

3GPP TSG GERAN #9

GP-020525

Seattle, Washington, USA

15-19 April 2002

Agenda Item 6.1, 7.1.5.6, 7.2.5.4

Title: U-TDOA in GSM and GPRS Feasibility Study

Source: TruePosition

Document for: DISCUSSION and DECISION

At GERAN #7 plenary 26-30 November, 2001 in Cancun, Mexico, TruePosition received approval to prepare a feasibility study examining U-TDOA location method in GPRS networks (GP-011999). A draft of the feasibility study was presented for comment at the G2 #8 bis meeting in Kista, Sweden and this document for consideration is the completed U-TDOA in GSM and GPRS Feasibility Study. Approval of this feasibility study will result in the creation of a Rel-6 work item. Release 6 timeframe is foreseen for completion of the required CRs.



Feasibility Study
Uplink TDOA in GSM and GPRS

Table of Contents

Table of Contents	i
1. Introduction.....	1-1
2. References	2-1
3. U-TDOA: System Description.....	3-1
3.1. Overview	3-1
3.2. Block Diagram	3-2
3.3. Implementation Considerations	3-3
3.3.1. Physical Implementation of the LMU	3-3
Stand-alone LMU	3-4
BTS Module	3-4
Integrated LMU	3-4
3.3.2. Latency	3-4
3.3.3. Synchronization	3-5
3.3.4. Location Determination Capacity.....	3-5
3.3.5. Intellectual Property Considerations	3-5
4. U-TDOA: Performance Analysis.....	4-1
4.1. Introduction.....	4-1
4.2. Review of the Fundamental Drivers of Location Accuracy	4-1
4.3. Comparison of GSM Versus IS-136 TDMA	4-2
4.4. Conclusion	4-4
5. U-TDOA: System Impacts	5-1
5.1. Protocol Impacts	5-1
5.1.1. GSM	5-1
Call Control.....	5-1

Mobility Management.....	5-1
Radio Resource Management.....	5-1
Short Message Service	5-1
Supplementary Services.....	5-1
5.1.2. GPRS.....	5-1
GPRS Mobility Management (GMM)	5-1
Session Management (SM).....	5-1
GPRS Short Message Service.....	5-1
BSSGP	5-1
RLC/MAC	5-2
5.1.3. Common Protocols for Location Services.....	5-2
BSSAP-LE.....	5-2
BSSLAP	5-2
LLP.....	5-2
RRLP.....	5-2
5.2. Impacts to Existing Nodes	5-2
5.2.1. BTS	5-2
5.2.2. BSC	5-3
5.2.3. PCU	5-3
5.2.4. MSC/VLR	5-3
5.2.5. SGSN.....	5-3
5.2.6. SMLC	5-3
5.2.7. LMU	5-3
5.2.8. MS.....	5-3
5.3. Network Capacity Impacts.....	5-3

5.3.1.	Network Assumptions.....	5-3
5.3.2.	Um Interface	5-4
5.3.3.	Abis Interface.....	5-4
5.3.4.	Lb Interface.....	5-5
5.3.5.	Gb Interface	5-5
5.3.6.	MS Power Consumption.....	5-5
5.4.	Impact on Specifications	5-5
5.4.1.	3GTS 48.018 BSSGP.....	5-5
5.4.2.	3GTS 49.031 BSSAP-LE	5-6
5.4.3.	3GTS 48.071 BSSLAP.....	5-6
5.4.4.	3GTS 44.071 LLP	5-6
5.4.5.	3GTS 43.059 LCS Stage 2 Document	5-6
6.	U-TDOA Call Flows.....	6-1
6.1.	Packet Switched	6-1
6.1.1.	General Location Procedure.....	6-1
6.1.2.	PS U-TDOA, Packet Idle Mode.....	6-2
6.1.3.	PS U-TDOA, Ready State, Uplink data transfer in progress	6-3
6.2.	Circuit Switched.....	6-4
6.2.1.	CS, Idle Mode	6-4
6.2.2.	CS, Dedicated Mode	6-5
7.	U-TDOA Advantages and Disadvantages.....	7-7
7.1.	Advantages of U-TDOA.....	7-7
7.1.1.	Excellent Performance in Urban and Indoor Environments	7-7
7.1.2.	Support for Legacy Mobile Stations	7-7
7.1.3.	Scalable Accuracy and Cost	7-7

7.1.4.	Support for Roaming Subscribers	7-7
7.1.5.	Efficient Use of RF Resources.....	7-8
7.1.6.	Protection from Obsolescence.....	7-8
7.1.7.	Proven Technology	7-8
7.2.	Disadvantages of U-TDOA.....	7-8
7.2.1.	U-TDOA is currently perceived as being prohibitively expensive.....	7-8
7.2.2.	Accuracy of U-TDOA degrades in some rural areas.....	7-8
APPENDIX A.	Analysis of GSM and GPRS Uplink Time Difference Of Arrival (U-TDOA)	1
A.1.	Introduction.....	1
A.2.	Review of the Fundamental Drivers of Location Accuracy	1
A.3.	Comparison of GSM Versus TDMA.....	2
A.4.	Comparison of U-TDOA and E-OTD Performance	35
A.5.	Conclusion	36
APPENDIX B.	Functional Description of TruePosition Predictive Model.....	1
B.1.	Calculation of rms error weighted HDOP.....	3
B.2.	The HDOP calculation.....	4
B.3.	Calculation of the partial derivatives	5

1. Introduction

Over the past ten years, several organizations within the wireless telecommunications industry have invested significant time and resources in studying wireless location technologies. All of the technologies investigated to date have proven to have certain strengths and weaknesses. No single location technology has been identified that provides optimal performance across all environments. As a result, it is desirable to have a set of complementary technologies that together can provide acceptable performance across all reasonable circumstances.

In a significant number of live field deployments, location technologies based on uplink time difference of arrival (U-TDOA) techniques have provided excellent performance in urban, suburban, and indoor environments. The U-TDOA technologies do not require modifications to handsets, performing excellently with existing mobile stations in these same environments. In some rural environments, where cell site densities are low and coverage is very limited, the performance of U-TDOA degrades in the absence of expensive angle of arrival (AOA) technologies. In addition, U-TDOA technologies have not been standardized to date and as a result have been implemented only in more expensive, standalone overlay product configurations.

The A-GPS and E-OTD location technologies currently supported in the GERAN standard possess significant capabilities. They also have weaknesses that would be mitigated by complementing with U-TDOA. For example, in urban and indoor environments that limit the reception of GPS signals, the performance of A-GPS technologies degrades significantly. In these same urban and indoor environments, U-TDOA location method performs well because the SNR of uplink channels remains high and cell site densities are most dense. Similarly, the performance of E-OTD location method in urban and dense suburban environments (where higher accuracy is an asset but the effects of multi-path become more significant) is limited by their inability to mitigate the effects of multi-path. In the same environments, U-TDOA technologies use advanced super-resolution techniques to mitigate the effects of multi-path, with excellent results. Also, since handset-based location methods like A-GPS and E-OTD work only with future location-capable mobile stations, U-TDOA compliments them by providing location support to all existing mobile stations.

It is desirable to support U-TDOA in the GERAN standard in order to take advantage of the complementarity of this location method with the currently standardized A-GPS and E-OTD methods. Products that support the gamut of location methods will increase the robustness of a location solution, enabling the widest and most valuable set of applications and services. Standardization of U-TDOA will permit significant cost improvements through integration with the network infrastructure, improving the viability and attractiveness of location technology for manufacturers and operators.

This document describes how the Uplink Time Difference Of Arrival (U-TDOA) location method works in GSM and GPRS environments.

2. References

3GPP TS 43.059: "Functional Stage 2 description of Location Services (LCS) in GERAN"

3GPP TS 44.071: "Location Services (LCS); Mobile Radio Interface Layer 3 Location Services (LCS) specification".

3GPP TS 44.060: "General Packet Radio Service (GPRS); Mobile Station (MS) - Base Station System (BSS) interface; Radio Link Control/Medium Access Control (RLC/MAC) protocol".

