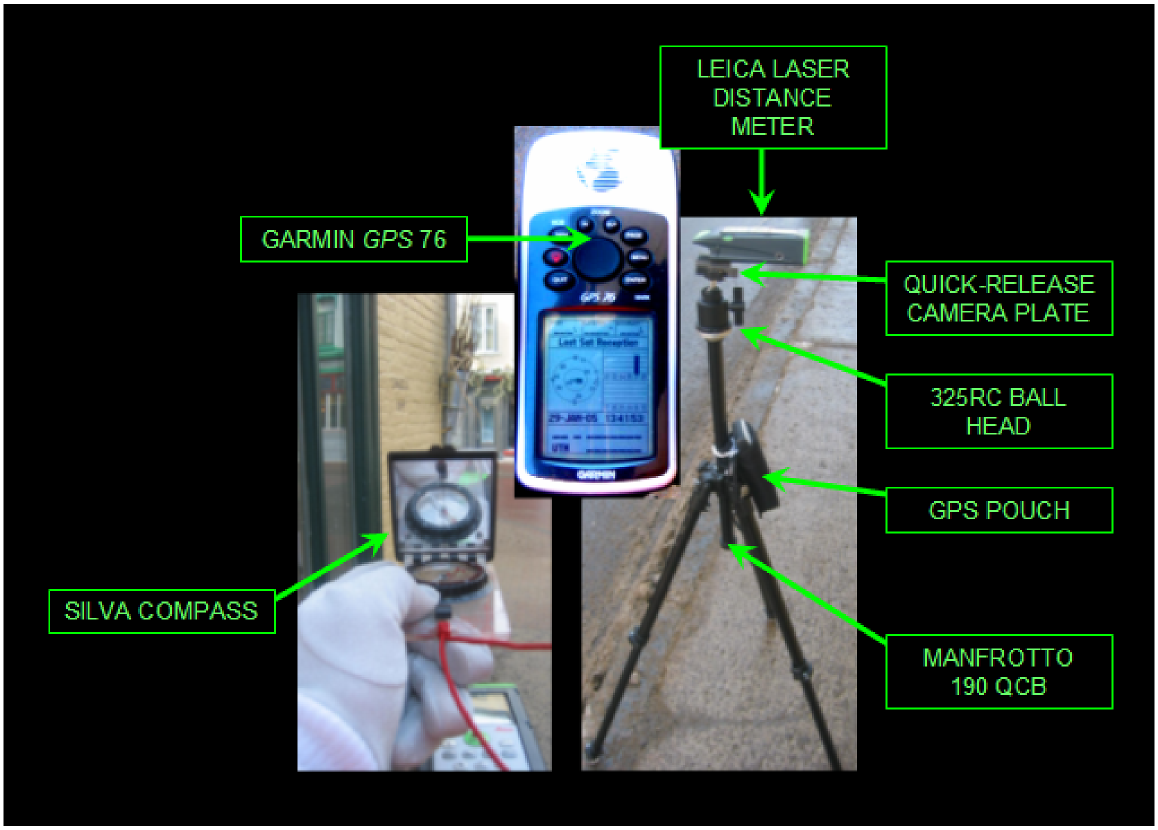


Figure 3. Field Measurement Equipment

7.2.1 Computing Resources

For all data entry and subsequent modeling we used a 32 GHz Pentium 4 computer equipped with 1Gb RAM, 20 Gb hard disk space and MapInfo 7.5 and 7.8 software. ESRI ArcGIS 8.3 software was used for one particular step of the modeling process (ANNEX F)

7.3 Data Collection Method

Prior to each field measurement session the battery power for the GPS and laser meter was verified. If under 70 % power, the batteries were replaced to ensure optimal performance of the equipment. In the field, if the battery power display on either piece of equipment reached half strength fresh batteries were inserted.

Having arrived on-site, the GPS was activated in an open area without any obstructions in a 50 meter radius. Satellite acquisition time allotted was 2 minutes and the average number of satellites displayed on the receiver was 6 before moving to the degraded signal environments. This was an attempt to simulate A-GPS technology where the receiver would not be operating under cold start conditions. Therefore, the receiver had obtained the current time, orbits of the satellites and its own current position before entering a degraded signal environment.

During this satellite acquisition time, the laser distance meter was locked in place using the camera plate and the tripod was adjusted to reach a height of 130 centimeters. A small holster or pouch for the GPS was attached to the neck of the tripod and the lanyard of the compass was secured to the right hand wrist and jacket sleeve for easy access.

While approaching the degraded signal environments the GPS was held in hand at approximately 130 centimeters above ground (waist height) with the receiver facing the sky at a 65-80 degree angle. This provided realistic potential usage conditions for a cellular phone (dialing position) and allowed reasonable GPS screen monitoring. All observations were taken on foot in an attempt to simulate conditions pedestrian cell phone users could encounter. The variables in Table 1 were recorded according to the following procedure:

1) Approach the obstruction until approximately 1 meter remains between the GPS receiver and the building wall.

2) Take a waypoint with the GPS receiver.

3) Open the tripod with the laser facing perpendicular to the first obstruction surface.

4) Note the observation point number under the column *numsit_pt.*

5) Note the total number of buildings surrounding the observation point under the column *nb_edif* and the sequential order of the building being measured under the column *Lecture*.

4) Using the waypoint information on the receiver display, note whether the signal was present or absent at the time the waypoint was taken under the column *Signal*, the number of satellites being used for navigation under the column *nomb_sat*, the UTM coordinates and the date and time of the waypoint.

5) Place the GPS receiver in the holster attached to the tripod facing toward the sky.

6) Turn on the *Disto* laser distance meter. Unlock the ball head handle and press the *Dist* button one time to activate the laser.

7) Aim the laser at the building surface so that a level, horizontal line is formed that is perpendicular to the obstruction and between the left and right extremities (from the observer's point of view) of the wall. Lock the ball head in place and gently press the *Disto* button a second time.

8) Note the distance displayed on the laser distance meter under the column *Dist_h1* and aim the compass at arms length and eye height where the laser was just aimed. Note the azimuth under column *Alpha_1*.

9) Reactivate the laser. Unlock the ball head handle and press the *Dist* button one time to reactivate the laser.

10) Aim the laser at the far right corner of the wall so that a level, horizontal line is formed between the laser and the far right corner. Lock the ball head in place and gently press the *Disto* button a second time.

11) Note the distance on the laser's display under the column *Dist_h2* and aim the compass at arms length and eye height where the laser was just aimed. Note the azimuth under column *Alpha_2*.

12) Unlock the ball head handle and press the *Dist* button one time to reactivate the laser.

13) Aim the laser at the far left corner of the wall so that a level, horizontal line is formed between the laser and the far left corner. Lock the ball head in place and gently press the *Disto* button a second time.

14) Note the distance on the laser's display under the column *Dist_h3* and aim the compass at arms length and eye height where the laser was just aimed. Note the azimuth under the column *Alpha_3*.

15) Unlock the ball head handle and press the *Dist* button one time to reactivate the laser.

16) Aim the laser at the building surface where *dist_h1* was taken. Trace a straight vertical line from that point to the top of the building with the laser. Lock the ball head in place and gently press the *Disto* button a second time.

17) Note the distance on the laser's display under the column *Elev_d1* and aim the compass at arms length and eye height where the laser was aimed for *dist_h1*. Note the azimuth under *Alpha_e1*.

18) Unlock the ball head handle and press the *Dist* button one time to reactivate the laser.

19) Aim the laser at the building surface where *dist_h2* was taken. Trace a straight vertical line from that point to the top of the building with the laser. Lock the ball head in place and gently press the *Disto* button a second time.

20) Note the distance on the laser's display under the column *Elev_d*2 and aim the compass at arms length and eye height where the laser was aimed for D*ist_h2*. Note the azimuth under the column *Alpha_e2*.

21) Unlock the ball head handle and press the *Dist* button one time to reactivate the laser.

22) Aim the laser at the building surface where *dist_h3* was taken. Trace a straight vertical line from that point to the top of the building with the laser. Lock the ball head in place and gently press the *Disto* button a second time.

23) Note the distance on the laser's display under the column *Elev_d3* and aim the compass at arms length and eye height where the laser was aimed for D*ist_h3*. Note the azimuth under the column *Alpha_e3*.

24) Remove the GPS from the holster holding it at waist height for 15 seconds and take a waypoint.

25) Using the waypoint information on the receiver display, note whether the signal was present or absent at the time the 2nd waypoint was taken, the number of satellites being used for navigation, the UTM coordinates and the date and time of the 2nd waypoint and street address or other location description.

26) Unlock the ball head handle and press the *Dist* button one time to reactivate the laser.

27) Rotate the quick release plate attached to the laser so that the laser is facing the next wall.

28) Repeat steps 2 through 26 for each consecutive wall surrounding the observation point until all obstructions have been measured.

29) Slowly increase the distance between the first obstacle and the receiver until a significant change takes place (i.e. satellite signal regained, several satellite signals become available). Repeat steps 2 through 28 for each additional observation point.

Figure 4 illustrates steps 7, 10 and 13 using the laser to measure horizontal distance. The first measurement is taken by aiming the laser directly at the obstruction wall so that a perpendicular line is formed with the wall (Dist_h1). This forms two right angles on either side of the laser beam. Then the distance to the extreme right hand corner of the wall is measured (Dist_h2). The final horizontal distance measurement is the distance from the observation point to the extreme left hand corner of the wall (Dist_h3).

It is extremely important that these measurements are executed in this order. Calculations during the post processing of the measurements are inaccurate if this sequence is not followed correctly.

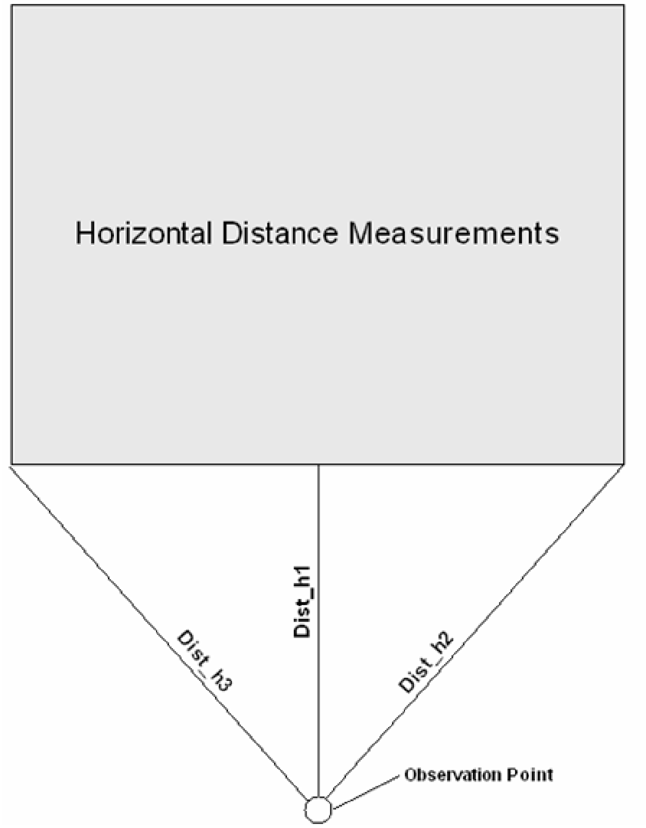


Figure 4. Level Horizontal Measurements w/ Laser

The vertical distance measurements in Figure 5 show steps 16, 19 and 22. For each vertical measurement the laser is aimed first at the same target for the horizontal measurements. Then, slowly tilting the laser toward the sky, maintaining a straight vertical line, the beam is pointed at the highest point of the wall surface and the measurement is taken.

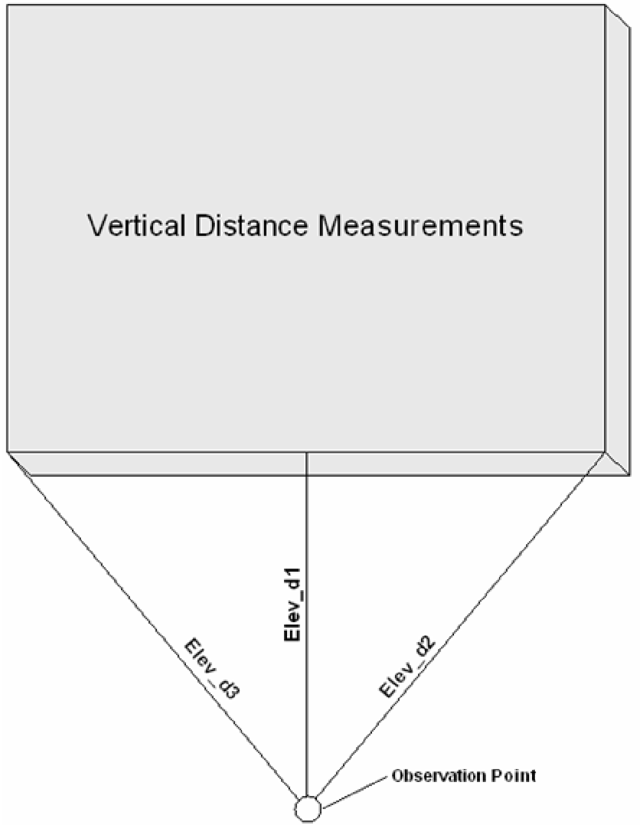


Figure 5. Vertical Measurements w/ Laser

Figure 6 represents steps 8, 11, 14, 17, 20 and 23. These measurements are taken using the compass with azimuth dial and one measurement is taken immediately after each distance measurement (horizontal and vertical). The values for the Alpha_*n* and Alph_e*n* are essentially the same measurement. The elevation measurement was taken for verification purposes and the acceptable difference between the measurements must be between 2 and 6 degrees. If not both measurements were repeated.

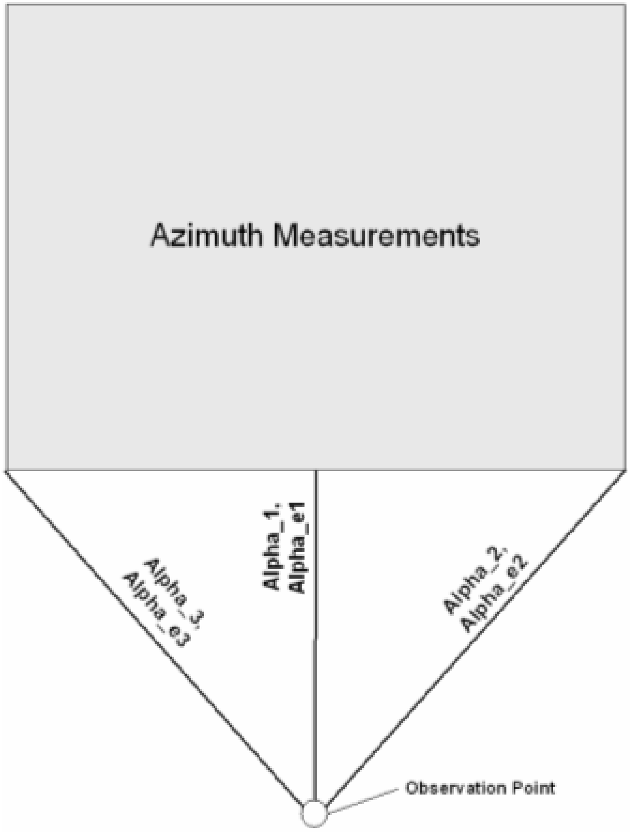


Figure 6. Measurements Used to Calculate Horizontal Obstruction

As the distance between a building wall surface and an observation point decreases, the angle of obstructed sky (horizontal and vertical obstruction) increases. This is illustrated by Figure 7.