3GPP TS 48.018: "General Packet Radio Service (GPRS); Base Station System (BSS) - Serving GPRS Support Node (SGSN); BSS GPRS Protocol (BSSGP)".

3GPP TS 48.071: "Serving Mobile Location Center – Base Station System (SMLC-BSS) interface; Layer 3 specification".

3GPP TS 49.031: "Location Services (LCS); Base Station System Application Part LCS Extension (BSSAP-LE)".

3. U-TDOA: System Description

This section presents the GSM and GPRS network architecture of Uplink TDOA (U-TDOA). The introduction of U-TDOA does not require major modifications to the architecture specified in 3GPP TS 43.059 (Functional Stage 2 Description of Location Services in GERAN), needing only limited revisions to LCS protocol message formats and functional/logical enhancements in the BSC/PCU network node.

The first part of this section presents a system description overview of U-TDOA in GPRS and discusses applicability to GSM, GPRS and UMTS. The second part presents the block diagram for U-TDOA in GPRS networks. The third part discusses the concepts and issues related to the implementation of U-TDOA in GPRS networks.

3.1. Overview

The U-TDOA location method requires the capture of RF energy that can be unambiguously associated with a particular MS. This requires knowledge of the allocated resources (frequency, timeslot, allocated blocks, etc.) for the target MS. This information is generated by the PCU. To implement U-TDOA location determination in GPRS it is necessary to transfer the RF resource assignment information to the SMLC directly from the BSC/PCU. The Lb and Gb interfaces should be enhanced to include U-TDOA functionality for LCS.

Location of a MS in the midst of an uplink data transfer, with enough remaining data to allow the appropriate U-TDOA setup time (approximately 250 mSec), requires no additional location-specific transmissions. In this case, the SMLC must receive the current and any subsequent PACK_UL_ASS messages associated with the ongoing uplink data transfer. In addition, the PCU must also inform the SMLC of the frame number of the first burst of an allocated uplink block. An alternative approach is proposed for situations in which insufficient data remains in an ongoing uplink data transfer to allow for location related setup time and 4 to 20 subsequent data Blocks (depending on the QoS requirement and MS transmit power level).

Location of mobiles not currently active in the uplink direction requires the MS to transmit for a range of 4-20 blocks, depending on the QoS requirement and resulting MS transmit power level. The proposed method covers a MS in the GMM Ready or Standby State and uses 4-20 executions of Polling for PACK_CTRL_ACK (Packet Control Acknowledgement) to provide sufficient RF energy in the uplink direction for accurate determination of MS location. The PACK_DL_ASS (Packet downlink assignment) message and each PACK_POLL_REQ (Packet polling request) message, including the valid RRBP field, shall be sent to the SMLC to provide the necessary information for the LMUs.

For mobiles in an idle state (Packet Idle Mode), a method is proposed that uses Timing Advance Polling for U-TDOA location determination. GSM 04.60 (MS-BSS interface; RLC/MAC protocol), Paragraph 11.2.12 indicates that the PACKET_POLLING_REQUEST message from the network to the MS can be used to cause the MS to transmit a PACK_CTRL_ACK message. This mechanism currently is used to derive the initial Timing Advance value of a particular MS. The TYPE_OF_ACK parameter in this message determines if the MS responds with an access or normal burst. To determine the TA after the initial burst, the PCU must indicate a response using a normal burst by setting the TYPE-OF ACK IE to "1" for all subsequent bursts associated with location determination.

It is proposed to use repeated execution (4-20, depending on the required location QoS and MS transmit power level) of the PACKET_POLLING_REQUEST message to cause an inactive mobile (Packet Idle Mode) to transmit for a time sufficient to acquire an U-TDOA location. Refer to Section 6.1 of this document for call flows and a more detailed description of this methodology.

The following provides an overview of how U-TDOA is well suited to perform in current GSM and future UMTS networks.

Classic GSM

In order to perform in all of the foreseen mobile networks (GSM, GPRS and UMTS) it will be necessary to re-introduce the uplink location technology previously specified in GSM 03.71 (U-TOA), with the following functional difference:

The RF energy associated with normal circuit switched activity is sufficient to provide an U-TDOA location determination. Consequently, the formerly specified handover command used to cause the MS to transmit is not required. For currently active MS, the BSC must send to the SMLC the Channel Assignment information and any subsequent Radio Resource management information. Because this is a slightly different functionality and for consistency with GPRS and UMTS, this re-introduced capability should be designated U-TDOA. These methodologies are illustrated in Figures 6.2.1 and 6.2.2.

As an alternative, the energy associated with call setup signaling activity on the SDCCH can be used to locate an idle MS. In this case the BSC must page the target mobile, proceed with normal call setup activity (authentication, ciphering and possible MS interrogation) and release the SDCCH after one to two (1-2) seconds based on the desired location QoS. The BSC must inform the SMLC of the assigned SDCCH prior to initiating the SDCCH assignment on the Access Grant channel.

UMTS

U-TDOA is particularly suited to UMTS. The wide bandwidth and potentially high bit rates (low spreading factors) enable even higher levels of accuracy. Moderate levels of accuracy can be achieved in UMTS using the high spreading factor (low bit rate) associated with control channels and common channels. High levels of accuracy can be achieved using low spreading factors (high bit rates) on dedicated resources. The higher power level (Eb/No) associated with the lower spreading factors improves the level of accuracy because more LMUs can participate in the location effort. As always, U-TDOA does not require any additional resource nor does it contribute to the noise level when a currently active UE is located.

Predictive models indicate that accuracies of 25-30 meters are achievable in UMTS through the use of low spreading factors.

3.2. Block Diagram

Figure 3-2 illustrates the network topology assumed throughout this feasibility study. The dotted lines between the SMLC and the BTS/Node B represent a possible architecture for an early implementation of U-TDOA prior to the upgrade of the BSC and BTS/Node B for SMLC-to-LMU data traffic.

System Block Diagram

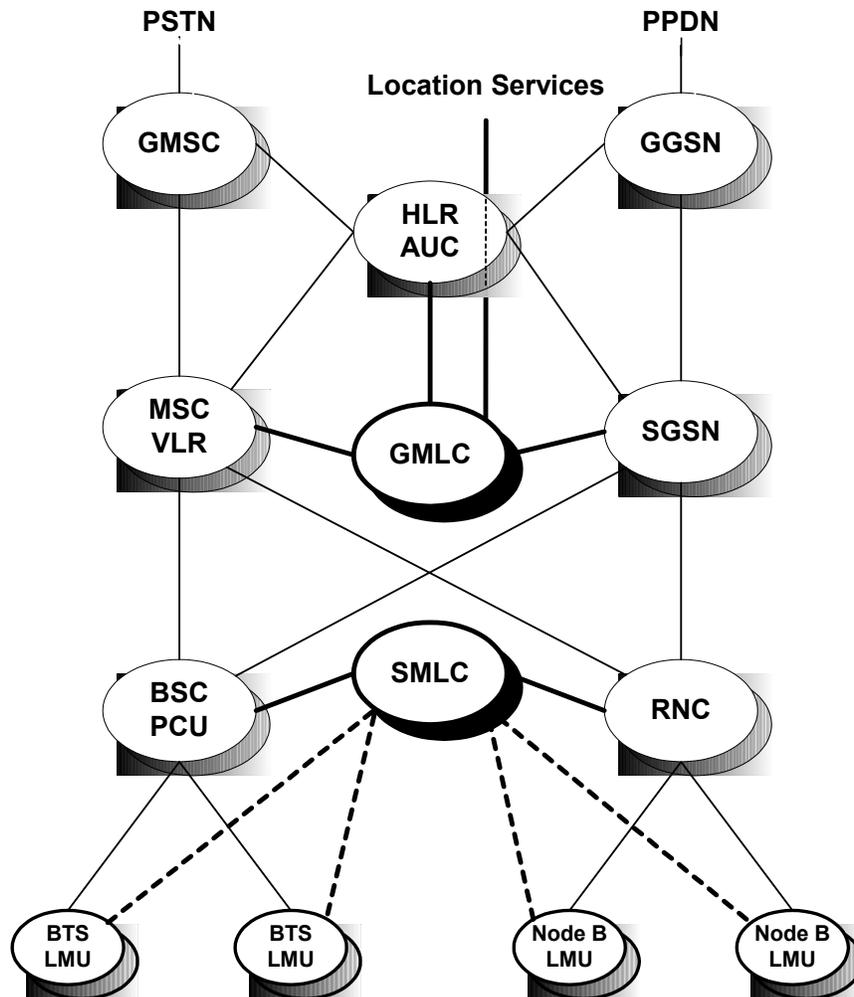


Figure 3.2

3.3. Implementation Considerations

This section describes specific implementation topics that need to be considered when implementing U-TDOA.

3.3.1. Physical Implementation of the LMU

An U-TDOA LMU can be physically implemented in three different ways, all of which are consistent with an evolutionary approach to LCS.

Stand-alone LMU

The initial implementation of LCS will almost certainly be into existing GSM/GPRS systems. This may require a separate stand-alone LMU. In addition, depending on existing BTS and BSC/PCU implementations, initial implementation may require an overlay interconnect to the SMLC that is a separate logical and possibly physical interconnect architecture.

BTS Module

The next level of integration would be the insertion of an LMU printed circuit board or outboard module into existing BTSs. This is the preferred LMU implementation for existing BTS installations. Such a LMU implementation would support specification-compliant LMU-to-SMLC interconnect that would be integrated with the BTS and BSC/PCU.

Integrated LMU

The final and most complete level of integration would be the inclusion of LMU functionality into the BTS, either as an addition to an existing circuit board or completely integrated as the result of a redesign effort.

Also, the RF front end of the LMU can be designed for multiple, non-contiguous frequency bands to accommodate fragmented frequency allocations.

3.3.2. Latency

Mechanisms have been developed to relieve the SMLC, LMU and existing infrastructure from the burden of tasking the LMU prior to the actual transmission of the MS for location purposes. “Real-time” tasking of the LMU allows for only very small latency from receipt of the connection-oriented information (frequency, timeslot, etc.) to the tasking of the LMU to capture the RF signal information. Severe delay (latency) restrictions would be imposed on the BSC and BTS for the transport of LLP (SMLC to LMU) messages. The GPRS domain permits very little delay between the assignment of resources and the transmission of information. A discussion of mechanisms that minimize real time performance requirements for U-TDOA follows.

In broad terms, a solution in which the LMU captures and stores the RF signal over a period of several seconds allows a reasonable amount of latency between the SMLC’s receipt of the Perform Location Request message, the provision of the connection definition information (frequency, timeslot, hopping information, block assignment, etc.) and the subsequent LMU tasking. The general sequence of events is as follows:

- Upon receipt of the Perform Location Request message the SMLC tasks the appropriate LMUs to begin caching RF signal data, based on the Cell ID.
- Based upon the connection definition information provided by the BSC/PCU, the SMLC will task the appropriate LMUs to extract only the information in the timeslots of interest on the indicated frequencies. Bursts occurring in these timeslots may have been transmitted significantly before the tasking information is received by the LMU, up to the limit of the cache memory. It is reasonable to implement sufficient memory for the capture of 3-5 seconds of RF signal.

- After analysis, each cooperating LMU returns the time of arrival information to the SMLC, which then calculates the MS location. Depending upon resource availability (RF and message transport capabilities), this process can be allowed to take many seconds (if necessary and allowable) without placing severe restrictions on the resource assignment and transport latency of the network infrastructure.

3.3.3. Synchronization

All U-TDOA capable LMUs are synchronized to an externally derived and very accurate clock. Periodically (every few minutes) the LMUs report to the SMLC the relationship between this system-wide clock and the GSM frame timing at the local site and/or surrounding sites. This information is maintained by the SMLC and used to optimize the collection of a particular MS signal in the cache memory at a remote LMU. The remote LMU is subsequently given the frequencies and system time at which to extract the relevant RF signal from the cache memory to begin the location calculation process.

3.3.4. Location Determination Capacity

Using existing hardware, an SMLC can execute approximately 100 location estimations per second with 16-32 cooperating LMUs per location, and 50 location estimations per second with 32-64 cooperating LMUs per location.

Additional SMLCs can be added to increase capacity as desired.

3.3.5. Intellectual Property Considerations

TruePosition, Incorporated may hold one or more patents or copyrights that cover information contained in this document. A license will be made available to applicants under reasonable terms and conditions that are demonstrably free of any unfair discrimination.

4. U-TDOA: Performance Analysis

4.1. Introduction

This section of the feasibility study provides an overview of this analysis and details the expected performance of the Uplink TDOA (U-TDOA) technology in a GSM environment. The goal is to provide insight into the theoretical aspects of the performance of U-TDOA in a GSM environment, as well as to relate this theoretical performance to previously measured performance in an IS-136 TDMA (North American TDMA) environment. The fundamental nature of this analysis should establish confidence in the expected performance of U-TDOA in GSM networks.

This analysis is then extended to predict the expected performance in GPRS networks by taking into account the reduced duration (number of bursts) of the available uplink signal.

4.2. Review of the Fundamental Drivers of Location Accuracy

U-TDOA estimates the position of a mobile station by measuring the time-difference-of-arrival (TDOA) between the signal received at the serving cell site and the same transmission received at other surrounding cell sites. The error in these TDOA measurements, not including the effect of multi-path, is given by the Cramer-Rao bound:

$$TDOA_{rms} = \frac{\sqrt{I2}}{2\pi B (2BT SNR_y)^{1/2}}$$

where B is the signal bandwidth, T is the coherent integration period, and SNR_y is the signal-to-noise ratio (SNR) of the remote signal. The location error that results is approximately:

$$Location\ rms \approx TDOA_{rms} P^{1/2} N^{1/2} GDOP_c$$

where P is the number of diversity antennas, N is the number of sites (valid only for $N \geq 3$), and $GDOP_c$ is the geometric dilution of precision (GDOP) relative to that at the center of a circular N -station configuration. From these relationships it is straightforward to conclude that location accuracy is a function of signal bandwidth, coherent integration time, SNR, number of receive antennas, number of receive sites, and the geometry of the receive sites.

In AMPS, IS-136 TDMA, and GSM environments the signal bandwidth is too small to resolve all multi-path components. The unresolved multi-path components result in additional error in the TDOA measurements. The effective multi-path delay spread is given by the square root of:

$$\tau^2_{effective-spread} = \sum_i \tau_i^2 |A_i|^2 \text{sinc}^2 x - \left(\sum_i \tau_i |A_i|^2 \text{sinc}^2 x \right)^2$$

where A_i is the voltage amplitude of the i^{th} multi-path component, $x = \pi B$, and B is the signal bandwidth.

The larger the signal bandwidth the more multi-path components can be resolved and the smaller the effective multi-path delay spread. This is illustrated more clearly for IS-136 TDMA and GSM in the following section. In most AMPS, IS-136 TDMA (hereafter just TDMA) and GSM environments the error caused by unresolved multi-path components dominates location accuracy. Sophisticated super-resolution techniques have been developed to help mitigate the effects of the unresolved multi-path. The performance of these techniques depends upon signal bandwidth, coherent integration time, and SNR.

4.3. Comparison of GSM Versus IS-136 TDMA

From a location accuracy perspective, the significant difference between GSM and TDMA is signal bandwidth. The wave-shaping filter for TDMA is a “35% excess bandwidth, root cosine filter” with a 3 dB bandwidth of 24.3 kHz (the symbol rate). The GMSK waveform used for GSM has an approximate bandwidth of 120 kHz. This approximately 5:1 difference in bandwidth and the resulting time spread of the signals makes GSM significantly more immune to multi-path than TDMA. The effects of this increased bandwidth on multi-path spread are illustrated in the more detailed document in Appendix A.

The illustrations in Appendix A show only the general effect of multi-path since the phase of these components is not included. To verify that the differences shown by these simple illustrations will also be seen in real GSM deployments, a sophisticated predictive modeling tool, using the actual location algorithms was modified to support the GSM signal bandwidth. Signals representative of both TDMA and GSM were generated and passed through a random multi-path model. For each TDOA measurement this model generated independent Rayleigh-distributed amplitudes and random phases for each of the multi-path components along with Gaussian noise added to the output. The results, averaged over many TDOA measurements, showed a 2:1 ratio of TDMA-to-GSM errors for the typical multi-path case.