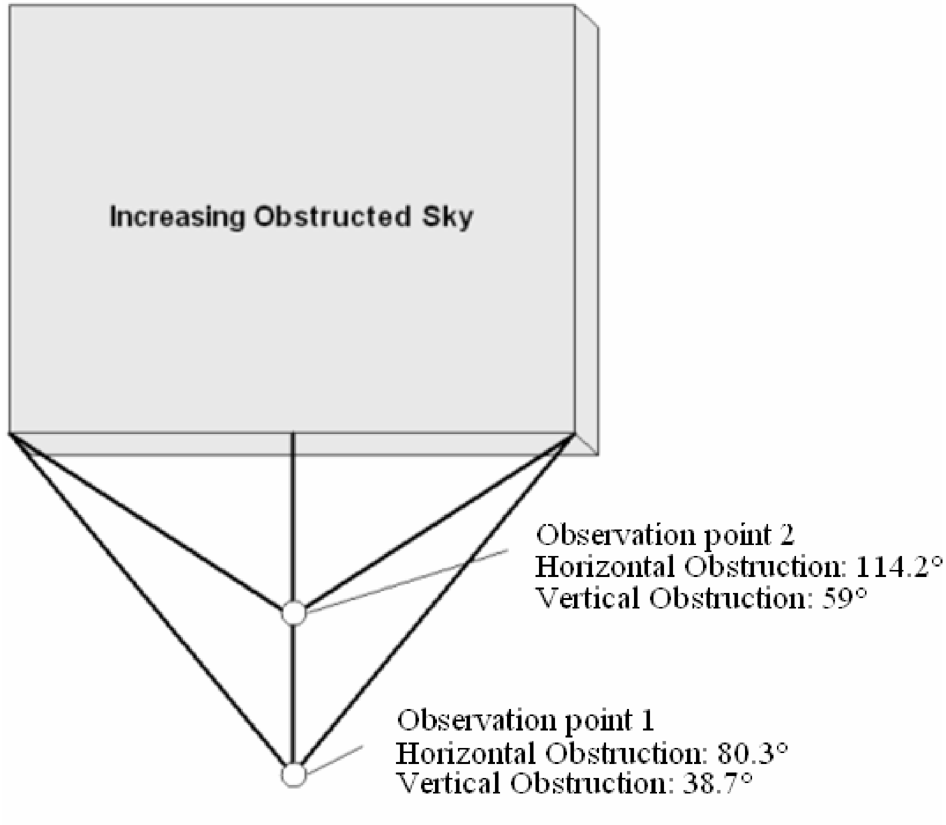


Figure 7. Effect of Distance on Obstruction Angles

7.3.1 Identifying Potential Observation Sites

Having decided on how the data for this experiment would be collected, it was still necessary to identify places where the observations would take place. The digital topographic maps at the 1:20 000 scale provided the relevant information to determine where building density was highest and where GPS signal quality would most likely be affected.

7.3.2 Test Site Observations

The Laval University campus served as a preliminary test site (Figure 8). There are numerous locations where effects similar to those experienced in urban canyons could occur. This aided in finalizing the procedures and requirements for field measurements.

The measurements on the Laval University campus began November 14th, 2004 and finished December 7th, 2004. During this time period, 162 points consisting of 186 building walls were observed. 137 of the 162 points were recorded in the presence of one building.

Our objective during the measurements for the first 20 observation points was to isolate the obstructing effect to a single building. We defined this as an external building wall where there were no other obstructions (buildings) within a 50 meter radius. After these first points were entered into our database, the field logbook was slightly modified to include observation points with more than one building around them.

The measurements for one building are illustrated in Figure 9. The six red lines represent the horizontal and vertical distances measured with the laser distance meter. Their compass direction was also recorded after each distance measurement. A more detailed description of each measure is listed under the Data Collection Method subheading.

Figure 8. Laval University Campus

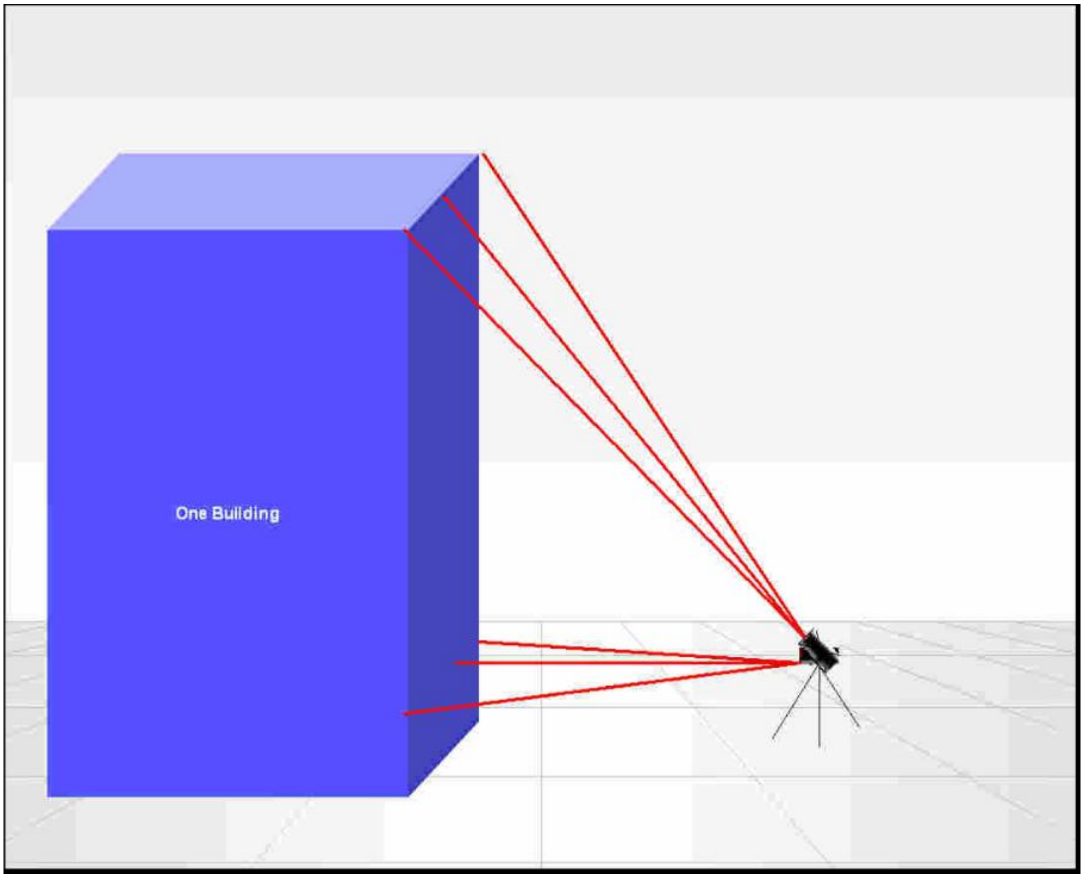


Figure 9. Measurements for One Building

7.3.3 Design and Structure of the Flat-File Database *GPS_Mesures*

The database used for initial data entry and additional post-processed variables was designed to maximize ease of data entry. This was accomplished by maintaining the same structure used for the field measurement data sheet and placing the observed variable columns to the far left and the post-processed variable columns immediately after to the right. To take full advantage of the table for subsequent analysis it was reduced to the simplest useful components.

7.4 Field Measurements

The off-campus measurements in the administration districts of Sainte-Foy/Sillery, La Cité, and Limoilou began on January 11, 2005 and were completed March 1, 2005. The majority of these points were in the presence of 2 or more buildings. As shown in Figure 10, the tripod was kept in the same place for each wall measurement. Using only the ball head to change the laser's orientation, it was aimed at the other surrounding obstructions as stated under the Data Collection subheading. For this period 184 points represented by 316 walls were observed and include 83 points with 1 building, 62 points with 2 buildings 34 points with 3 buildings and 5 points with four buildings.

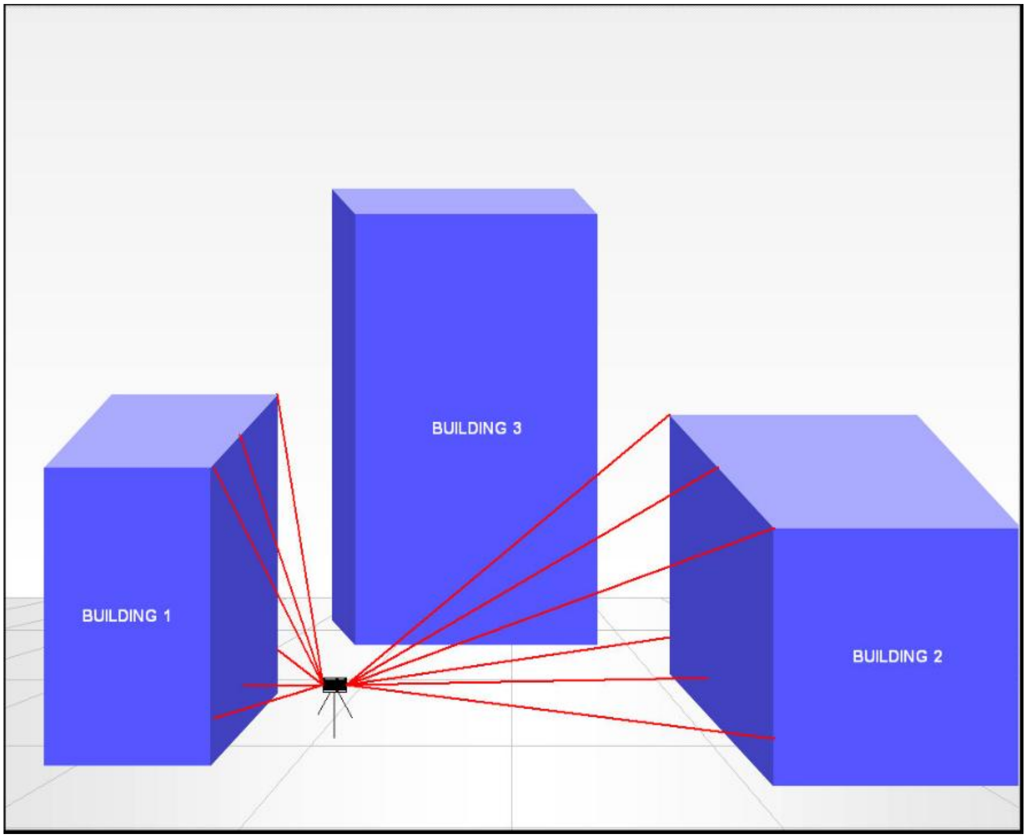


Figure 10. Measurements for Multiple Buildings

7.4.1 Sample Description

The observation point sample collected between the period of November 14, 2004 and March 1, 2005 consists of 2 representative sub samples taken on the Laval University campus and in urban areas of Quebec City (Figure 11). The general areas of the sites were selected using the 1:20 000 scale building files from the Quebec Topographic Database. We attempted to represent many possible obstruction conditions by varying observations in areas of low medium and high density with buildings of different size and spacing. For the first sub sample, minimal obstruction conditions of only one building, were given highest priority. Although several observation points in the second sub-sample were observed in these same conditions, preference was given to more diverse conditions with two or more building walls present.

The sample is made up of 346 observation points in a variety of degraded GPS signal environments. Approximately half of these observations were taken while the receiver had lost satellite signal lock, or reception, and the number of satellites captured varies from 0 to 9. The necessary time to perform and record measurements was significantly influenced by the number of buildings present at the observation points. This ranged from as little as 10 minutes for one building to nearly an hour for points with three and four buildings.

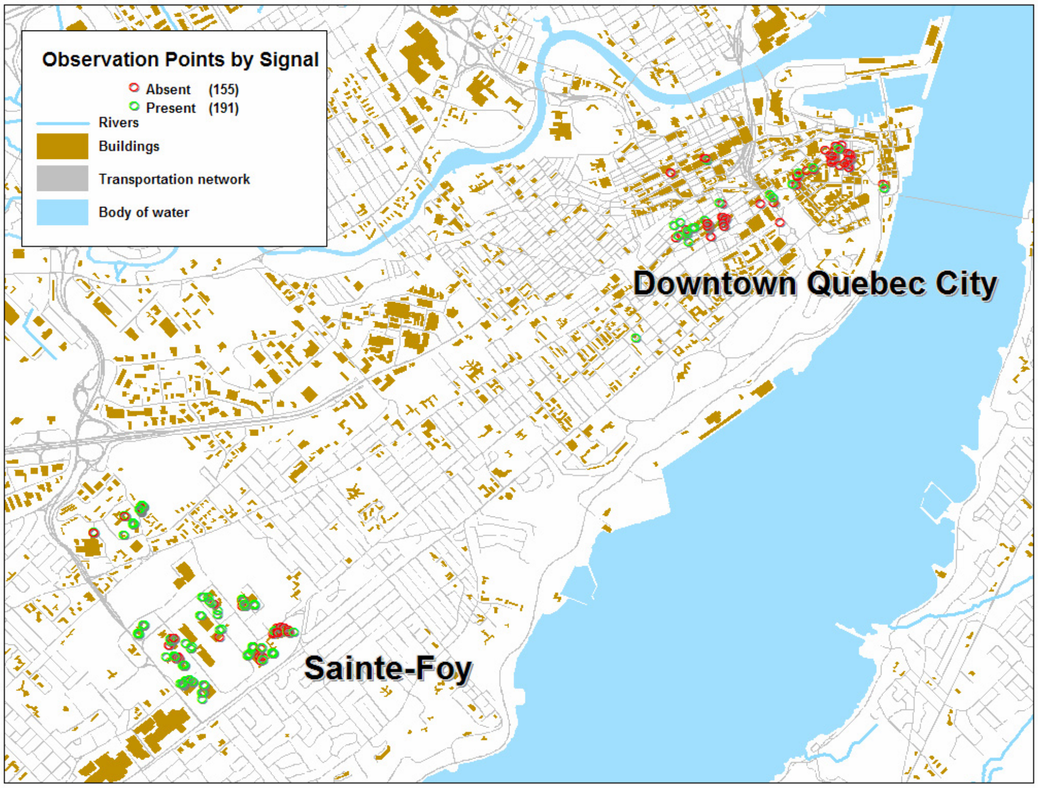


Figure 11. GPS Measurements

7.4.2 Measured Variables

All observed variables included in the study are given in Table 4. A variable from the database, satellite signal reception (Signal), was used in part to define satellite signal quality. In the case of a signal lock loss the receiver displayed the most recent location in UTM coordinates prior to signal loss until the signal was regained.

The other component of our definition of satellite quality was the number of satellites (nomb_sat) variable. This variable was defined by the presence and number of signal strength bars in black (indicating usage for positioning) appearing on the GPS display at the time the waypoint was taken. Signal strength bars in a lighter shade were not counted as valid signals as these signals are merely beginning to be acquired and not used for location identification purposes. Using the Garmin GPS 76, a minimum of 3 black indicators are required to get an updated 2 dimensional position fix (x and y coordinates) and a minimum of 4 black bars are required to get an updated 3 dimensional position fix (x and y coordinates, elevation).

The minimum and maximum number of satellites observed ranged from 0 to 9. Using the logic that three GPS satellite signals are required to obtain a location, one would assume that losing satellite signal reception equates to obtaining less than three signals. However, up to 5 black satellite signal strength bars on the Garmin display were observed while the receiver had lost satellite reception throughout the course of the field measurements. Both of these variables were used as outcomes in the statistical analyses, however only satellite reception was valid for use in the spatial analysis.

Determining the heights of the buildings and the angles from the observation point to the top of the building obstruction required several direct observations to be recorded. Using simple triangulation formulas, these field observations were then used to calculate missing variables necessary to perform the analyses.

Several variables were not used in the investigation. However, these variables could prove to be useful for subsequent studies using this database. These studies might include the time elements (hours, minutes, year, month and day) which would allow the satellite constellation to be accounted for. Another potential study could focus on demographic transportation characteristics using the Origin-Destination database to estimate the relative percent of individuals affected by degraded signal environments at various times throughout a 24 hour period. These studies could provide a more effective means of identifying high priority areas for the Quebec City PSAP.

Table 4. Observed Variables

Variable	Explanation	Abb.
Observation point number	Codes observation point with numeric ID	numsit_pt
Total number of buildings	Total number of buildings at observation point; Min = 1 Max = 4	nb_edif
Reading identification	Specific building number of total number of buildings for a particular observation point	Lecture
Satellite signal reception 1	Presence or absence of satellite signal at time of first waypoint 0 = satellite signal loss, 1 = satellite signal present	signal
Number of satellites 1	Number of satellites displayed at time of first waypoint	nomb_sat
Easting 1	6 figure UTM easting position at time of first waypoint	utm_est
Northing 1	7 figure UTM northing position at time of first waypoint	utm_nord
Date	Day-month-year format	date
Time 1	Military time as decimal associated with the first waypoint	heure_deb
Horizontal distance 1	Horizontal distance in m from observation point to obstruction between extreme left corner and extreme right corner of wall	Dist_h1
Compass bearing 1	Compass bearing of the first horizontal distance measure	Alpha_1
Horizontal distance 2	Horizontal distance in meters from observation point to the extreme right corner of the obstruction	Dist_h2
Compass bearing 2	Compass bearing of the second horizontal distance measure	Alpha_2
Horizontal distance 3	Horizontal distance in m from observation point to the extreme left corner of the obstruction	Dist_h3
Compass bearing 3	Compass bearing of the third horizontal distance measure	Alpha_3
Elevation distance 1	Distance in meters to the highest observable point of the obstruction in line with the first horizontal distance	Elev_d1
Compass bearing 1	Additional reading of alpha_1 for verification	Alpha_e1
Elevation distance 2	Distance in meters to the highest observable point of the obstruction in line with the second horizontal distance	Elev_d2
Compass bearing 2	Additional reading of alpha_2 for verification	Alpha_e2
Elevation distance 3	Distance in meters to the highest observable point of the obstruction in line with the third horizontal distance	Elev_d3
Compass bearing 3	Additional reading of alpha_3 for verification	Alpha_e3
Number of satellites 2	Number of satellites captured at time of second waypoint	Nomb_sat2
Satellite signal reception 2	Presence or absence of satellite signal at time of first waypoint	Signal2
Easting 2	6 figure UTM easting position at time of second waypoint	utm_est2
Northing 2	7 figure UTM northing position at time of second waypoint	utm_nord2
Time 2	Military time as decimal associated with the second waypoint	heure_fin
Commentary	General identification of observation point location; street, building	commentaire

7.4.3 Alpha Measurements

In order to quantify the magnitude of the obstructions around the observation points, additional variables had to be calculated from the observed field data measurements. Much in the same way one would create a rectangular sky plot for obstructions around control points, the buildings had to be defined using azimuth and elevation.

Figure 12 illustrates a rectangular sky plot with bearing on the X-axis and vertical elevation on the Y-axis. The horizontal axis is labeled 0 to 360 degrees, where 0 degrees corresponds to North, 90 degrees to East, 180 degrees to South, and 270 degrees to West. The vertical axis is labeled 0 to 90 degrees, where 0 degrees corresponds to a point on the horizon and 90 degrees to a point directly overhead. The measurements of the obstacles attempted to reflect the skyline as seen in all directions from the specific point of observation.

The two buildings represented in Figure 12 are measurements taken for the observation point number 124 of the *GPS_Mesures* database. Building one has a vertical elevation of 87.43 degrees and the Alpha measurements are 157°, 296° and 31°. Building two has a vertical elevation of 47.93 degrees and the Alpha measurements are 318°, 334° and 296°.

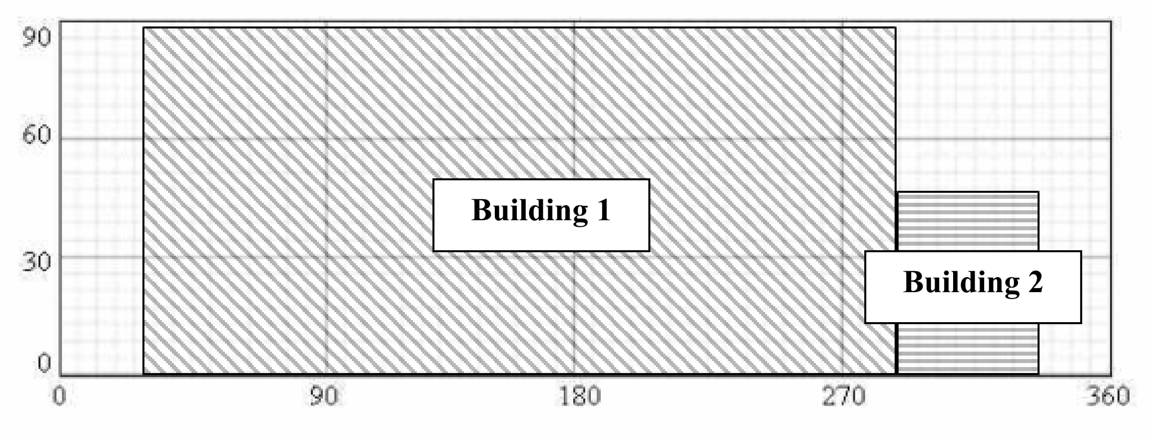


Figure 12. Rectangular Sky Plot

7.5 MapBasic Application *GPS_Update*

A procedure for automating calculations was developed to provide additional variables from the observed measurements. The primary function of the MapBasic application *GPS_Update* was to automate the inclusion of information that could be derived through calculation. Using the *GPS_Measurement* database, the application generated the additional variables necessary for statistical analysis, provided a means of data verification and created a graphic component of the observation points in a map browser.

Table 5. Post-Processed Variables

Variable	**Explanation**	**Abb.**
Vertical building height 1	$h1 = \sqrt{(elev\_d1)^2 - (dist\_h1)^2}$	h1
Vertical building height 2	$h2 = \sqrt{(elev\_d2)^2 - (dist\_h2)^2}$	h2
Vertical building height 3	$h3 = \sqrt{(elev\_d3)^2 - (dist\_h3)^2}$	h3
Vertical elevation	$elev\_vert = (Radians)(\pi / 180) * xAtn(h1 / dist\_h1)$	elev_vert
° horizontal obstruction	$ouv\_horiz = beta\_2 + Beta\_3$	ouv_horiz
° from alpha_1 to alpha_2	If alpha_1 > alpha_2 Then beta_2 = (360 – alpha_1) + alpha_2 If alpha_1 < alpha_2 Then beta_2 = (alpha_2 – alpha_1)	beta_2
° from alpha_1 to alpha_3	If alpha_1 > alpha_3 Then beta_3 = (alpha_1 – alpha_3 If alpha_1 < alpha_3 Then beta_3 = (360 + alpha_1) – alpha_3	beta_3
Logical statement	False = ouv_horiz > 360, True = ouv_horiz =< 360	valid
Beginning time in fractions of a day	temps_deb = the two digit hour of (heure_deb) /24) + (two digit hour and minutes of heure_deb – two digit hour of heure_deb)/14.40	temps_deb
End time in fractions of a day	temps_fin = the two digit hour of (heure_fin) /24) + (two digit hour and minutes of heure_fin – two digit hour of heure_fin)/14.40	temps_fin
Refined equation for % of sky masked by building obstacles	$masque = (ouv\_horiz * \int_{e=1}^{elev\_vert} Cos(e) / \int_{e=1}^{90} 360 * Cos(e)) * 100$	masque

The first step is to alert the user if there are inconsistencies in the measurements. The vertical distance measurements for points 256, 257, 258, 259 and 260 were less than the horizontal distance readings. According to our field measurement assumptions, all measured walls are flat surfaces. This is therefore an impossibility and these points were eliminated from the database.

Given that the errors in distance measurement for points 256, 257, 258, 259 and 260 were observed in consecutive order, one might assume that there was a period of time where the Leica laser distance meter was not properly functioning. While this may be explained by equipment instability or failure, we do not have a means of determining the exact reason behind these inconsistencies.

The heights of the obstructions are then calculated using the Pythagorean Theorem. The vertical elevation angle or *elev_vert* of the obstruction is determined by returning the arc-tangent value of the first vertical distance divided by the first horizontal distance measurement and then converting the results in radians to degrees (maximum 90°). If the results from this calculation exceed 90° an error message is displayed. This did not occur for any of the observation points.

The degrees of obstructed horizontal sky or *ouv_horiz* (maximum 360°) were determined by calculating the horizontal angles of each wall at a given point and adding these values. For a point with one building wall obstruction this is the Beta_2 + Beta_3 angle (Figure 13). This angle is formed by the extreme left-hand corner horizontal azimuth and the extreme right-hand corner horizontal azimuth of a building wall. As with the vertical elevation angle, an error message is displayed if the sum of the degrees of obstructed horizontal sky exceeds 360° for a given point. None of the points had an *ouv_horiz* value greater than 360°.

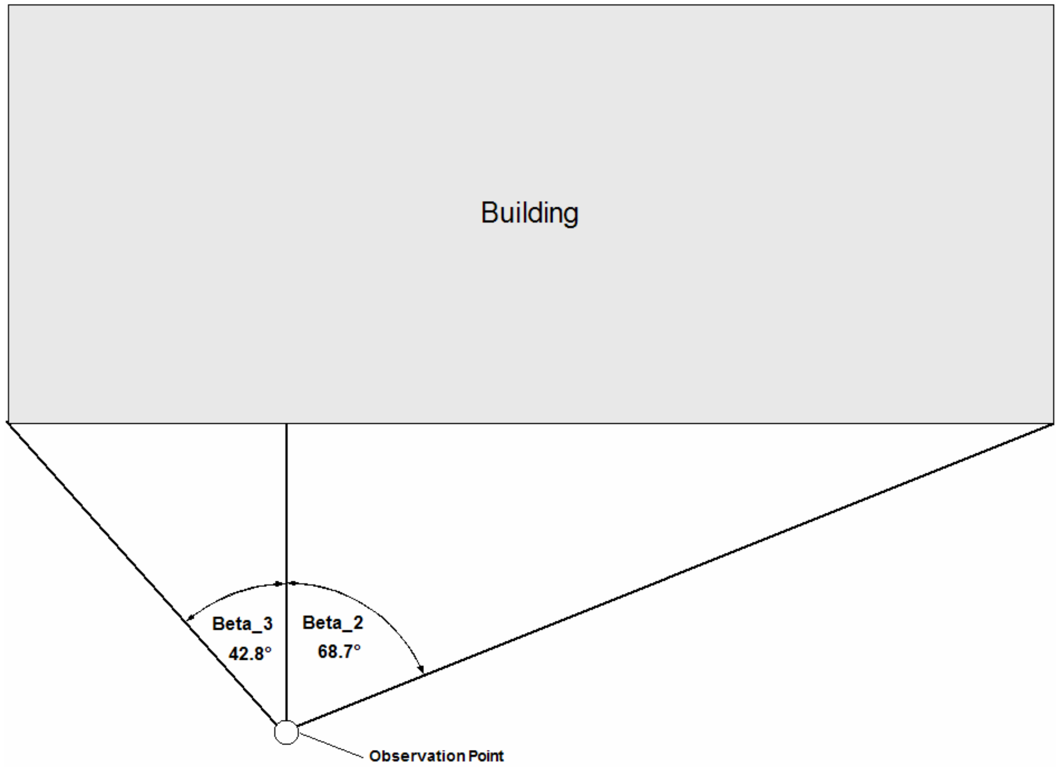


Figure 13. Beta Variables

These additional variables, *elev_vert* and *ouv_horiz*, were then entered into further calculations to derive one obstruction variable. The obstruction variable *masque* is the product of the degrees of horizontal obstruction times the integral of the cosine from 1 to the observed degrees of vertical elevation divided by the constant times 100 (see Table 6). The constant was derived by multiplying the maximum horizontal obstruction (360°) by the integral of the cosine of all of the values of the maximum vertical elevation (from 1 to 90 degrees).

Due to the fact that variables for observation points with more than one building would not be correctly represented, a summation was performed for several variables for each observation point. Variables for minimum satellite signal, minimum number of satellites, maximum number of satellites, maximum vertical elevation, minimum horizontal distance from a building, maximum horizontal distance from a building and variables that add the associated *masque* values for each observation point were automatically calculated using the MapBasic program *GPS_Summary* (Table 6). These variables were saved in a Database File (Summary.dbf) for use in other software.

Table 6. *GPS_Summary* Variables

Variable	**Explanation**	**Abb.**
Minimum satellite signal	Compares variables signal1 and signal2 for all walls and takes the lowest value (either 1 for presence or 0 for absence)	Signal
Minimum number of satellites	Compares the variables nomb_sat1 and nomb_sat2 for all walls and takes the lowest value	MinSat
Maximum number of satellites	Compares the variables nomb_sat1 and nomb_sat2 for all walls and takes the highest value	MaxSat
Maximum vertical elevation	Compares the variable Elev_vert for all walls and takes the highest value	elev_vert
Minimum horizontal distance	Compares the variable dist_h1 for all walls and takes the lowest value	MinDist
Maximum horizontal distance	Compares the variable Dist_h1 for all walls and takes the highest value	MaxDist
Total obstructed sky	Adds the variable *masque* for all walls surrounding observation point	Summasq

7.6 Statistical Analysis

Prior to analysis the sample was split into two groups: points with only one building and points with one or more buildings (all points in the database). For both of these groups invalid entries were omitted by applying a filter for any observations with a S*ummasq* value equal to or greater than 100 (this figure represents the percent of total obstructed sky), an impossibility for the actual measurements. This occurred for point 307 and was not included in the statistical analysis.

Removing points 256, 257, 258, 259, 260 and 307 does introduce a selection bias in our sample. However, this is not due to a direct manipulation of the data. Their rejection is based upon strict selection criteria that allow only realistic observations to be included in the analysis. Points 256-260 and 307 were not geometrically possible.

A scatter plot for the dependent variable *Summasq* (adds the degrees of obstructed sky for all walls surrounding a given observation point) and the independent variables *MinSat* (minimum number of satellites at a given point) and *nomb_sat* (number of satellites displayed at time of first waypoint) were run in SPSS 11.0 individually. A linear relationship did not exist between *Summasq* and either one of these variables, simple linear regression was ruled out.

Next, binary logistic regression was performed on the dependent variable S*ignal* with several predictor variables. Two predictor variables proved to be significant. However, the subsequent logistic regression was performed on the variable S*ignal* for the explanatory variable S*ummasq* only, using all observation points in the database with the exception of points 256-260 and point 307.

7.6.1 Interpretation of Logistic Regression

For this study, logistic regression was used with a dichotomized form of satellite signal quality as the outcome variable to determine whether the average satellite signal reception observed in our field measurements could be explained by building obstruction conditions.

Binary logistic regression analysis aims to describe the relationship between a binary dependent variable and a set of independent variables. This model is often cited for its flexibility and meaningful interpretation. Unlike linear regression, where the outcome variable has a normal distribution, the outcome variable in binary logistic regression has only two values. As Figure 14 illustrates, the model is not linear.

The logistic regression model is used primarily to compute an index of estimated probability for an individual event given the probability of the sample. When fitted to our data, this model allows us to estimate the expected GPS signal quality according to the building obstruction conditions of a given point.

The categorical dependent variable used for this analysis is *Signal* and is summarized in Table 8. Of the 340 valid observation points in our sample, satellite signal reception was present at 190 points and reception was absent at the remaining 150 points. The independent variable is S*ummasq* which is the sum of the number of degrees of obstructed sky for each wall surrounding the observation point divided by the maximum number of degrees of possible obstructed sky. Each value is represented as a percentage in the database.

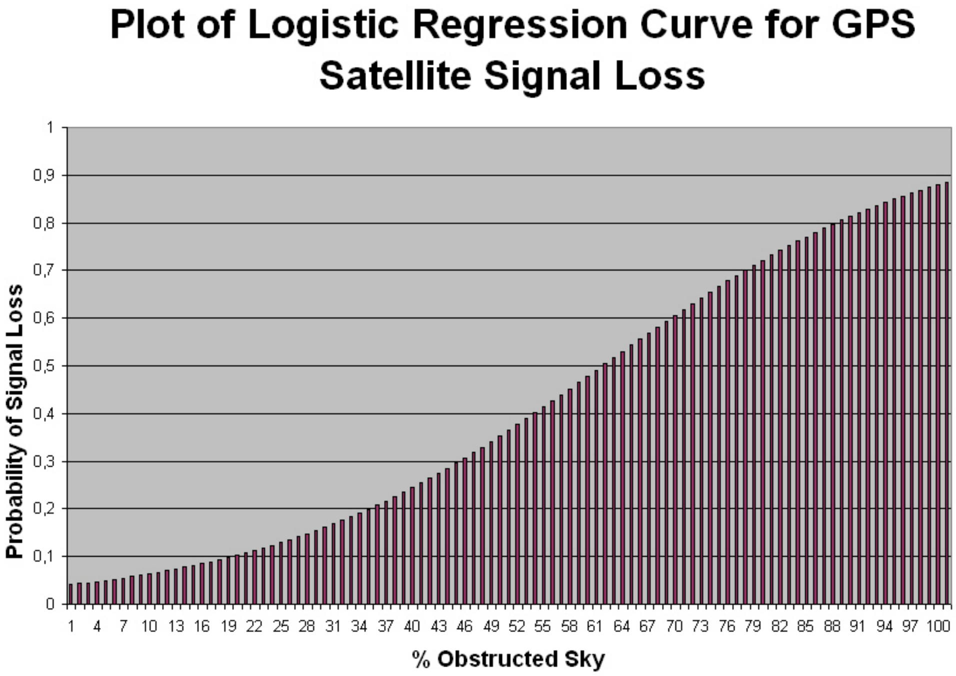
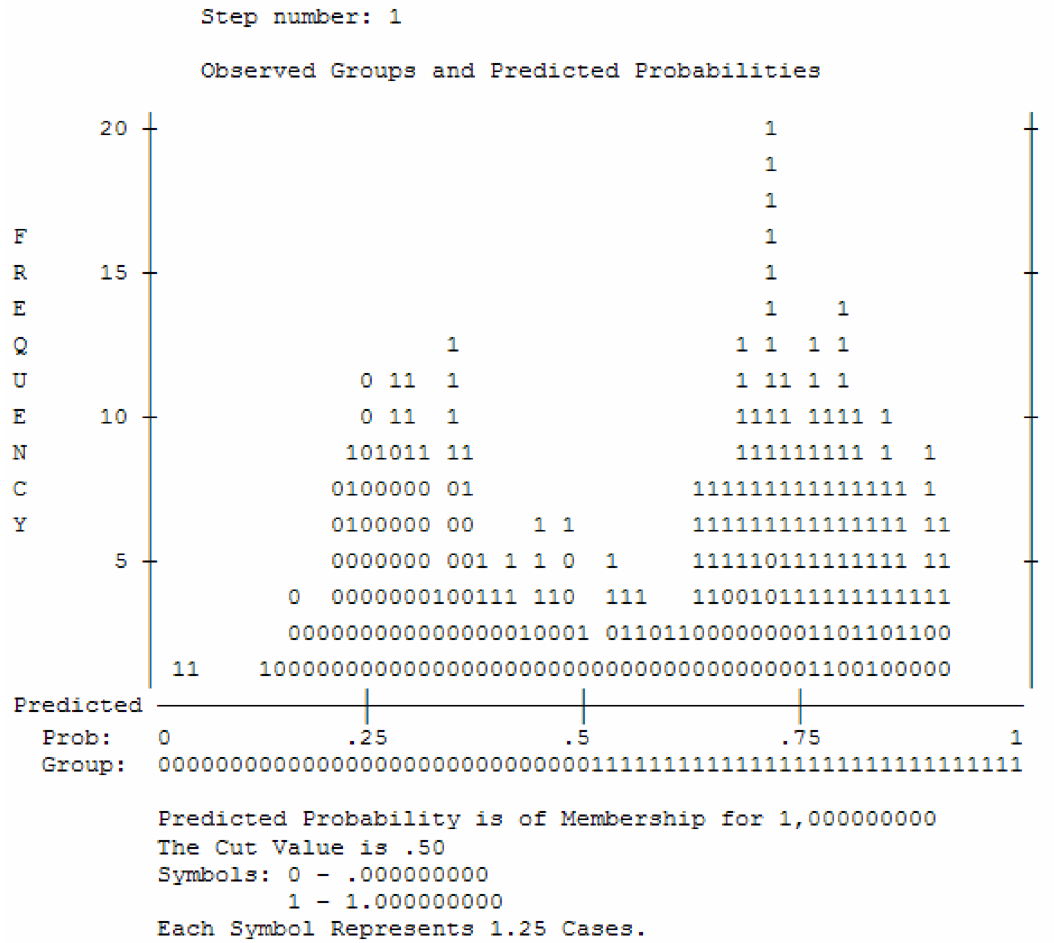