Based on this analysis of the effect of signal bandwidth, and the fact that the integrated SNR effectively is equivalent for GSM and TDMA, RMS TDOA errors for GSM are predicted to be approximately half of those for TDMA. Assuming that in similar network deployments the number of receive antennas, number of receive sites, and the geometry of the receive sites will be the same, the accuracy for GSM should be at least twice that of TDMA.

To verify this conclusion, an analysis was conducted to determine the expected performance of U-TDOA in deployed networks. Both TDMA and GSM performance were modeled using a predictive modeling tool. An 18-site TDMA Trial network in Wilmington, Delaware (USA) was used to establish a frame of reference with actual measured TDMA performance. In addition, 172 sites covering the portion of Houston, Texas inside the Sam Houston Parkway were used to provide a more comprehensive test. Finally, an example 1900-MHz GSM network covering the same portion of Houston was used to provide insight into the effects of the different propagation environment, cell site density, antenna configurations, etc. GSM performance for both 100% and 50% LMU deployment densities were analyzed. A more detailed presentation of this material can be found in Appendix A.

Additional analysis was done to evaluate the location accuracy of the proposed U-TDOA approach for GPRS. Packet polling requests would be used to initiate transmission from the MS. A range of 4 to 20 requests, resulting in the transmission of 16 to 80 bursts, has been considered. Analysis was therefore performed for both the 16- and 80-burst cases to compare with the 650-burst GSM voice mode results. Note that the 80-burst performance also applies to locations performed for GSM during the Circuit Switched Idle

Mode through use of a commanded handover to the same channel (the total amount of signal contained in 145 access bursts is approximately the same as 80 normal bursts).

Table 7-1 provides the overall results of the analysis. The figure numbers refer to the diagrams in the report included in Appendix A.

Network	Air Interface	LMU Deployment Density	67% Performance (meters)	95% Performance (meters)	Figure
<i>Wilmington (Trial Results)</i>	<i>TDMA</i>	<i>100%</i>	<i>81.2</i>	<i>189.9</i>	N.A.
Wilmington	TDMA	100%	81	137	7
Wilmington	GSM (CS)	100%	42	71	8
	GPRS (80 burst)		48	81	9
	GPRS (16 burst)		55	94	10
Wilmington	GSM (CS)	50%	57	100	11
	GPRS (80 burst)		65	113	12
	GPRS (16 burst)		73	129	13
Houston (850 MHz)	TDMA	100%	84	143	16
Houston (850 MHz)	GSM (CS)	100%	44	74	17
	GPRS (80 burst)		49	84	18
	GPRS (16 burst)		55	94	19
Houston (850 MHz)	GSM (CS)	50%	50	86	20
	GPRS (80 burst)		57	98	21
	GPRS (16 burst)		65	112	22

Network	Air Interface	LMU Deployment Density	67% Performance (meters)	95% Performance (meters)	Figure
Houston (1900 MHz)	GSM (CS)	100%	56	100	25
	GPRS (80 burst)		65	116	26
	GPRS (16 burst)		76	139	27
Houston (1900 MHz)	GSM (CS)	50%	66	117	28
	GPRS (80 burst)		79	142	29
	GPRS (16 burst)		100	185	30

Table 7.1 Predicted Location Accuracy Performance

4.4. Conclusion

From a location accuracy perspective, the significant difference between GSM and TDMA is signal bandwidth. The 5:1 difference in bandwidth makes GSM significantly more immune to multi-path than TDMA. A comprehensive analysis showed a 2:1 ratio of TDMA-to-GSM errors for the typical multi-path case and nearly a 4:1 ratio for the severe case. Based on this analysis, it is predicted that the RMS TDOA errors for GSM will be approximately half of those for TDMA. As a result, the accuracy of TDOA for GSM should be at least twice that of TDMA. In addition, it should be possible to achieve the stated levels of accuracy (Table 1) in most GSM networks when LMUs are deployed at only 50% of the cell sites.

The U-TDOA performance results presented in this analysis are conservative. They take into account only the increased signal bandwidth of GSM. They do not take into account frequency hopping on the uplink channels and the significant resulting benefit in reducing multi-path. Also, they do not take into account more aggressive techniques for mitigating the effects of multi-path in a GSM environment that are currently under development. These techniques for super-resolving multi-path and detecting leading edge components have the potential to improve results even further. As a result, the performance of U-TDOA in actual deployments will be more accurate than the results presented in this analysis.

5. U-TDOA: System Impacts

5.1. Protocol Impacts

5.1.1. GSM

Call Control

No impact.

Mobility Management

No impact.

Radio Resource Management

No impact.

Short Message Service

No impact.

Supplementary Services

No impact.

5.1.2. GPRS

GPRS Mobility Management (GMM)

No impact.

Session Management (SM)

No impact.

GPRS Short Message Service

No impact.

BSSGP

The BSSGP must be changed to inform the PCU that a location estimation using the U-TDOA method is requested.

The **Location Type** IE in the **Perform_Location_Request** message must be extended to include U-TDOA as a location type. There are undefined values within this IE.

This IE is specified in Paragraph 11.3.53 (Location Type IE) of 3GTS 48.018 (BSSGP) which points to Paragraph 10.18 (Location Type IE) of 3GTS 49.031 (BSSAP-LE). New values must be specified for Octet 3 (Coding of location information) and Octet 4 (Positioning method).

RLC/MAC

No impact.

Only standard RLC/MAC messages are used to force the MS to transmit.

5.1.3. Common Protocols for Location Services

BSSAP-LE

As in BSSGP (Paragraph 6.1.2.4 above), the Location Type IE in the Perform_Location_Request message must be extended to include U-TDOA as a location type. There are undefined values within this IE.

BSSLAP

A new message indicating U-TDOA Request to the PCU has to be implemented. This message consists of the Message type IE only (like the TA Request message in 48.071 Par. 4.2.1)

Also the U-TDOA Response message from the PCU to the SMLC has to be specified. This message consists of the Message type IE and an additional Cause value. It is used exclusively to inform the SMLC that the PCU has finished its tasks.

In addition to the already defined messages new messages supporting transparent information transfer between the SMLC and the PCU have to be specified.

LLP

In addition to the already-defined messages, new messages that support transparent information transfer between the SMLC and the LMU have to be specified. This also must support segmentation in case the transferred volume exceeds the maximum message size of the LLP SDU.

RRLP

This protocol is not used or affected by U-TDOA.

5.2. Impacts to Existing Nodes

5.2.1. BTS

None.

5.2.2. BSC

Implement physical interface to the SMLC:

- Implement logic and messaging for GSM 03.71 “False Handover” LCS
- For additional detail refer to the Circuit Switched call flows in paragraphs 6.4 and 6.5 of this document.

5.2.3. PCU

- Implement physical interface to the SMLC
- Implement logic and messaging for the Timing Advance Polling method detailed in the Packet Switched call flows in paragraphs 6.2 and 6.3 of this document.

5.2.4. MSC/VLR

None.

5.2.5. SGSN

- Implement logic and messaging for U-TDOA
- Primarily messaging and protocol modifications

5.2.6. SMLC

- Implement U-TDOA functionality
- Implement messaging and protocol modifications

5.2.7. LMU

- Implement logic and messaging for U-TDOA

5.2.8. MS

None.