Figure 14. Binary Logistic Regression Distribution

The histogram resulting from the application of the model to our database presents expected probabilities of GPS satellite signal reception of a point as either an absence (0) or presence (1). In Figure 15, each symbol represents 1.25 cases. In order to qualify as a model that manages to distinguish between these categories, the cases for signal presence should be to the right of .05 and the cases for signal absence should be to the left of .05. Clustering of matching symbols on both sides is therefore an indication of a successful model.



```
             Step number: 1

             Observed Groups and Predicted Probabilities

      20 +                                          1                 +
         |                                          1                 |
         |                                          1                 |
F        |                                          1                 |
R     15 +                                          1                 +
E        |                                          1    1            |
Q        |                    1                   1 1  1 1            |
U        |              0 11  1                   1 11 1 1            |
E     10 +              0 11  1                   1111 1111 1         +
N        |             101011 11                  111111111 1  1      |
C        |            0100000 01               111111111111111 1      |
Y        |            0100000 00    1 1        111111111111111 11     |
       5 +            0000000 001 1 1 0  1     111110111111111 11     +
         |         0  0000000100111 110  111   110010111111111111     |
         |         000000000000000010001 011011000000001101101100     |
         | 11    10000000000000000000000000000000000000001100100000     |
Predicted ---------------+--------------+--------------+--------------
   Prob:  0            .25            .5             .75             1
   Group: 000000000000000000000000000000111111111111111111111111111111

          Predicted Probability is of Membership for 1,000000000
          The Cut Value is .50
          Symbols: 0 - .000000000
                   1 - 1.000000000
          Each Symbol Represents 1.25 Cases.
```

Figure 15. Histogram of GPS Satellite Signal

Table 7 contains the overall test of the model known as the "Omnibus Tests of Model Coefficients" table in SPSS. In binary logistic regression there are steps 0 and 1. Step 0 is used to determine the intercept only; none of the predictors are included. Step 1 output in SPSS begins with the Chi-Square results in Table 7. The chi-square test determines the overall model fit for the data set. This is the change in the -2 times the log likelihood (-2LL) of the log likelihood function from the previous step, block, or model (SPSS, 11.0). From the results in Table 9 our model is adequate at p = <.0001.

Table 7. Chi-Square Results

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	78,546	1	,000
	Block	78,546	1	,000
	Model	78,546	1	,000

Table 8 is the classification table produced from the model. This table is another means of assessing model performance by comparing the observed dependent variable categories with the predicted response categories. For signal absence (S*ignal* = 0) 102 predictions were correct and 39 were incorrect. For signal presence (S*ignal* = 1) 151 predictions were correct and 48 predictions were incorrect. The probability of expecting signal loss when a signal is absent is 72.3%. The probability of expecting signal presence when a signal is present is 75.9%. The predictive value for signal loss is 68%, and is the probability of signal absence when signal loss is predicted. The predictive value for signal presence is 79.5%, and is the probability of signal presence when signal presence is predicted. Thus, the total correct predictive classification ability is equal to 74.4%.

Table 8. Observations VS. Predictions for *signal*

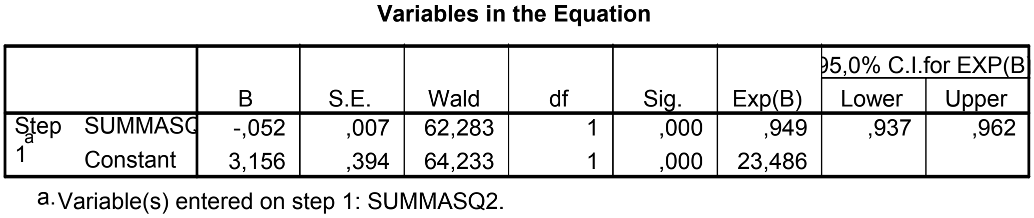
Classification Table[a]

			Predicted		
			SIGNAL		Percentage Correct
	Observed		,000000000	1,000000000	
Step 1	SIGNAL	,000000000	102	48	68,0
		1,000000000	39	151	79,5
	Overall Percentage				74,4

[a] The cut value is ,500

From Table 9 we see that the predictor variable S*ummasq* is clearly a significant independent variable (p <.0001). The first column of Table 9 represents the coefficient (B) of the logistic regression model. These coefficients are difficult to interpret using logistic regression and so were converted to an odds ratio (Equation 2). S.E. is the Standard Error of the predictor variable. The Wald statistic tests for significance (whether the coefficient equals 0) and is the ratio of the estimated coefficient over the standard error squared at 1 degree of freedom. The Exponential of the B coefficients is the predicted change in odds for a unit increase in the predictor. If the Exp(B) is less than one, increasing values of the variable correspond to decreasing odds of the event's occurrence (Hosmer, 2000). For every 1% increase in the obstruction of the sky (Summasq), there is a .949% reduction in the probability of obtaining a signal. The Confidence Interval or C.I. determines if the odds ratio is statistically significant. If the 95% C.I. includes 1 the odds ratio is not statistically significant. Our model's low end is below 1 and the difference between the low and high end is rather small (.025).

Table 9. Logistic Regression Output



Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)	95,0% C.I.for EXP(B	
								Lower	Upper
Step 1[a]	SUMMASQ	-,052	,007	62,283	1	,000	,949	,937	,962
	Constant	3,156	,394	64,233	1	,000	23,486		

a. Variable(s) entered on step 1: SUMMASQ2.

7.6.2 Determining the odds ratio

For this analysis, an important algebraic substitution for obtaining the odds ratio was performed. On the log scale, addition is the equivalent to multiplying, e.g.: Log (a*b) = Log (a) + Log (b). As demonstrated in the example, this was accomplished by replacing the terms added on the log scale with multiplication. The reason behind this substitution is that if the terms are added there is very little variability in the odds ratio, thus resulting in a poor model of signal variability. However, when multiplied there is a significant difference in the variability of the odds ratio.

This allowed a means of calculating the approximate probability of satellite reception presence or absence according to the portion of sky masked:

Equation 2. Odds Ratio Substitution

Odds = Exp (A) + Exp (B*Summasq) = Exp (A * (B*Summasq))

The pseudo r-square statistics, Cox & Snell and Nagelkerke, indicate the approximate variation explained by the model to a maximum value of 1. Table 10 presents these test statistics and indicates that the variable *masque* explains between 20 and 27 percent of the variability in GPS signal loss.

Table 10. Pseudo R-Square Statistics

Model Summary

Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	388,077	,206	,276

The primary objective of this analysis is to generate a cartographic display of the estimated likelihood of GPS signal presence. The results of the application of this model allow us to give a spatial representation of the average conditions for satellite signal loss according to the built environment.

7.6.3 Statistical Modeling

In Figure 16, the worst scenarios for building obstruction conditions (80-100%) are assigned probabilities of GPS satellite signal presence and absence using the formulas in Equations 3 and 4. Equation 3 establishes the odds ratio at a given percent of obstructed sky. Equation 4 then assigns probabilities for signal presence and signal absence according to the obstruction conditions.

Equation 3. Odds Ratio

Odds = Exp (A*(B*Summasq))

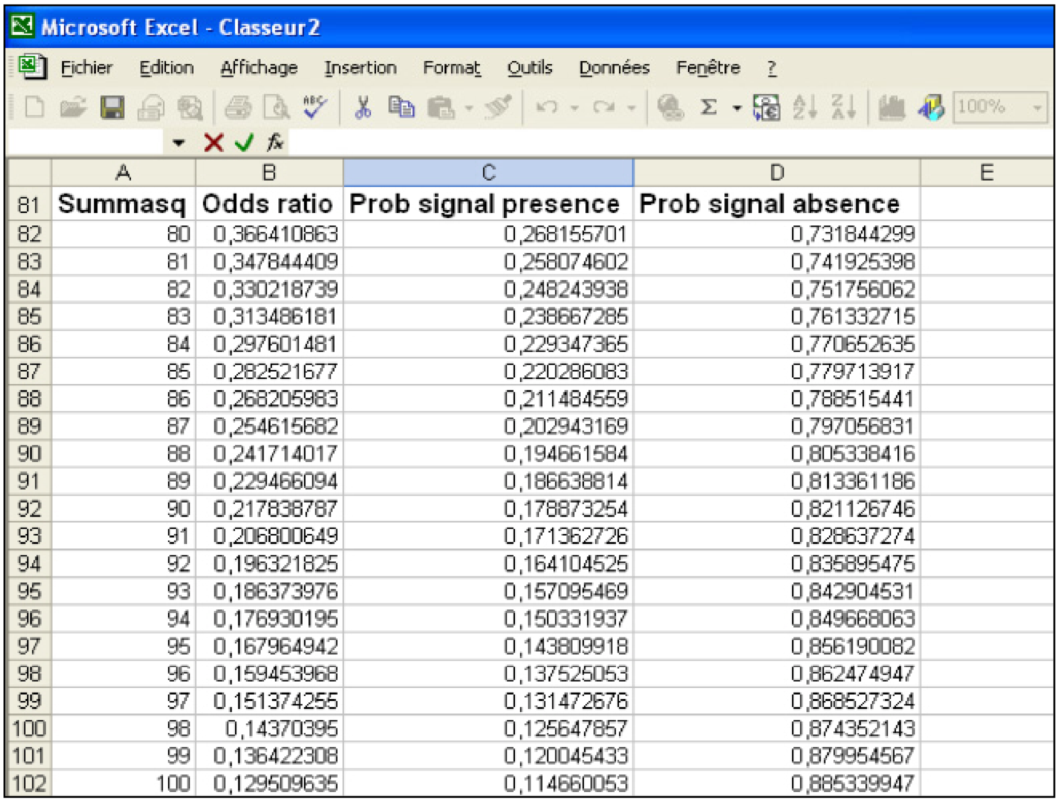
For each unit of obstructed sky (1%), the odds ratio determined the variation in the probability of signal presence and absence. For example, at a point with 90% obstruction of total available sky, there is a 17.8% chance of signal presence and an 82.1% chance of signal absence. These probabilities were calculated with the formulas in Equation 4.

Equation 4. Signal Probabilities

Presence = Odds/(1+Odds)

Absence = 1-(Odds/(1+Odds))

With all the estimated probabilities for conditions of obstructed sky between one and one-hundred percent, the probability index for satellite signal quality was complete. If the total percent of masked sky conditions for a given point were known, the probability of observing GPS signal presence or absence could then be estimated.



	A	B	C	D	E
81	Summasq	Odds ratio	Prob signal presence	Prob signal absence	
82	80	0,366410863	0,268155701	0,731844299	
83	81	0,347844409	0,258074602	0,741925398	
84	82	0,330218739	0,248243938	0,751756062	
85	83	0,313486181	0,238667285	0,761332715	
86	84	0,297601481	0,229347365	0,770652635	
87	85	0,282521677	0,220286083	0,779713917	
88	86	0,268205983	0,211484559	0,788515441	
89	87	0,254615682	0,202943169	0,797056831	
90	88	0,241714017	0,194661584	0,805338416	
91	89	0,229466094	0,186638814	0,813361186	
92	90	0,217838787	0,178873254	0,821126746	
93	91	0,206800649	0,171362726	0,828637274	
94	92	0,196321825	0,164104525	0,835895475	
95	93	0,186373976	0,157095469	0,842904531	
96	94	0,176930195	0,150331937	0,849668063	
97	95	0,167964942	0,143809918	0,856190082	
98	96	0,159453968	0,137525053	0,862474947	
99	97	0,151374255	0,131472676	0,868527324	
100	98	0,14370395	0,125647857	0,874352143	
101	99	0,136422308	0,120045433	0,879954567	
102	100	0,129509635	0,114660053	0,885339947	

Figure 16. Statistical Models

7.7 Topographic Elements of the GIS

Ideally, the topographic data used for this study would have been large scale (1:2,000 – 1:5,000) cadastral data allowing more precise measurements to be taken. However, digital maps and data at this scale are not available in all places for all municipalities in the province of Quebec. For this reason we chose to use the 1:20,000 scale topographic data available for all of southern Quebec from the province's Department of

Natural Resources and Wildlife. This is a common, intermediate scale for building representation of urban landscapes.

The objects from this topographic database are represented as points, lines and polygons. A combination of factors is used in the selection process to determine which real world objects are represented at the 1:20 000 scale and their symbology in the topographic database. One of these factors is the dimensions of the object. According to the norms of production issued by the Quebec Department of Natural Resources and Wildlife, all buildings are judged essential and are therefore located and defined regardless of their dimensions. However, their geographic representation depends on minimal dimensions. Real world buildings represented as point objects are below the minimal dimension threshold for representation as either lines or polygons. To be represented as lines, buildings must have one side at least 26 meters long. For polygons, buildings are required to have a minimal area of 500 m^2.

Therefore, the most accurately depicted buildings in this database are represented by polygons with reliable measured dimensions. The line and point objects provide incomplete information regarding the real dimensions of the objects they represent. From the line buildings we are able to determine the measured length of the longest side of the building and can assume that their width is less than 19 meters (minimum area of building polygons/minimum length of building lines). The point objects indicate location; however, these buildings are represented with 0 dimensions leaving nothing to be measured from them.

The transportation network is represented by line segments connected by nodes. Each line segment belongs to a particular level of the transportation network’s functional classification system. The classes of this system are divided into two sub categories: the superior arterial system and the complementary network to the superior system are maintained by the Cartography Office of the Quebec Department of Natural Resources and Wildlife. The superior system uses the following classes according to the character of service: highways, national roads, regional roads, collector roads, local roads and access roads. The complementary system uses this specific classification: road, path, abandoned transportation corridor and transportation corridor under construction (Québec, 2000). As illustrated in Figure 17, the line segments in the topographic database were intended to represent the centerline of the road allowance for the given corridor.

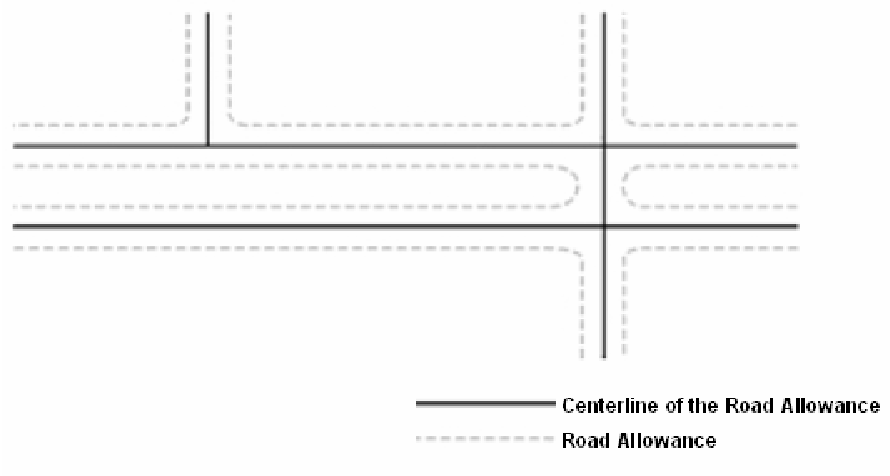


Figure 17. Cartographic Representation of Transportation Network

(Québec, 2000)

In an attempt to reproduce the building and transportation network objects with a cartographic representation similar to what one would expect from a 1:5,000 scale map, buffers of varying size were applied to the objects according to their estimated average dimensions.

Increasing the surface area of these objects in densely inhabited areas created object overlap. To prevent this from occurring, portions of the new buffer objects were reshaped. This was accomplished by establishing an object hierarchy and attributing a specific rank for each object relative to the other objects.

The object hierarchy in Table 11 lists the elements of the transportation network and the building layers. As the table indicates, the object category determines the buffer size and object rank for these elements. When an object of higher rank intersects a lower level object the lower level object is reshaped to reflect the higher ranking object's form.

The functional classes of the transportation network previously mentioned were aggregated to represent three corridor categories: Local, Collector and Arterials.

Table 11. Object Hierarchy

Layer	**Geographic Representation**	**Object Category**	**Buffer Size**	**Object Rank**
Transportation Network	Line	Local (street)	4 m	2
	Line	Collector (road)	5 m	2
	Line	Arterials (highway)	7 m	2
Buildings	Point	Small Building (area <500 m^2, length <26 m)	4 m	No priority
	Line	Medium Building (area <500 m^2, length >26 m)	4 m	3
	Polygon	Large Building (area >500 m^2)	No Buffer	1

(Québec, 2000)

The major setback in modeling the urban landscape with the available data is a lack of building height information. The topographic files do not indicate this attribute. Therefore, an alternative means of obtaining this data for a large urban area was developed to give an approximation of building height. This method uses the real estate assessment role database for Quebec City. Buildings are represented as point objects which in the vast majority of cases is the centroid of the land parcels on which they are built. This database contains a wealth of information of attributes for these points. For our study, we were interested only in the point coordinates and the associated number of floors. To determine building height estimates, the number of floors was multiplied by three meters. The building objects were then spatially matched with the points and attributed height information (ANNEX F). This method in combination with our attempt to better represent building and network objects introduces considerable errors. However, our goal was to estimate GPS signal quality for a vast area and the available data is not intended for high-precision micro-measurements.

Although the addition of terrain data for our study area would increase the precision of signal quality estimates, this variable was not observed during the field measurements.

Adding this variable to our model would require another intensive measurement campaign which is not possible due to current time constraints. The relatively flat topography in the observation areas included in our sample and the excessive computational resources required in terms of processing power support our reasoning for the exclusion of the terrain as an explanatory variable for this step of the research.

7.7.1 MapBasic Application *ModeleTerritoire*

This program was developed in MapBasic and executed in MapInfo. The primary aim of developing the program was to create a suitable geographic model of the effects of building obstructions on two dimensional GPS location prediction ability (minimum of 3 satellites). The application requires the following base layers in order to execute: transportation network, polygon buildings, line buildings, point buildings and assessment role database points. If any of these tables is not present in the MapInfo workspace it is automatically opened by the application.

Once these tables are available a timer is started to keep track of the elapsed time from the beginning of the program execution until completion of each sub procedure. Depending on the size of the study area, some of the application tasks require only a few seconds to complete, whereas the more complex commands can take up to several weeks. The calculations performed by this application for the area of the two digital topographic database files 21L14-101 and 21L14-102 were very intense on the available computational resources. To improve computation speed the first command divides the given territory (whatever its' extent may be) into 1 minute longitude by 1 minute latitude or 800 meter by 1100 meter tiles. Next buffers of varying sizes are created around the linear objects of the transportation network according to their level in the functional hierarchy to model the road allowance (Table 4). The road allowance dimensions are then restricted to remain outside of the building objects. Buffers around the point and line building objects are created to represent small and long, narrow buildings. The dimensions for the building objects are readjusted according to their relative level in the object hierarchy (Table 4). These reshaped building objects are then placed in a separate table representing synthesis coverage of all buildings. Using the assessment role database points, elevation is then attributed to the building objects in this table.

Some difficulties were experienced when attributing building heights to the building objects. The vast majority of points in the assessment role database were located inside the building objects. In some instances two or more points were present for one building object. However, there was also a significant number of building objects that did not contain a point from the assessment role database. The procedure followed to attribute height values to buildings in these cases is covered in detail in ANNEX F.

With the urban landscape modeled the next step of this application creates randomly distributed points to allow the application of interpolation methods for the entire study area. The point density factor for generating randomly distributed points in each tile is set at 10,000 by default. However, this may be changed in the MapBasic source file to reflect a higher density. For each point, the distance and elevation of the nearest buildings in a 50 meter radius in all 360 degrees are used in the calculation of the overall obstruction. This equates to simulating the creation of a rectangular sky plot for each randomized point. The probability index for signal absence is then applied to each point using its percentage of obstructed sky. These points along with their associated obstructed sky attribute are saved in a separate table.

For this study, the MapBasic application began execution at 18:40 on April 20, 2005 and ended at 16:26 on May 7, 2005. The application ran without interruption for nearly 430 hours before completion. These points were then interpolated using MapInfo.

7.7.2 Interpolation Procedure

The purpose of the spatial interpolation performed in our investigation was to generate a continuous grid surface of estimated GPS receiver location determination capability in areas where samples were not collected. This is rather difficult using the *GPS_Summary* data set because of the small number of sample observations collected (341 points over the course of three months) and their representation as static points whereas at differing times of day the GPS satellite constellation configuration changes, potentially translating to more or less available GPS satellites. To compensate for the small sample size random points representing satellite signal loss probability were created using MapBasic. The points are randomly created in each tile with a point density factor of 10,000. This increased our sample to 7,902,180 points in the 530 Km^2 study area.

Spatial interpolation refers to a method of predicting unknown values as a function of distance to known values. This procedure has two basic assumptions about the consistency of the distribution of data points in a layer: the tessellation assumption and the field assumption. The tessellation assumption assumes that the study area is divided into regions and that points are attributed the values of the nearest sampling unit. The field assumption assumes that points are attributed values of weighted averages of neighboring points. There are a great number of weighting functions and these may be altered to best fit the data and desired results (Thurston *et al.*, 2003).

The most common spatial interpolation technique used in the context of GIS is Inverse Distance Weighting (Boots *et al.*, 2002). This technique assumes that as distance increases between a data point and the center of a grid cell, or grid point, the influence of the data point on the grid point's value decreases.

For example, interpolating a surface of recreation travel propensity during an oil crisis is likely to show that travel to distant locations will have less influence because individuals are more likely to travel to destinations close to home.

According to the parameters entered (number of neighboring data points per grid point, search distance, cell size) the distance between selected data points and a grid point is determined. The inverse of this distance is then multiplied by the value of the associated data point. The sum of these values is divided by the sum of the inverse distances. The default setting in MapInfo is the square of the inverse and is commonly used to ensure continuity (Thurston *et altri*, 2003).

For our study, the parameters were limited to search distance and cell size. The number of neighboring points was not included in the GRID calculation as we were concerned only with the search radius from each grid cell center and the output size of each grid cell. The search radius was set at 50 meters and the grid cell output was set at 5 meters.

In order to use these parameters the study area had to be divided into much smaller areas. A full explanation of this process is described in ANNEX G. Nine classes of signal loss probability were applied to each of the 36 sheets making up the study area.

An example of the cartographic representation of one sheet is illustrated in ANNEX I.

After the interpolation was finished these overlapping grid files were placed together as the final step in the modeling process. Downtown Quebec City has the highest probability of satellite signal lock loss and is displayed in ANNEX H.

8 RESULTS AND DISCUSSION

The primary goal of this study was to identify and document some of the major developments of the Wireless Enhanced Emergency 9-1-1 telecommunication system in the North American context. This was accomplished through a case study of one of the primary Canadian cities currently integrating new telecommunication technologies in their emergency response infrastructure to meet the objectives outlined in the CRTC decision 2003-53. Following this objective, the study also aimed at spatially quantifying the effect of the built environment on the quality of the leading location determination technology for cellular phones (A-GPS). Proposing a sampling strategy of GPS signal observations with the use of common surveying equipment and GIS methods allowed a spatial evaluation of the average expected GPS signal quality in urban areas. Two sub samples of observations of building obstruction conditions and GPS reception quality were systematically collected and analyzed using geostatistical tools. The results provide evidence for the existence of spatial variability in the probability of losing GPS signal lock in numerous conditions of degraded signal environments in urban areas of Quebec City. From one observation point to another the probability of signal loss will vary in time. However, calculating the probability for all possible observation points in the study area with a temporal dimension is not computationally feasible. Therefore, we attempted to generalize this phenomenon using average weighted observation estimations over our entire study area to gain an informed perspective of potential problem areas for locating individuals in distress for the city’s PSAP.

The geostatistical analyses performed on our observation database allowed us to confirm that there was significant spatial variability in GPS signal quality at night in winter for both the Laval University campus measurements and the measurements in urban areas of Quebec City. This variation is represented in the 3.4x5 meter cells of the GRID created using Inverse Distance Weighting in MapInfo. The extent of the cells within the same category varies for overlapping sheets covering the same area. This is due to a different makeup of the constituents (points) used in the interpolation for a given GRID cell.

The extent of clusters of the same class of signal loss probability varies according to the building density or lack of buildings in the immediate area. The signal loss probability results from the degree of obstructed sky as well as a number of other factors not considered in the scope of this study.

These other factors are satellite constellation, angle of arrival of satellite signals, terrain elevation, non-building obstructions, atmospheric conditions and certain frequencies of radio wave causing interference or jamming (signal to noise[23]) (Spilker and Parkinson, 1996). At an observation point, these factors can greatly influence satellite signal reception.

Recent studies have shown how A-GPS technology receivers perform in the presence of Radio Frequency Interference (RFI) from various sources. Deshpande (2005) demonstrated that AM signals have a significant negative impact on GPS signal acquisition and signal tracking. Karunanayake *et al.* (2004) found that Time to First Fix (TTFF) was lower for an A-GPS receiver than for a High Sensitivity GPS receiver and conventional GPS receiver. However, they concluded that there was no major difference in tracking ability among the three types of receivers. In another study, this same team discovered that in all conditions of RFI tested the receivers were more vulnerable to interference when acquiring signals than when tracking (Karunanayake *et al.*, 2005).

Since our study did not consider the temporal dimension of GPS satellite signal quality, TTFF is not a relevant factor for our results. Given that in a study previously mentioned, A-GPS and conventional GPS technologies were shown to perform comparably when tracking

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[23] Signal-to-noise ratio is the measured GPS signal strength relative to background noise from Radio Frequency Interference.

GPS signals, lacking the temporal aspect does not reduce the significance of our findings. However, our observations were static and the effects of continual movement could have a tremendous impact on the average conditions for losing signal lock.

8.1 Limits of the Study

To the best of our knowledge, this investigation is the only study which allows the demonstration, with the aid of geostatistics, of the spatial variability of the average GPS signal lock loss in a given administrative area. However, the GRID maps created in this study are represented by pixels of generalized values and extreme caution must be exercised when interpreting these maps. The values attributed to the pixels are average condition estimates and cannot be guaranteed to maintain the same value at all times.

The resources at our disposal allowed us to create a cartographic representation of the phenomenon examined at a regional scale (digital topographic data files at 1:20,000). With higher grade equipment more accurate observations could be taken. This in combination with larger scale maps would allow a more realistic representation of the variation in GPS signal quality in urban areas. However, the maps produced do provide a means of establishing priority zones where emergency service dispatchers accepting calls at the PSAP may have difficulty in locating the individual allowing them to recognize certain technological limitations and warn responding units of the possibility of a difficult search.

Nevertheless, a more randomized sample taken at varying seasons and times within a 24 hour period would have given a more accurate representation of the phenomenon in terms of establishing a valid average. The use of only one sample collected in only one city during only one season limits the application of our observations. The fact that the observations were collected outdoors in an uncontrolled environment makes it difficult to make a direct link between loss of satellite signal lock and the percent of obstructed sky since there are several other factors not taken into account. A sample taken over several seasons at varying time periods during day and night could help identify combinations of the most problematic reception conditions for GPS receivers.

8.2 Future Research

The extent of signal loss projected by our model is quite high. Recent studies conducted within the urban core of Quebec City using mobile GPS by the Centre for Research in Regional Planning and Development reported successful results in accurately tracing itineraries on the road network. However, our primary objective was simulating pedestrian cell phone usage of individuals who would be much closer to the surrounding building obstructions. Walking as opposed to driving also introduces very different signal reception conditions. Instead of quickly moving in and out of challenging obstruction conditions in a vehicle, pedestrians slowly proceed along sidewalks often less than two meters from obstructions. These obstructions are therefore present for significantly longer periods of time producing higher and more intense rates of interference with GPS signal reception.

Conducting further observations in the interpolated locations with another field measurement campaign would allow a more thorough analysis and conclusion of the validity of our model. Considering the numerous areas in Quebec City where GPS signal loss probability of 78% and greater was estimated, one might conclude that the model is far too conservative. Comparing additional observations with model estimates would allow a more accurate reflection of the model's potential in assessing uncertainty in GPS signal reception.

The current governmental initiatives of both the US and Canada favor the integration and adoption of these new technologies by wireless telecommunications companies and emergency response centers. However, the effects of new location determination technologies on Emergency 9-1-1 response capabilities are not well known. Such studies would only be possible after successful installation and operation of the new equipment were achieved. The commercial interests in location based services would also be enabled with the adoption of this technology offering new possibilities for economic development with unique services based on location.

LBS could prove to be an invaluable research tool for many planning related fields. Individual subjects would obviously be more inclined to act in a natural fashion if required to carry only a cell phone with them at all times during an observation period. Given the habitual nature that many of us have developed regarding cell phones, participants could be lured to studies with free limited cell phone time in return for automated data collection on their usage and travel. The detail and realistic portrayal of individual decision making made possible with such technology is promising. This is one tool that could significantly improve upon traditional research methods, bringing to light new relationships that are evolving between humans and our environment.

Townsend (2001, 2004) presents a unique perspective on these new relationships and believes that they are essential considerations for planners. According to Townsend, during the 1990's it was widely believed that the Internet would eliminate physical and cultural distance creating a "spaceless" global community. Ironically, in this virtual community we were physically bound, absorbed by the pixels of our monitors, operating desktop computers on fixed internet connections surrounded by walls.

At the same time, wireless telephones allowed us to experience continually increased levels of independence and freedom of environments in our communication behavior. As the wireless internet matures and our needs for instant mobile communication and information intensify, "location" is regaining focus as the vital link between these needs and how we will perceive and what we will perceive in our urban surroundings.

Visualizing spatio-temporal location and interaction requires advanced computing power and costly equipment and software. This will certainly be a barrier for many researchers unable to feasibly access such technology. Computer software capable of handling all of this real-time information while producing updated analyses and continual monitoring is not readily available. The possibility of extracting information from such a rich data source is likely to continue spurring technological innovation in visual GIS and with time this type of analytical capability could be commercially available (Sustainable Transport in Europe and Links and Liaisons with America, 2005).

Nearly two years after the adoption of CRTC decision 2003-53 a functional Phase II Wireless 9-1-1 system looms on the horizon for many Canadian cities. The interdisciplinary nature of this system requires an enormous investment of time and money to effectively complete the technological transfer of equipment, knowledge and expertise, locally and internationally. Having gained such overwhelming importance since September 11, 2001, safety is always on our collective minds and this topic is one that will surely be revisited as progress and new advances are experienced.

Improving daily operations with such technological enhancements as Wireless E-911 is an investment that aims to maximize the efficiency of a vital system in our communities. Finding alternative means of assessing the technological feasibility of this new service could contribute to more effective risk management and further the mission and aims of emergency response personnel dedicated to saving lives and preserving property.