5.3. Network Capacity Impacts**5.3.1. Network Assumptions**

- One (1) LMU at each BTS

- 16 LMUs involved with each Location Estimation on average
- Location Event – one execution of the Pack_Polling_Request procedure
- Location Estimation – Eight (8) sequential Location Events (executions of the Pack_Polling_Request procedure) on average
- One (1) Location Estimation per cell/sector per minute for initial LCS implementation
- Ten (10) Location Estimations per cell/sector per minute for mature LCS implementation

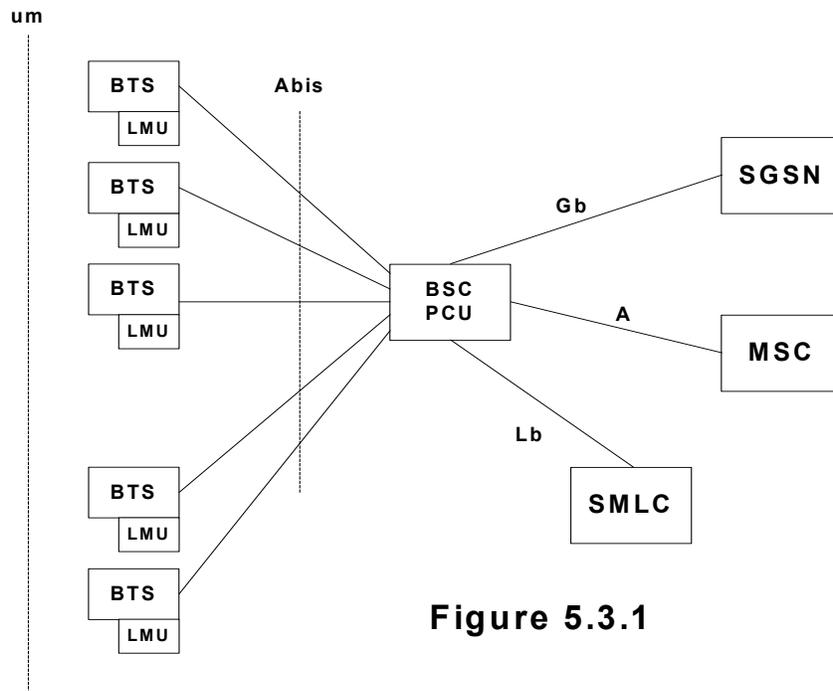


Figure 5.3.1

5.3.2. Um Interface

The U-TDOA location method requires the mobile station to transmit from 4 to 20 blocks of information (16 to 80 normal bursts), depending on the accuracy required. For initial implementations with a single location estimation per cell/sector per minute, this activity is not significant. For more mature systems with 10 location estimations per minute per cell/sector, an average load of between 2.7 bursts per second (160 burst per minute) and 17.7 bursts per second (800 bursts per minute) is offered to the air interface. For the mature implementation, this level of traffic requires 8.2% of the available bursts in one timeslot.

5.3.3. Abis Interface

The traffic on the Abis interface, for location activity in a particular cell/sector is analogous to the traffic on the air interface. On the Abis interface each execution of the Packet_Polling_Request message represents one PCU frame. Therefore, the peak load for a mature implementation is 200 PCU frames per minute (10 location estimations per minute, 20 executions of the Packet_Polling_Req for a high accuracy location

estimation) or 3.3 TRAU frames per second (320 bits per PCU frame x 3.3 frames = 1.067 Kbits per second). This traffic is distributed across several Abis links for sites with multiple ARFCN.

In addition to the BSC-to-MS messaging, the SMLC-to-LMU tasking and response information is also present on the Abis interface. This traffic consists of the LMU tasking for the residence cell as well as for the location estimations occurring in the surrounding cells. In an ideal system with evenly distributed traffic in all cells (the case with maximum offered load) and an average of 16 cooperating LMUs per location, each Abis link will carry the LMU traffic for 16 location estimations. For an average of 10 location estimations per minute per cell/sector, this results in 160 tasking messages or 160 PCU frames per minute (2.67 frames per second) per Abis link.

5.3.4. Lb Interface

The Lb interface carries the BSSAP-LE and BSSLAP messaging associated with all location requests and responses as well as the LLP LMU tasking and response information. The BSSAP-LE and BSSLAP messaging traffic is the same for all of the proposed location methodologies. In the U-TDOA methodology, the LMU tasking and response traffic represents the vast majority of the traffic. For each location estimation, up to 30 LMUs may be tasked to capture the resulting RF energy. A more typical number is 16.

The primary LMU demodulates the MS transmission and forwards the resulting RLC/MAC control message in a LLP message container to the SMLC along with additional timing and phase information. This RLC/MAC control message and U-TDOA associated data require approximately 250 bits to encode. The SMLC then forwards this information to all cooperating LMUs (16 in this model). Each location event offers 4000 bits of traffic to the Lb interface. For a location estimate consisting of 10 location events, this translates to 40 kbits of load per location estimation on the Lb interface.

5.3.5. Gb Interface

The two additional messages (Perform Location Request and Perform Location Response) for each location request add the same amount of traffic to Gb interface for all of the proposed location methodologies.

5.3.6. MS Power Consumption

If any specific MS infrequently requests a location (a few times per day) and the Packet_Polling_Request method is executed within a few seconds, the additional power consumption will be minimal and similar to other location methodologies.

5.4. Impact on Specifications

5.4.1. 3GTS 48.018 BSSGP

The IE specified in Paragraph 11.3.53 (Location Type IE) which points to Paragraph 10.18 (Location Type IE) of 3GTS 49.031 (BSSAP-LE) must be extended. New values must be specified for U-TDOA in Octet 3 (Coding of location information) and Octet 4 (Positioning method).

5.4.2. 3GTS 49.031 BSSAP-LE

The IE specified in Paragraph 10.18 (Location Type IE) of 3GTS 49.031 (BSSAP-LE) must be extended. New values must be specified for U-TDOA in Octet 3 (Coding of location information) and Octet 4 (Positioning method).

5.4.3. 3GTS 48.071 BSSLAP

New message formats that support U-TDOA must be included as follows:

- An U-TDOA Request message to the PCU must be implemented. This message consists of the Message type IE only (like the TA Request message in 48.071 Par. 4.2.1)
- An U-TDOA Complete message must be implemented. This message consists of the Message type IE and an additional Cause value.
- In addition to the previously defined messages, new messages supporting transparent information transfer between the SMLC and the LMU must be specified.

5.4.4. 3GTS 44.071 LLP

New messages supporting transparent U-TDOA information transfer between the SMLC and the LMU must be specified.

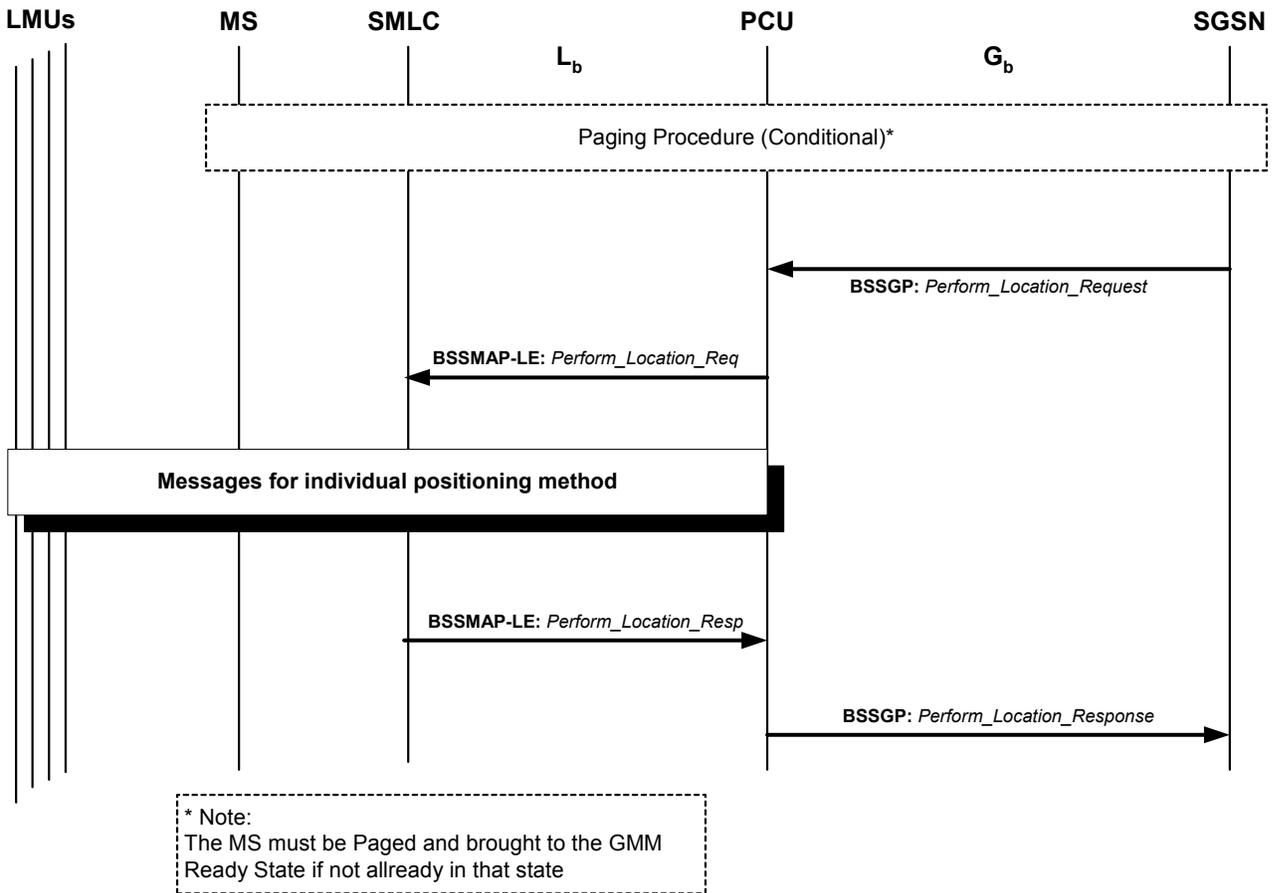
5.4.5. 3GTS 43.059 LCS Stage 2 Document

U-TDOA as a location method must be added to this specification.