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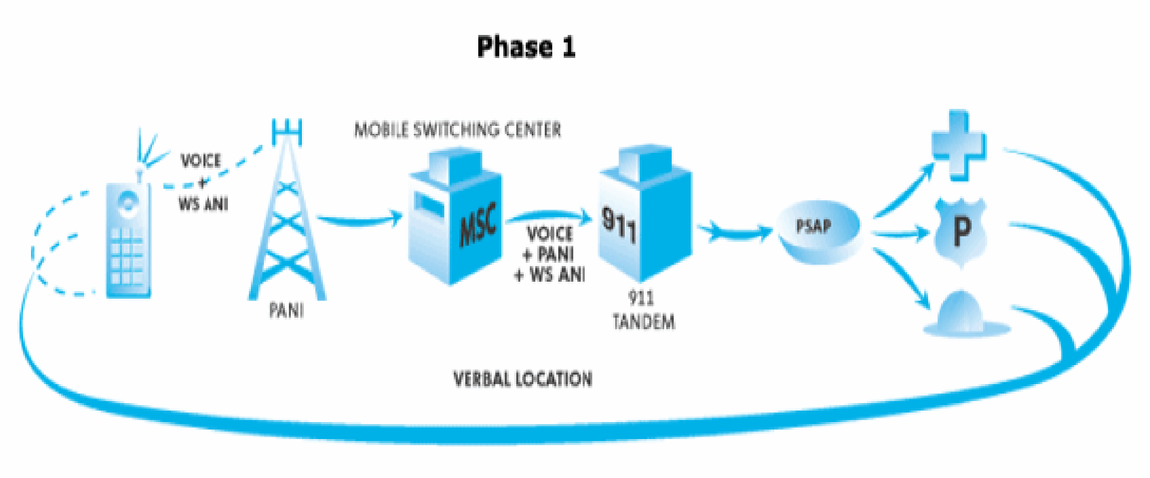
ANNEX A: PHASE I WIRELESS E-911



(Bell South, 2004)

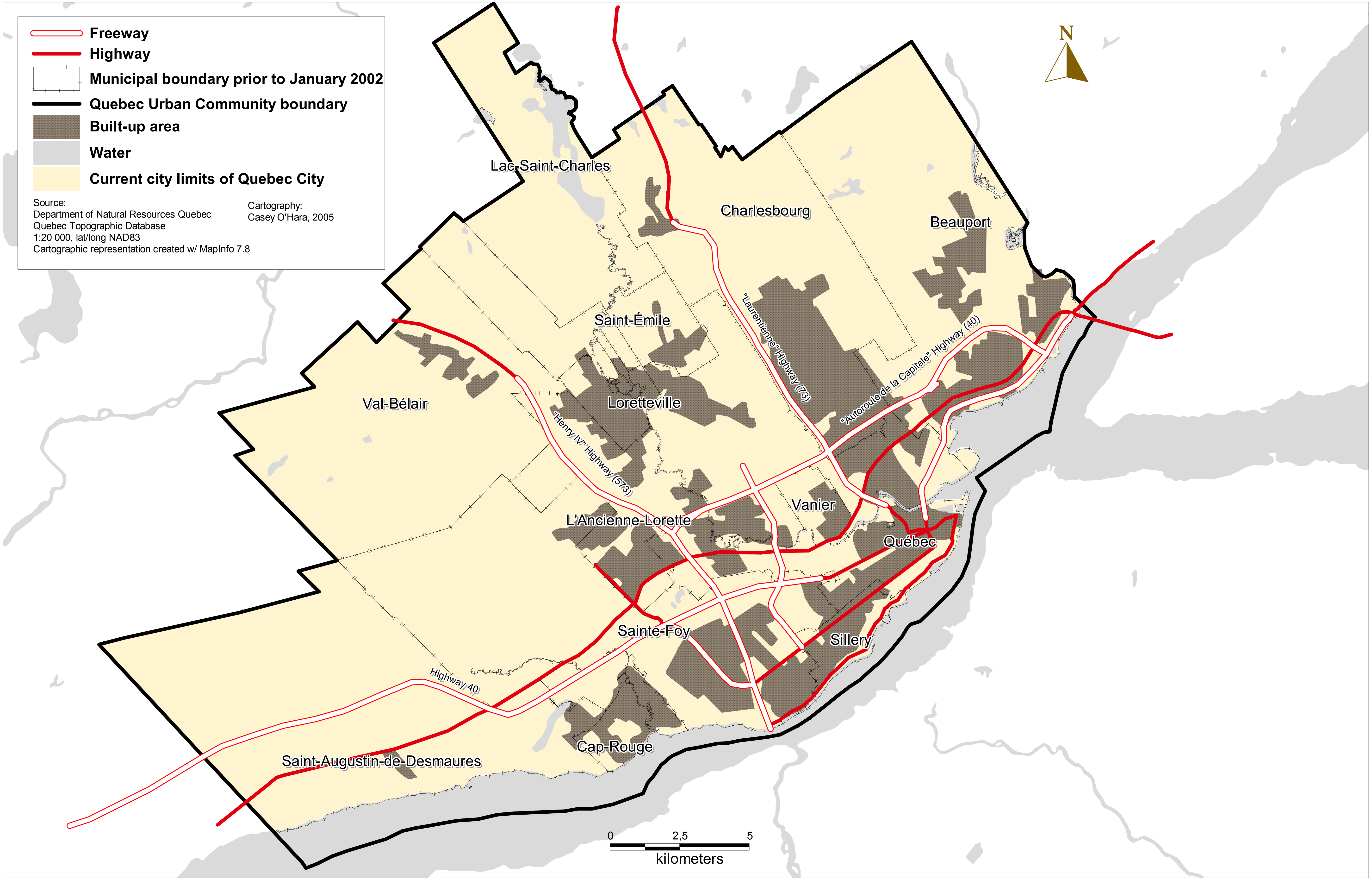
WS ANI – Wireless Automatic Number Identification

PANI – Pseudo Automatic Number Identification

MSC – Mobile Switching Center

PSAP – Public Safety Answering Point

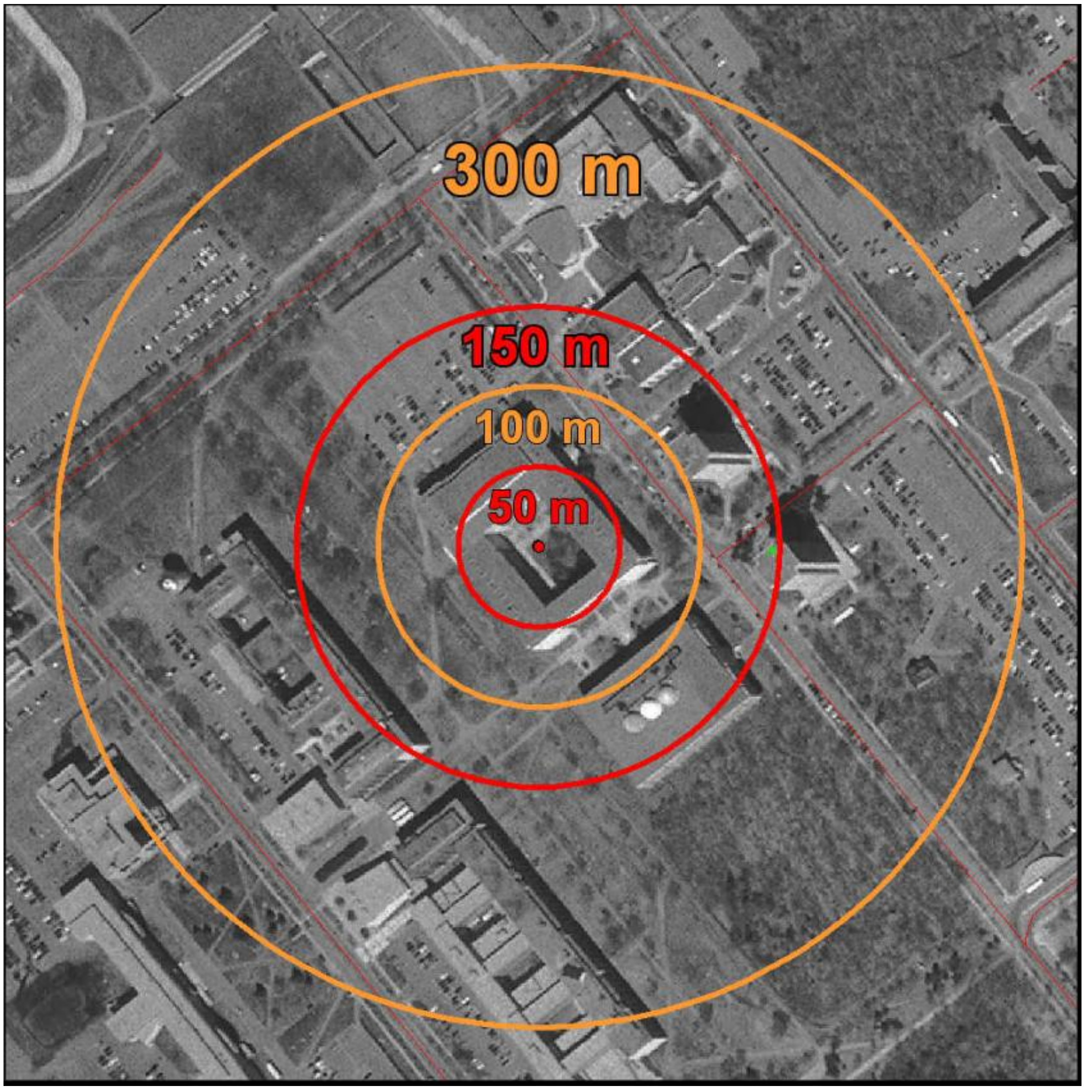
ANNEX B: QUEBEC URBAN COMMUNITY



Source:
Department of Natural Resources Quebec
Quebec Topographic Database
1:20 000, lat/long NAD83
Cartographic representation created w/ MapInfo 7.8

Cartography:
Casey O'Hara, 2005

ANNEX C: VARYING DEGREES OF LOCATION ACCURACY

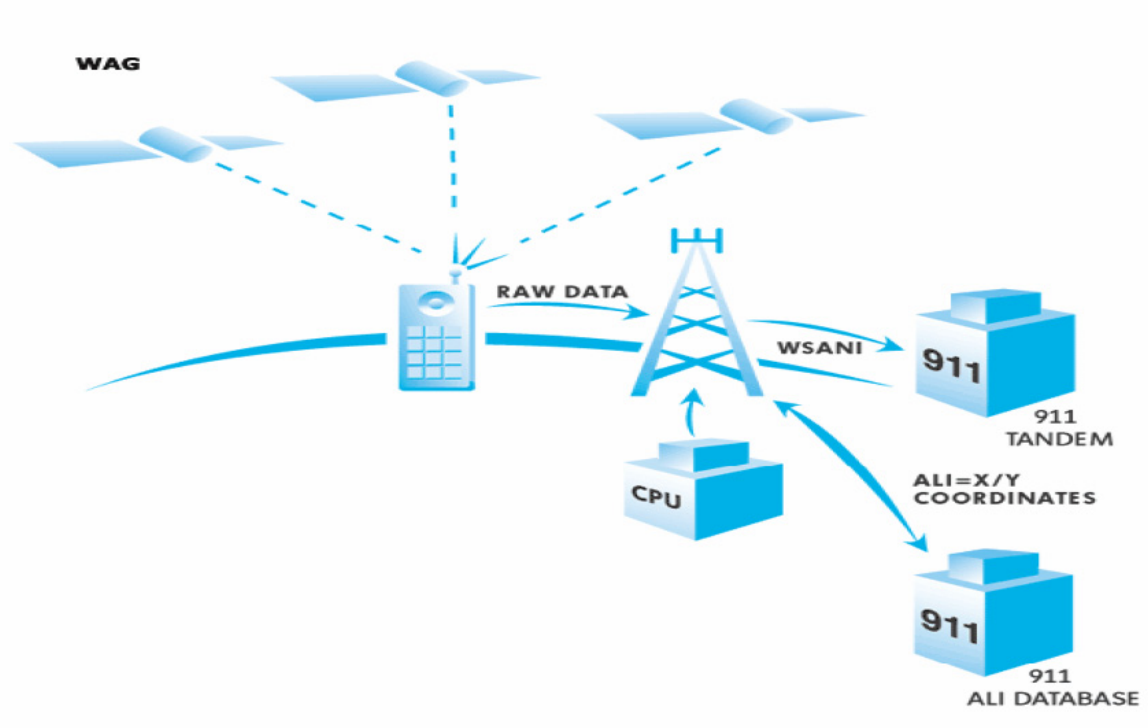


Circular area of the FCC requirements of radii of 50, 100, 150, and 300 meters on Laval University campus from a preliminary test zone observation point.

🟥 Handset Requirements

🟧 Network Requirements

ANNEX D: PHASE II WIRELESS E-911 WITH A-GPS



(Bell South, 2004)

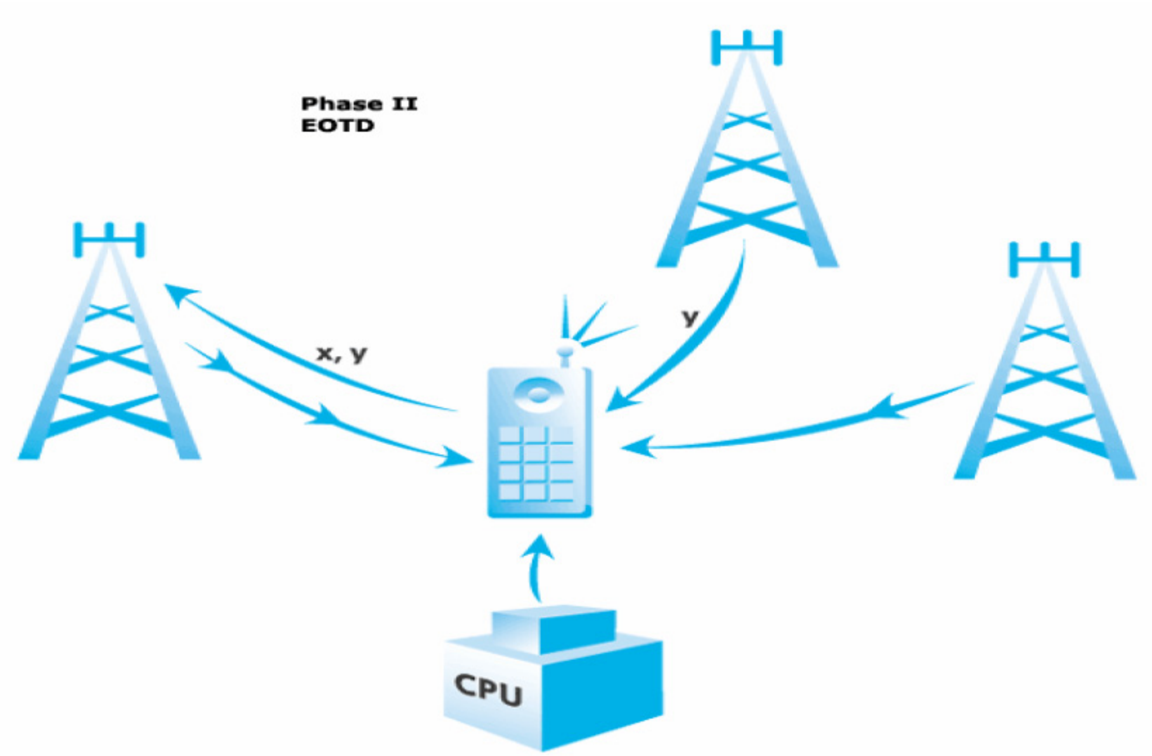
WAG- Wireless Assisted GPS

WSANI – Wireless & Satellite Automatic Number Identification

CPU – Central Processing Unit

ALI Database – Automatic Location Identification Database

ANNEX E: PHASE II WIRELESS E-911 WITH E-OTD



(Bell South, 2004)

CPU – Central Processing Unit

ANNEX F: ATTRIBUTING BUILDING HEIGHT VALUES

Problem:

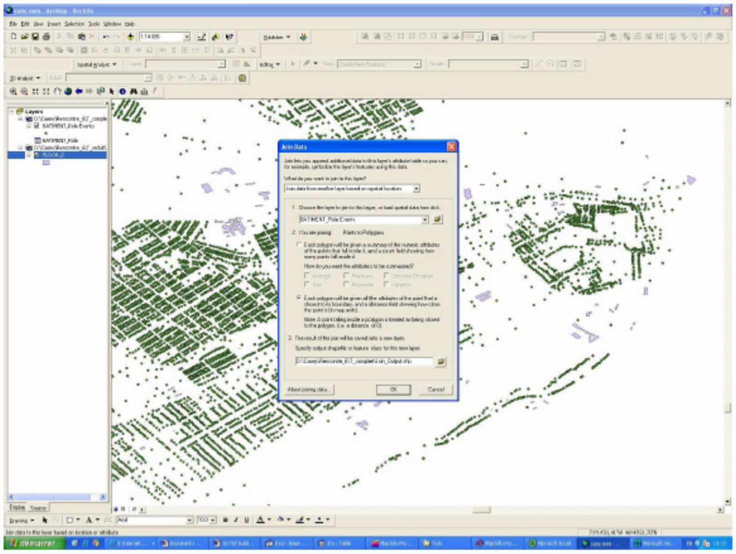
Building objects that were not attributed a height after the MapBasic application *ModeleTerritoire* was run were saved in a separate table. The maximum search radius from the building polygons to points from the valuation role database was set at 12 meters in the application.

Procedure:

A multi-step process was developed to assign a height attribute to each of these buildings using ArcGis 8.3 and MapInfo 7.5. The objective was to add point data to the valuation role database of points that would be within the threshold.

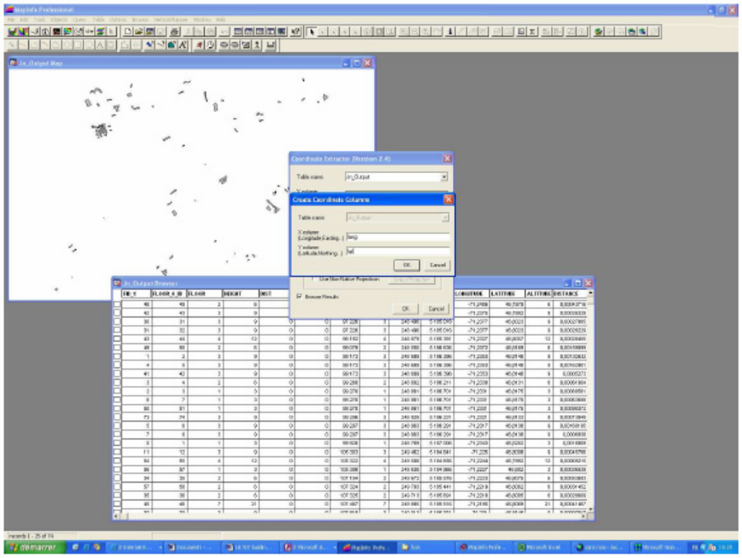
Using the join function in ArcMap the building objects were given the attributes of the closest point in the valuation role database regardless of how far they were apart (Figure 1).