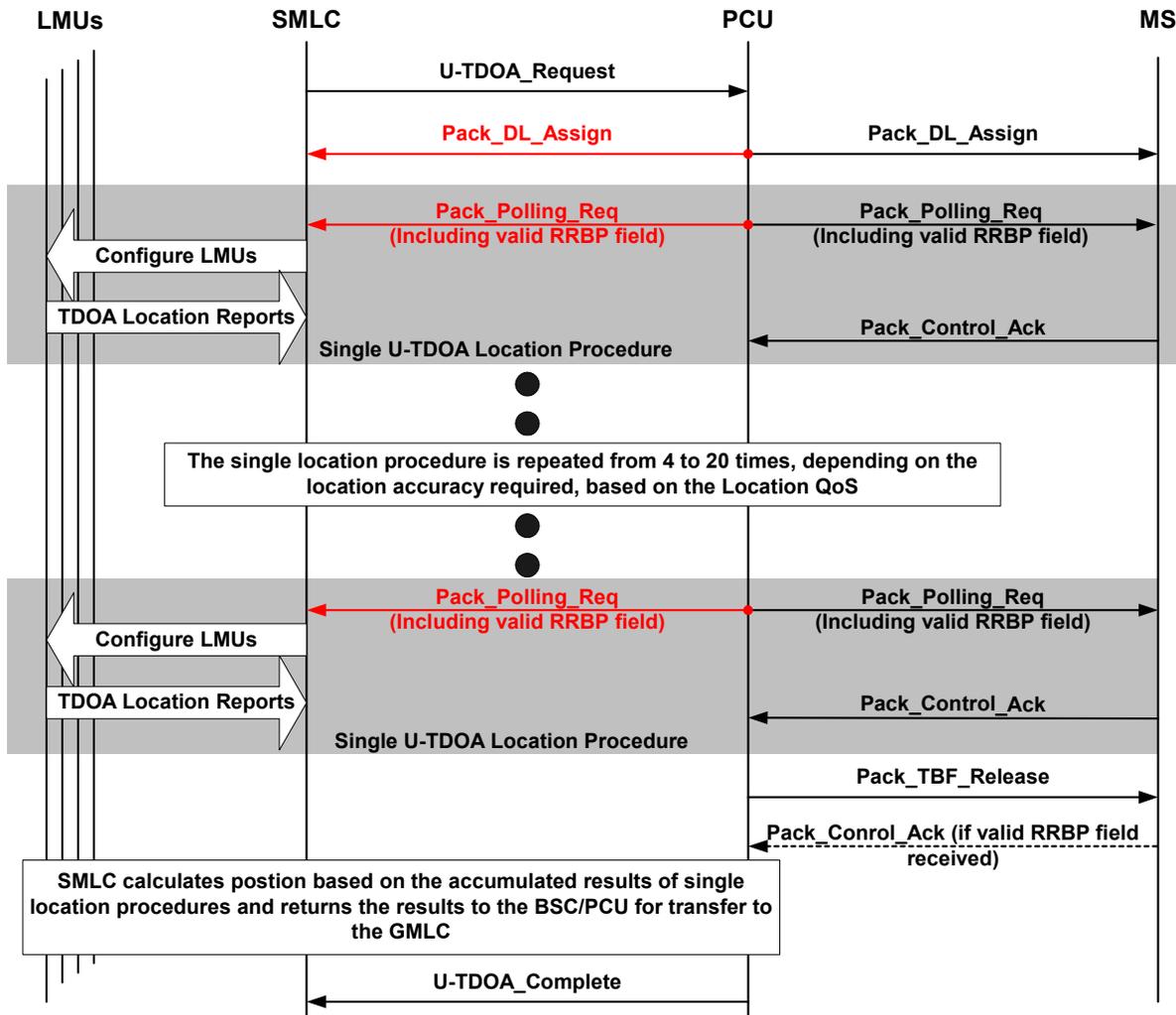
6. U-TDOA Call Flows

6.1. Packet Switched

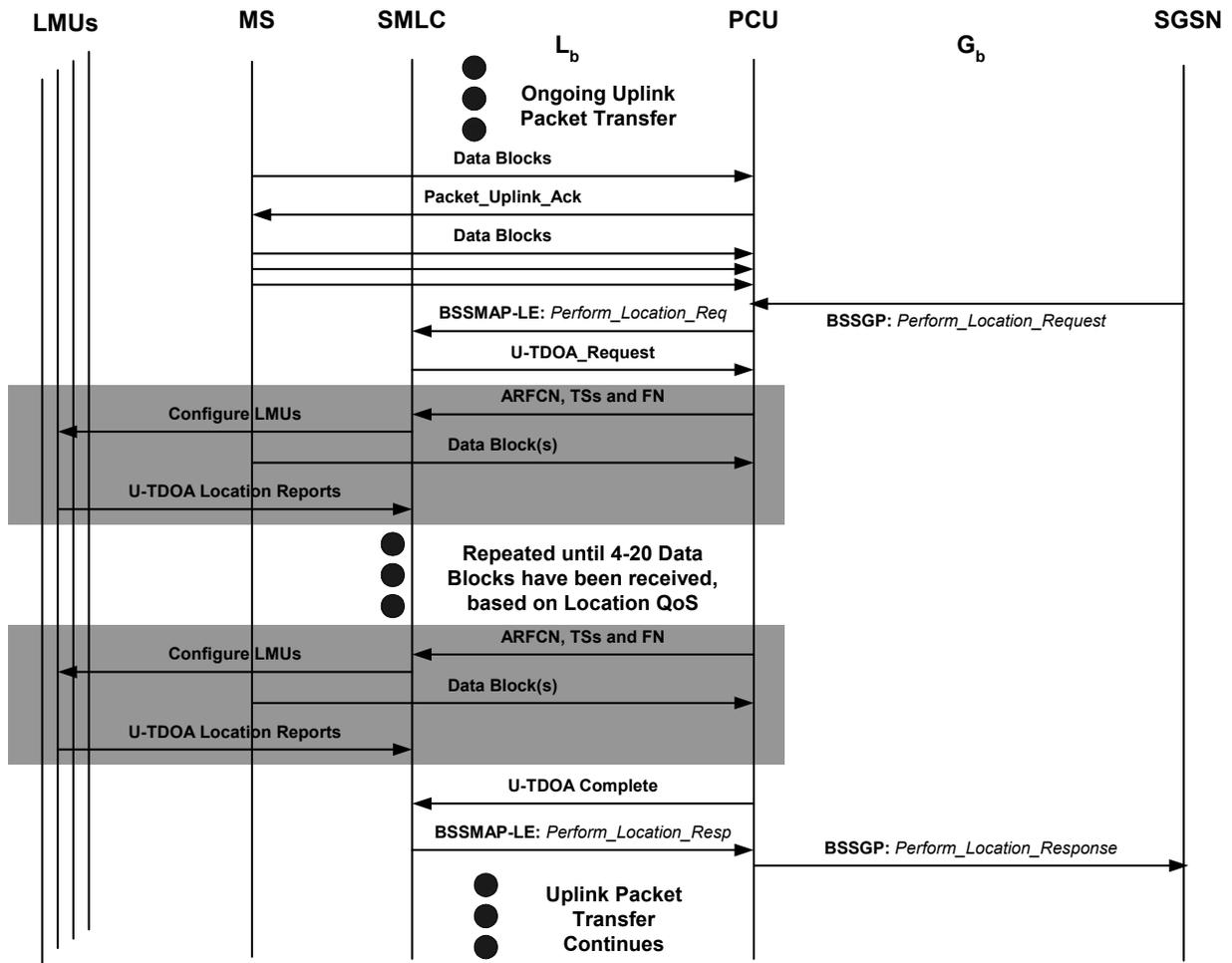
6.1.1. General Location Procedure



6.1.2. PS U-TDOA, Packet Idle Mode

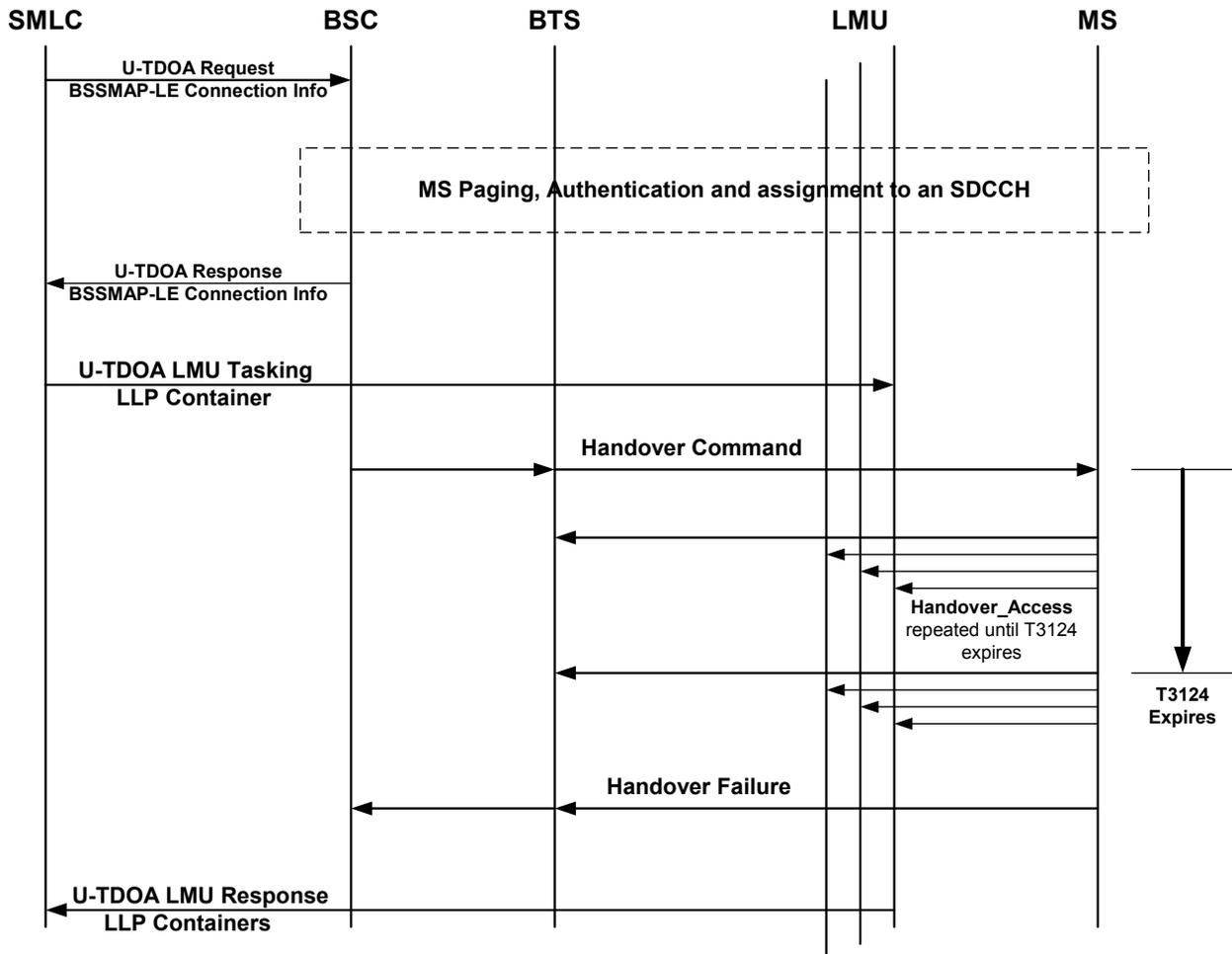


6.1.3. PS U-TDOA, Ready State, Uplink data transfer in progress

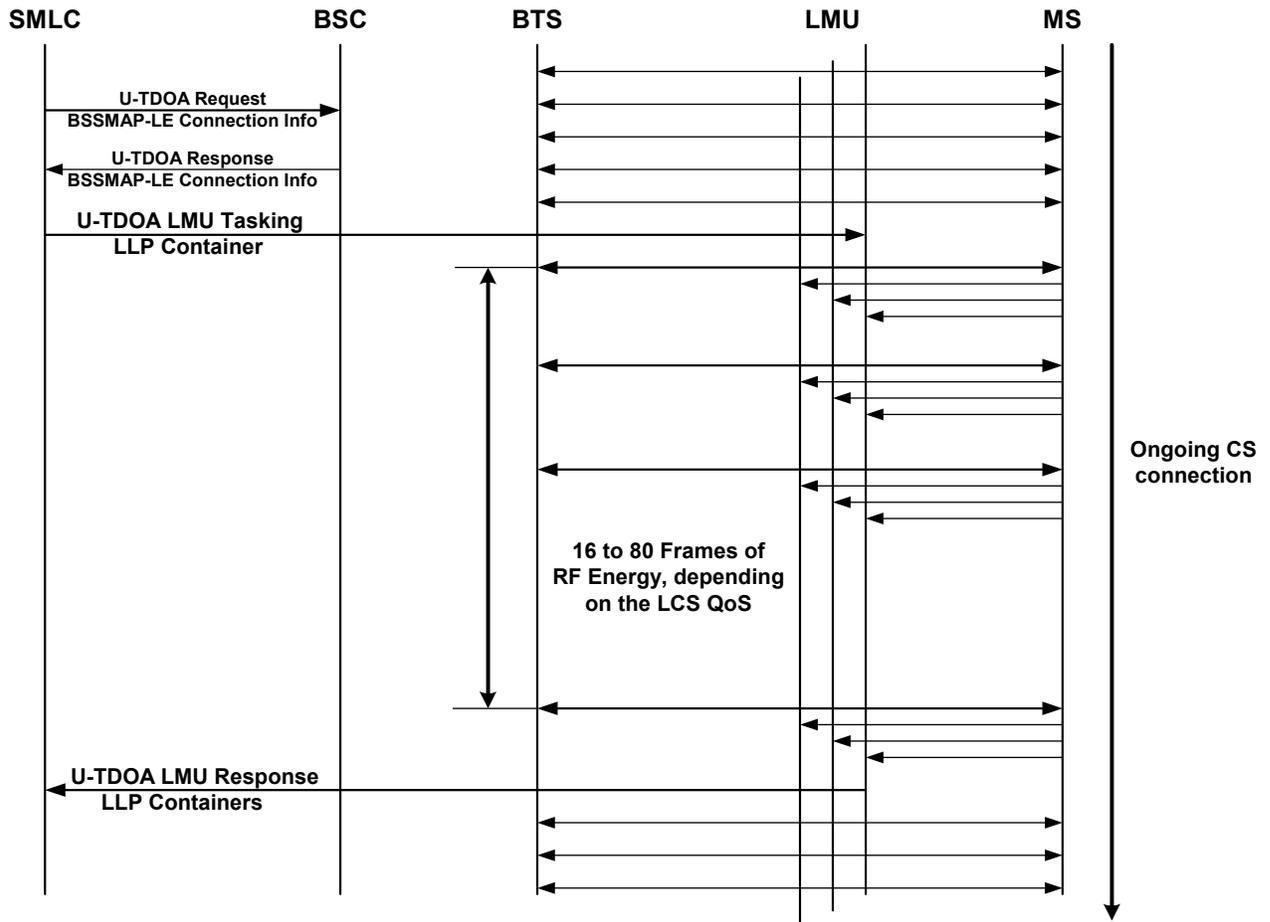


6.2. Circuit Switched

6.2.1. CS, Idle Mode



6.2.2. CS, Dedicated Mode



7. U-TDOA Advantages and Disadvantages

This section describes the advantages and disadvantages of U-TDOA relative to other location technologies when implemented in GSM and GPRS environments.

7.1. Advantages of U-TDOA

7.1.1. Excellent Performance in Urban and Indoor Environments

In urban and indoor environments cell site densities are high and mobile stations overcome the attenuating effects of the challenging propagation environment by increasing transmit power as necessary. As a result, a significant number of U-TDOA LMUs are able to make TDOA measurements for each location estimate. In addition, directional cell site receive antennas deployed in a diversity configuration minimize the amount of multipath and help overcome the effects of fading while maximizing the total number of independent TDOA measurements. The significant signal processing capacity available at each U-TDOA LMU allows the use of advanced super-resolution techniques, which along with the frequency hopping on the uplink signals mitigate the effects of multipath even further. All these features combine to allow U-TDOA to achieve high levels of accuracy in the most challenging urban and indoor environments.

The ability to achieve high levels of location accuracy and availability in urban and indoor environments allows U-TDOA to mitigate the performance limitations of A-GPS and E-OTD in these same environments.

7.1.2. Support for Legacy Mobile Stations

U-TDOA uses the normal uplink transmissions from GSM and GPRS mobile stations to compute accurate position estimates. U-TDOA requires no changes to the mobile station to support positioning. As a result, U-TDOA provides accurate location capability for all existing legacy mobile stations as well as all future mobile stations. This unique feature allows operators to provide location-based services to their entire existing subscriber base.

7.1.3. Scalable Accuracy and Cost

It is predicted that over time higher accuracies will be required for the higher revenue consumer and enterprise applications (e.g. personal safety, navigation and security, etc.). U-TDOA can be implemented in a phased approach that minimizes the initial investment while permitting incremental upgrades that improve accuracy as market opportunities mature. For example, an U-TDOA network can be deployed initially in only 50% of cell sites to achieve sub-100m accuracy; as applications and accuracy requirements change, the density can be increased up to 100% to achieve 50m accuracy.

7.1.4. Support for Roaming Subscribers

For roaming coverage, U-TDOA locates roaming subscribers regardless of the type of MS equipment or the presence and compatibility of MS-based LCS software.

7.1.5. Efficient Use of RF Resources

For mobile station equipment that is actively engaged in sufficiently large uplink data transfer or an active circuit switched call, U-TDOA does not use any additional system resources for location determination. U-TDOA technology locates mobile stations using the energy associated with the existing traffic and control information.

7.1.6. Protection from Obsolescence

U-TDOA provides protection against obsolescence. As improvements are made and as air interfaces evolve U-TDOA LMU and SMLC software can be easily upgraded.

7.1.7. Proven Technology

U-TDOA has been tested in extensive field trials and commercial deployments over the course of the past six years. Over 1000 sites have been implemented by manufacturers to date, with over 750 sites deployed by TruePosition alone. These deployments have included dense urban, suburban, rural, and indoor environments. Millions of location estimates, collected over thousands of square kilometers have been analyzed and used to improve the performance and operability of the technology to a very mature level.

7.2. Disadvantages of U-TDOA

7.2.1. U-TDOA is currently perceived as being prohibitively expensive