Figure 1. Joining Attributes



This shape file was then opened in MapInfo using the universal translator. The centroid of each building object was identified using the coordinate extractor tool. This tool creates additional columns for the longitude and latitude of the centroid for each feature (Figure 2).

Figure 2. Determining centroid of building features



Coordinate Extractor (Version 2.4)

Create Coordinate Columns

Table name: Jn_Output

X column (Longitude, Easting...): long

Y column (Latitude, Northing...): lat

The table associated with these objects contained the attributes from the polygon features from the Buildings table, the attributes for the closest point from the valuation role table and the coordinates of the centroid of each polygon. In order to append the new points and their associated height value, the table was modified in MapInfo.

Using the update column function, the latitude and longitude of the associated point were replaced with the coordinates of the polygon centroid. The second modification consisted of removing all fields not included in the valuation role table and changing the field order to match the order of the valuation role table. The new centroid points were then added to the valuation role table using the append row function.

The number of entries was verified to ensure that all new points were included. Due to the associated polygon map objects, the create points function was not able to be performed in MapInfo. The dbf. Version of the table was opened in ArcMap and the display xy data function was used to save a point shape file (Figure 3). This file could then be opened in MapInfo and used in the MapBasic program (Figure 4).

Figure 3. Creating points to represent valuation role modifications

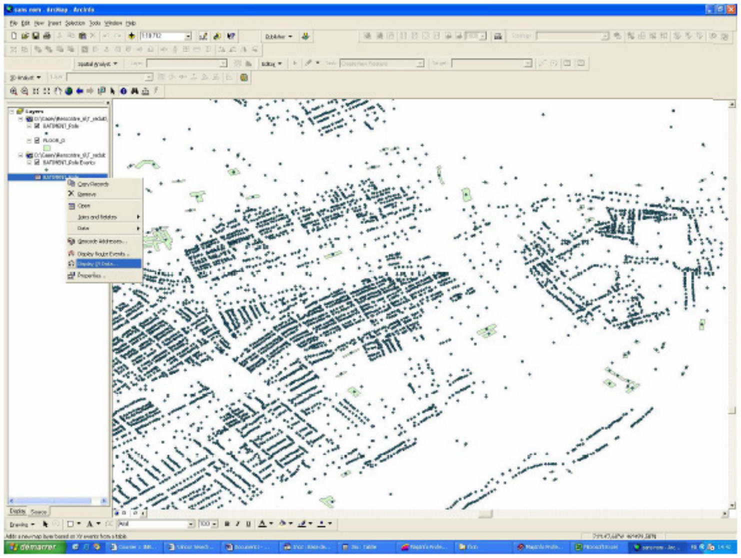
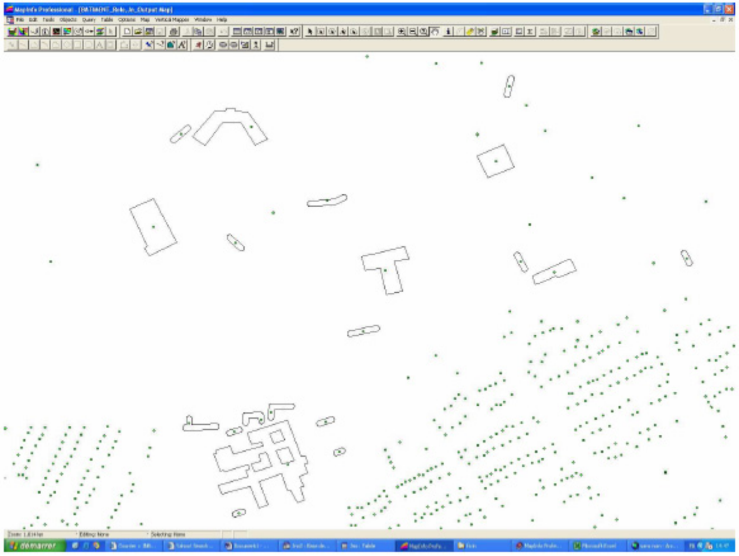


Figure 4. New valuation role point features in MapInfo

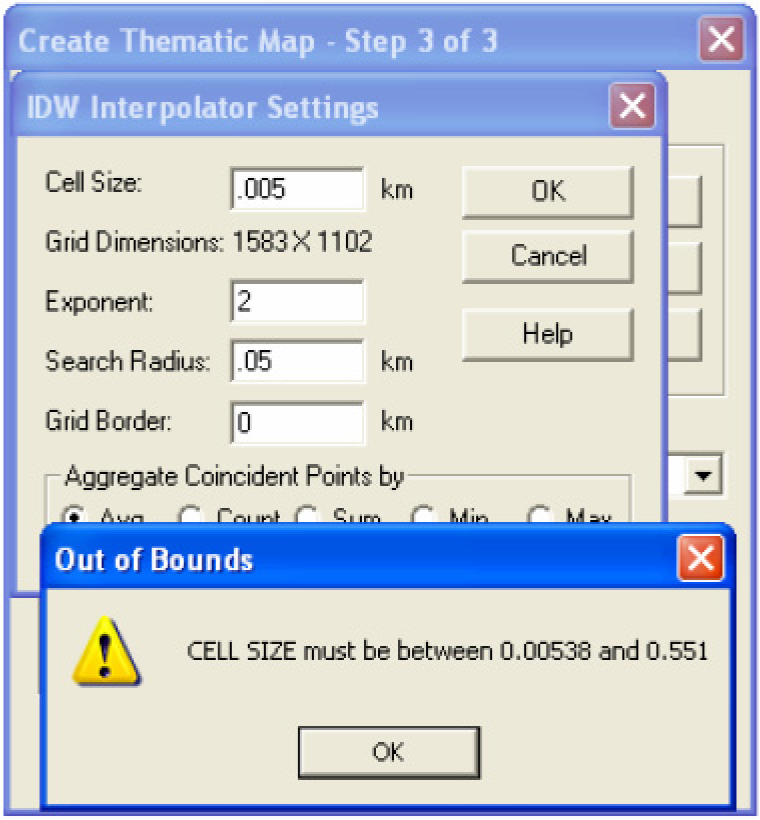


ANNEX G: INVERSE DISTANCE WEIGHTING

Problem:

Creating a thematic map with Inverse Distance Weighting (IDW) interpolation using parameters that produce a cell size of 5 meters and a search radius of 50 meters is not possible for the entire study area at the same time using MapInfo (Figure 1).

Figure 1. Error Message for IDW



Create Thematic Map - Step 3 of 3

IDW Interpolator Settings

Cell Size: .005 km

Grid Dimensions: 1583 X 1102

Exponent: 2

Search Radius: .05 km

Grid Border: 0 km

Aggregate Coincident Points by: ● Avg ○ Count ○ Sum ○ Min ○ Max

Out of Bounds

CELL SIZE must be between 0.00538 and 0.551

Objective:
Define a method for dividing the study area to produce an acceptable cartographic representation of GPS signal loss.

Procedure:

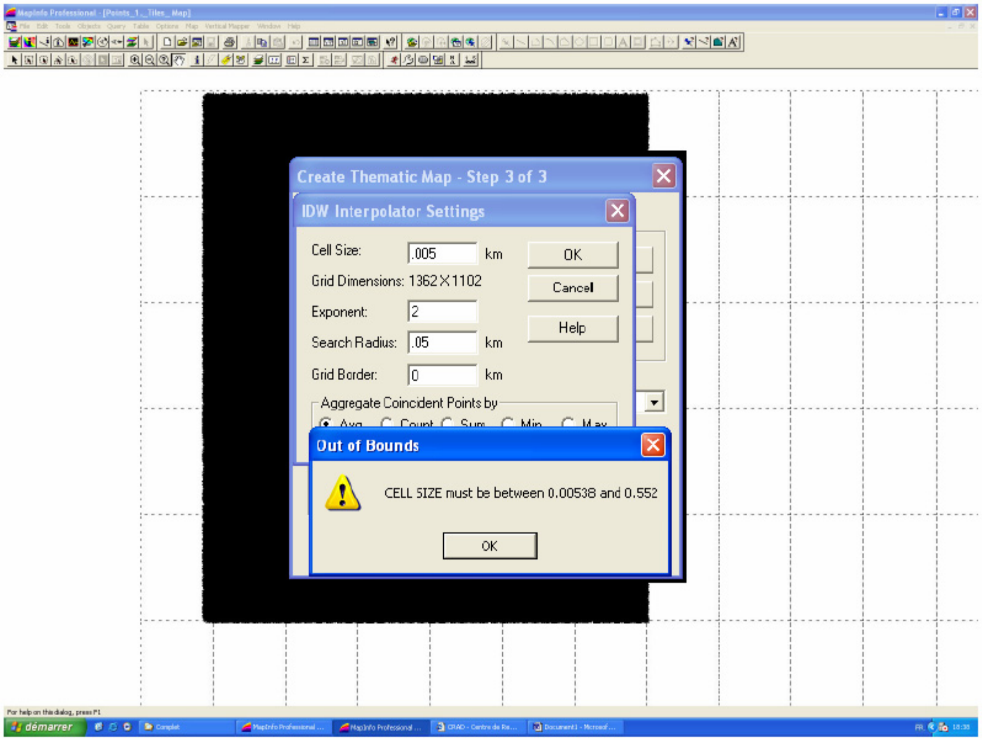
1. Identify the maximum tile dimensions allowing IDW interpolation with cell size of 5 meters and search radius of 50 meters by trial and error
2. Determine if this size is well represented in the MapInfo layout
3. Divide the study area using some combination of the 1 minute latitude by 1 minute longitude GRID used to increase efficiency and speed of the MapBasic program *ModeleTerritoire*

4. Perform interpolation
5. Aggregate overlapping sheets to create one representation for the entire study area

Step 1) The maximum tile dimensions were discovered by experimenting with the *Tiles* table and the table of random points. These points represent the GPS satellite signal loss probability attribute generated from the ModeleTerritoire application. In order to test the area size a rectangular object with selected dimensions was created in a new table using the tile objects as a guide.

The point objects from the random points table within this rectangular area were then saved in a separate table. The last step of each attempt was to verify the validity of using these dimensions. The Create Thematic map function for IDW with the same settings as previously stated determined whether or not the selected area was in or out of bounds (Figure 2). The maximum dimensions were discovered at 4x6 tile panels.

Figure 2. Failure on Final Step of Verification for 5x7 Panel

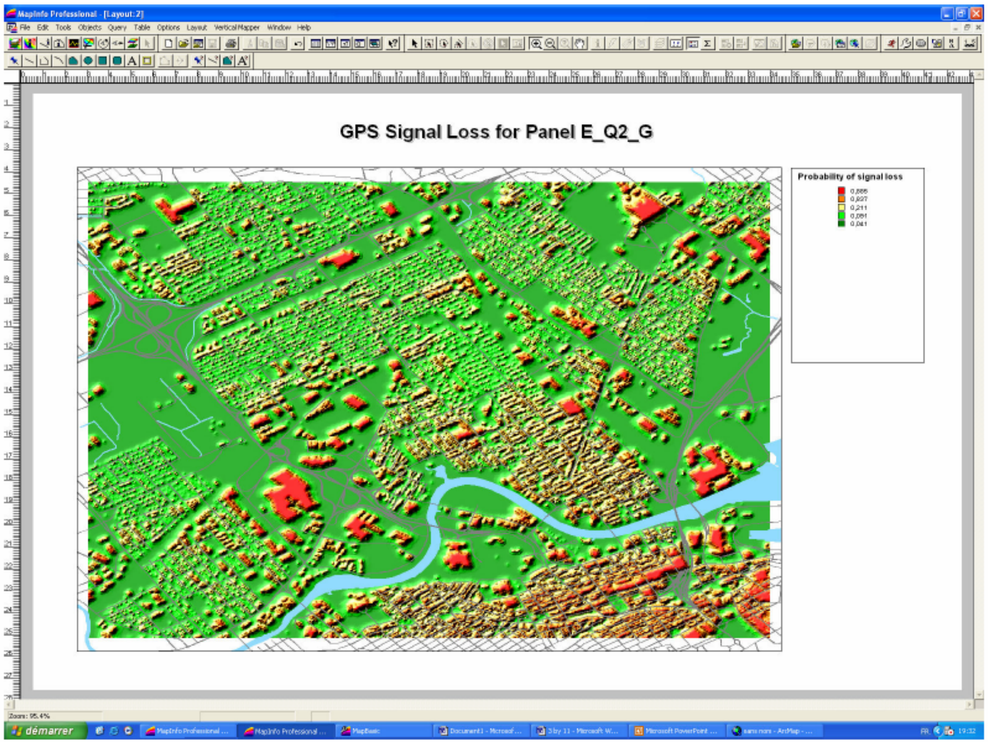


Cell Size: .005 km
Grid Dimensions: 1362 X 1102
Exponent: 2
Search Radius: .05 km
Grid Border: 0 km
Aggregate Coincident Points by
● Avg ○ Count ○ Sum ○ Min ○ Max

CELL SIZE must be between 0.00538 and 0.552

Step 2) This size panel has a relatively conventional display possibility using the MapInfo Layout (Figure 3).

Figure 3. Layout for Maximum Dimensions



Step 3) The study area was first divided into two sections, east and west, with three columns of files overlapping in the middle. The dimensions for each section are 15x29 tiles (Figure 4). Then each section was divided into quadrants with dimensions of 8x16 tiles (Figure 5). In the example of the east section we see that the quadrants overlap by three tile columns vertically and one tile row horizontally.

Figure 4. Study Area: East and West

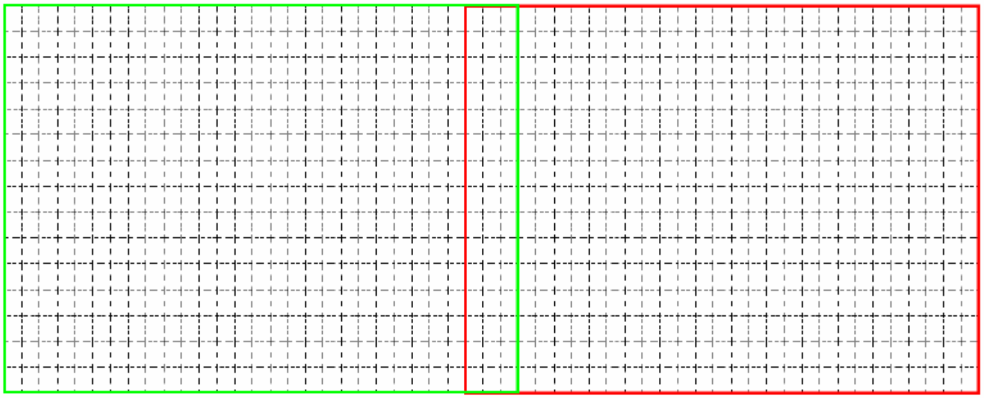
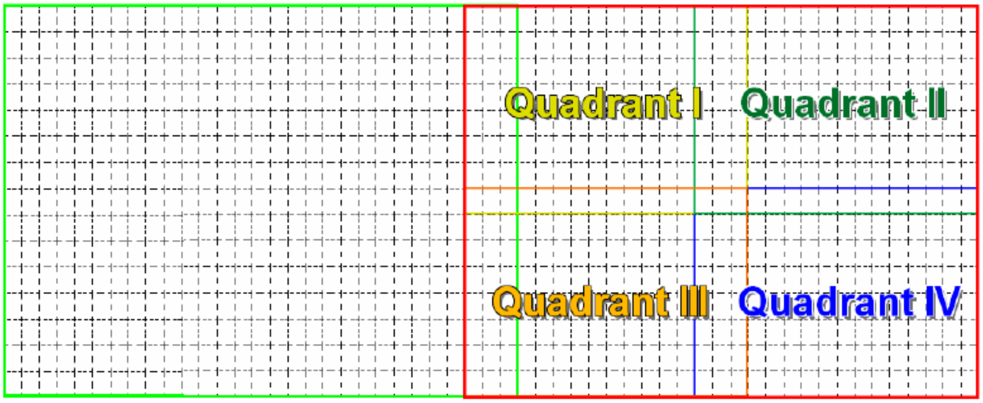


Figure 5. East End Quadrants



Each quadrant was then divided into a series of 4x6 tile panels (Figure 6,7). The number of panels per quadrant is nine and they are labeled alphabetically from A to I. This provides an effective means of ensuring that there is significant overlap and none of the pixels are lost while the program is executed.

A multi-step process was developed to assign a height attribute to each of these buildings using ArcGis 8.3 and MapInfo 7.5. The objective was to add point data to the valuation role database of points that would be within the threshold.

Figure 6. One 4x6 Panel in Quadrant I

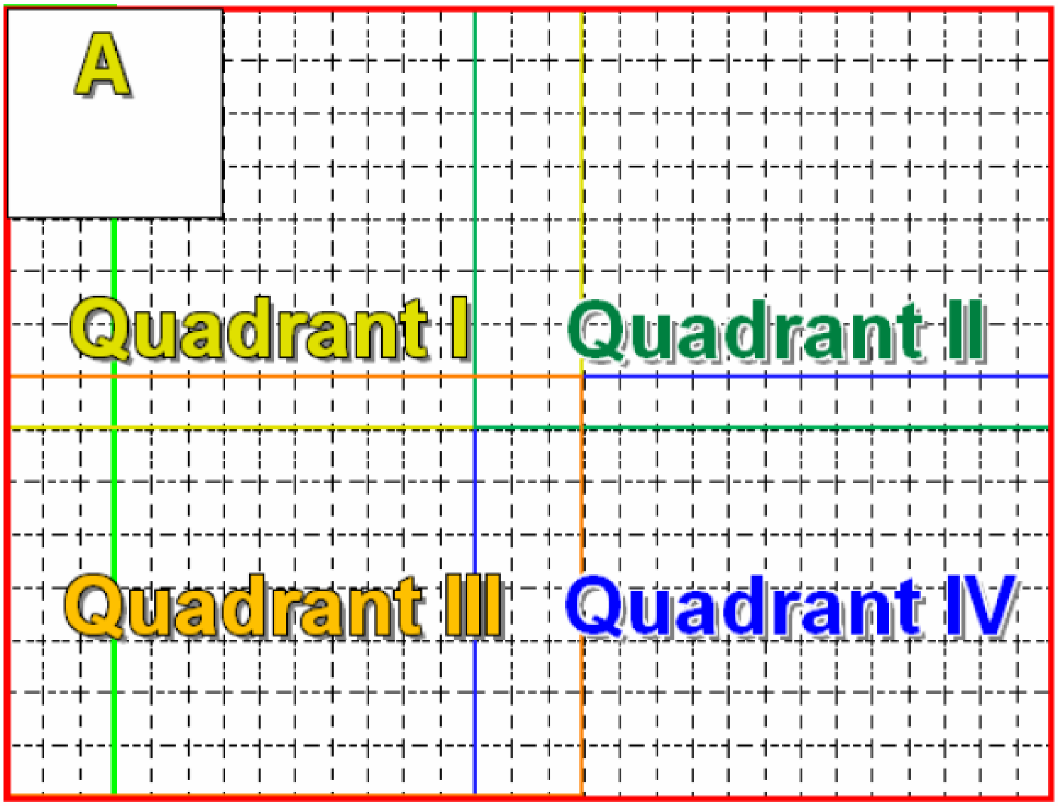
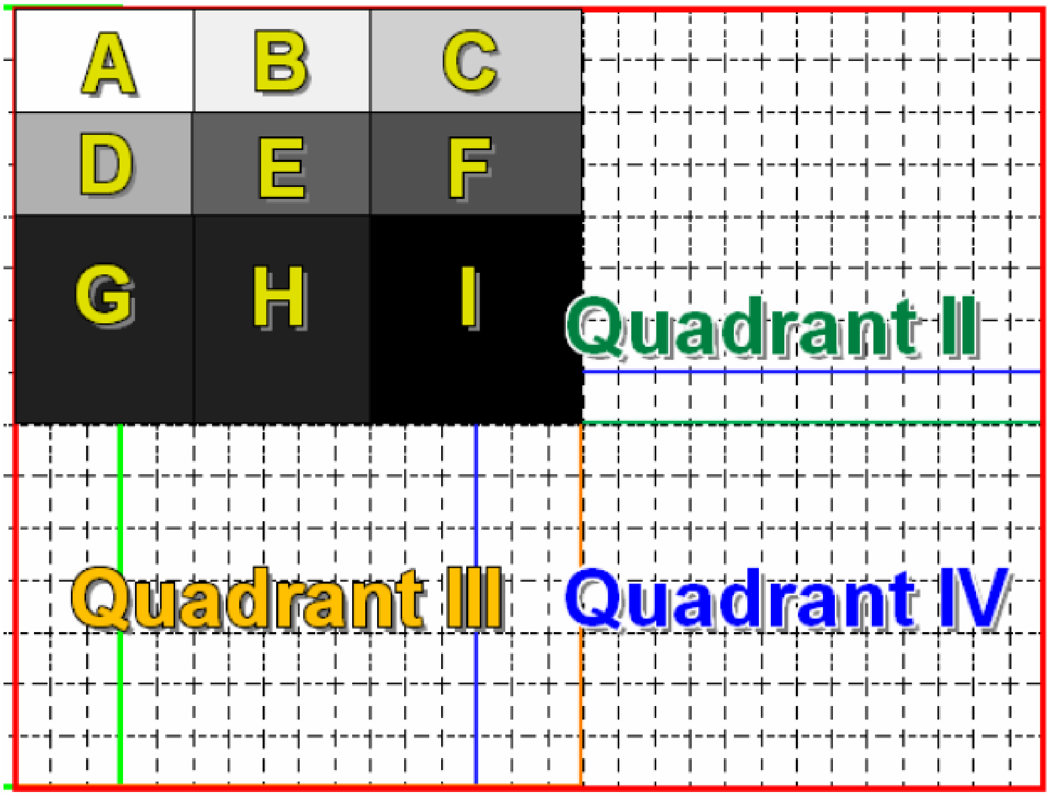
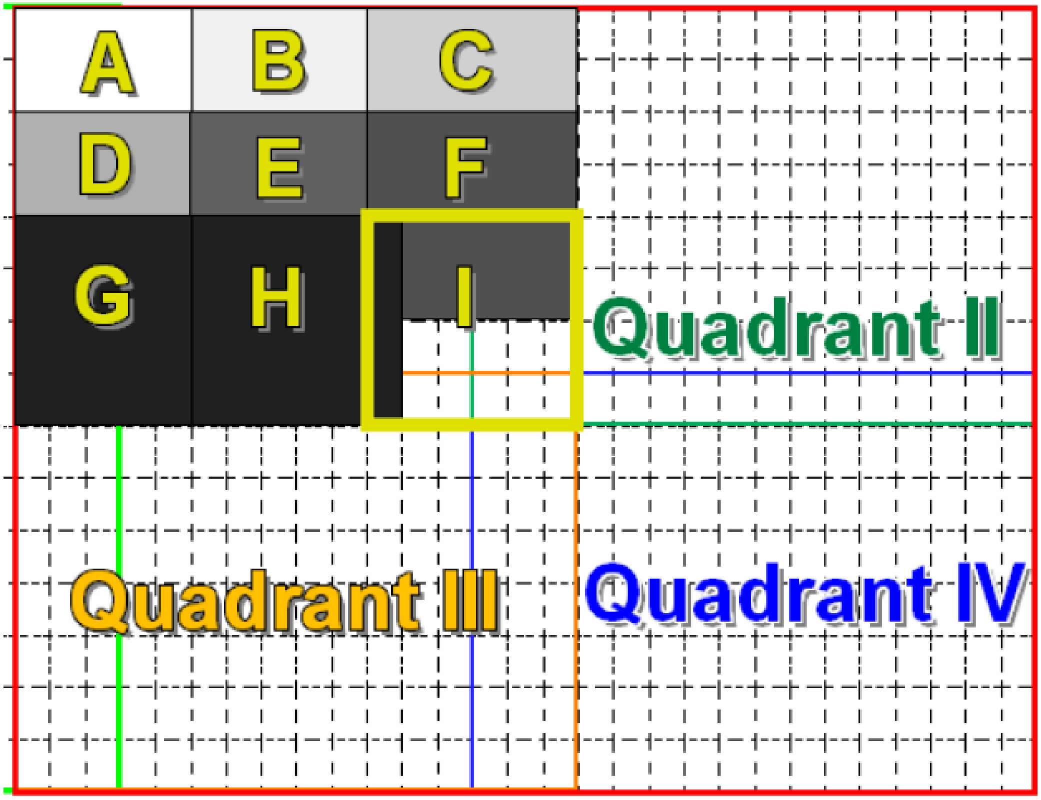


Figure 7. Panels Per Quadrant



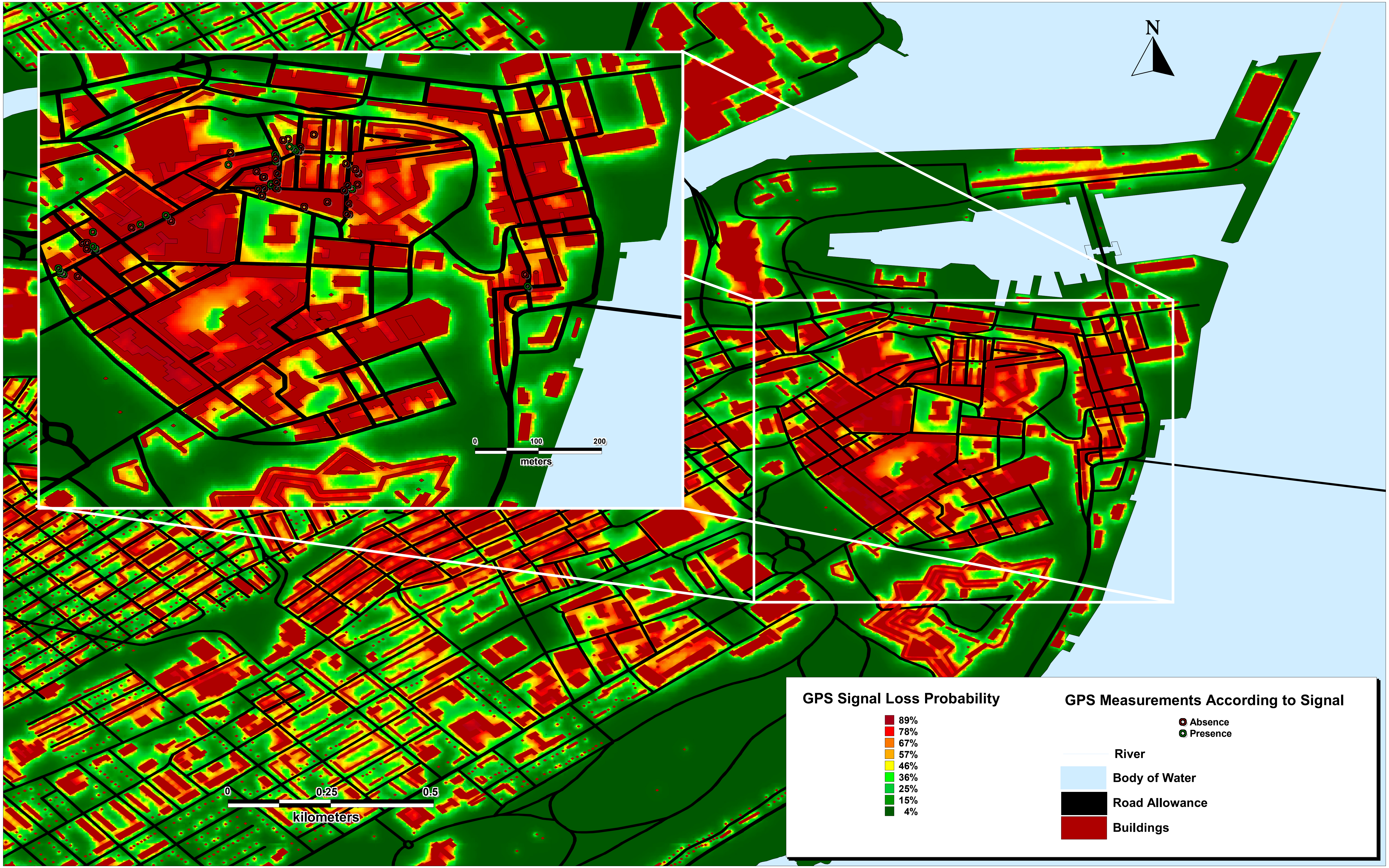
As Figure 8 illustrates, in a given quadrant each panel overlaps the adjacent panel in that particular quadrant by one tile column. The middle panels D, E and F also overlap in tile rows above and below them. Essentially they are a mix of the panel above and below them.

Figure 8. Panel Overlap

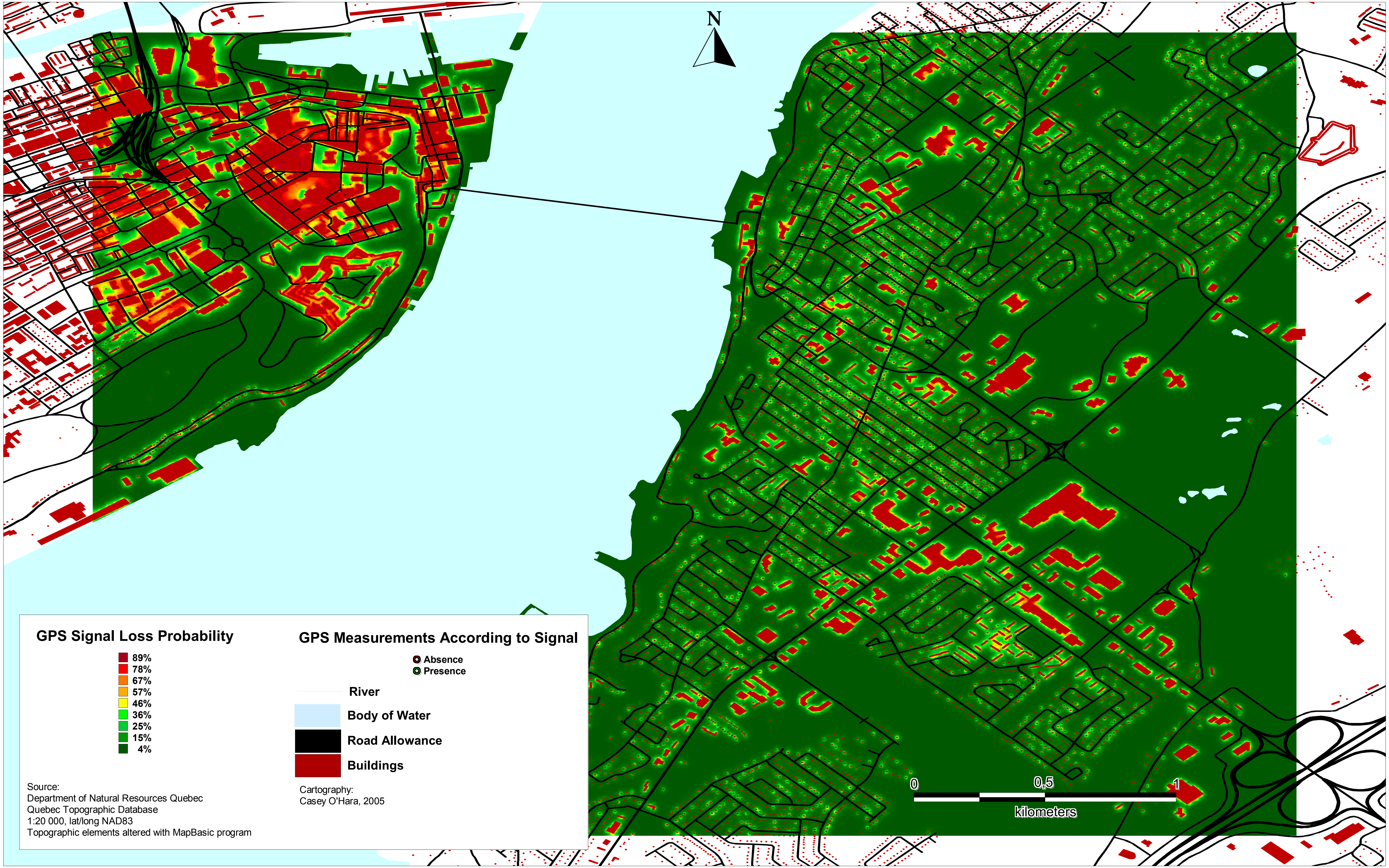


A MapBasic program was created to automate the task of saving point files for each panel and creating a cartographic representation of signal loss. Despite the fact that all of the files were created using the same automated procedure, when these panels are put together to produce a single layer there is a slight difference in the values attributed to each pixel due to the way the boundaries include certain point values for calculation and exclude others. However, this is the best representation possible using these parameters.

ANNEX H: GPS SATELLITE SIGNAL LOCK LOSS PROBABILITY


N
0
100
200
meters
0
0.25
0.5
kilometers
GPS Signal Loss Probability
89%
78%
67%
57%
46%
36%
25%
15%
4%
GPS Measurements According to Signal
Absence
Presence
River
Body of Water
Road Allowance
Buildings

ANNEX I: SHEET E_Q3_B SIGNAL LOSS PROBABILITY GRID



Source:
Department of Natural Resources Quebec
Quebec Topographic Database
1:20 000, lat/long NAD83
Topographic elements altered with MapBasic program

Cartography:
Casey O'Hara, 2005