To date U-TDOA technology has only been deployed in AMPS, TDMA (IS-136) and CDMA (IS-95) networks. Due to a lack of standardization of location technologies in these networks, the U-TDOA technology has been implemented in expensive stand-alone overlay configurations. The LMU and BTS network elements have not been able to share common equipment or communications interconnect. The cost efficiencies achieved from integration with the network infrastructure have not been realized.

Standardization of U-TDOA technology within GERAN will allow integration with the GSM/GPRS network infrastructure, which will result in U-TDOA costs comparable to the network component of E-OTD. In addition, since both cost and accuracy scale as a function of LMU-to-cell site deployment ratio, the cost of deploying U-TDOA can be mitigated by scaling U-TDOA LMU deployment density to meet the accuracy requirements of the applications and services being offered.

7.2.2. Accuracy of U-TDOA degrades in some rural areas

To provide accurate position estimates, standalone U-TDOA requires time difference measurements from at least four sites distributed in a reasonable geometry around the transmitting mobile station. In some very rural environments, where cell site spacing is very large and geometries are limited by constrained network coverage (e.g. very rural highways, mountainous areas, etc.), these fundamental requirements cannot be met and the accuracy of U-TDOA degrades.

Typically, very rural environments with lower cell densities and limited geometries are sparsely populated and require less accuracy to satisfy applications. U-TDOA typically provides adequate accuracy in such environments. In cases where additional accuracy is required, a hybrid U-TDOA/A-GPS system solution provides excellent performance. Also, angle of arrival (AOA) technology can be added to augment U-TDOA in order to significantly improve accuracy.

APPENDIX A. Analysis of GSM and GPRS Uplink Time Difference Of Arrival (U-TDOA)

A.1. Introduction

Over the past nine years TruePosition has developed comprehensive knowledge about the capabilities and performance of Time Difference of Arrival (TDOA) based wireless location systems. This knowledge was developed through extensive research, analysis and field deployments. Although TruePosition has not yet deployed a TDOA-based wireless location system in a GSM network, a comprehensive analysis has been performed and the expected performance is well understood.

This document provides an overview of this analysis and details the expected performance of the TruePosition Wireless Locations System (WLS) in a GSM environment. The goal is to provide insight into the theoretical aspects of the performance of the TruePosition WLS in a GSM environment, as well as to relate this theoretical performance to previously measured performance in an IS-136 TDMA (North American TDMA) environment. The fundamental nature of this analysis should establish confidence in the expected performance of the TruePosition WLS in GSM networks.

This analysis is then extended to predict the expected performance in GPRS networks by taking into account the reduced duration (number of bursts) of the available uplink signal.

A.2. Review of the Fundamental Drivers of Location Accuracy

The TruePosition WLS estimates the position of a mobile station by measuring the time-difference-of-arrival (TDOA) between the signal received at the serving cell site and the same transmission received at other surrounding cell sites. The error in these TDOA measurements, not including the effect of multi-path, is given by the Cramer-Rao bound:

$$TDOA_{rms} = \frac{\sqrt{12}}{2\pi B (2BT SNR_y)^{1/2}}$$

where B is the signal bandwidth, T is the coherent integration period, and SNR_y is the signal-to-noise ratio (SNR) of the remote signal. The location error that results is approximately:

$$Location\ rms \approx TDOA_{rms} P^{1/2} N^{1/2} GDOP_c$$

where P is the number of diversity antennas, N is the number of sites (valid only for $N \geq 3$), and $GDOP_c$ is the geometric dilution of precision (GDOP) relative to that at the center of a circular N-station configuration. From this it is straightforward to see that location accuracy is a function of signal bandwidth, coherent integration time, SNR, number of receive antennas, number of receive sites, and the geometry of the receive sites.

In AMPS, IS-136 TDMA and GSM environments the signal bandwidth is too small to resolve all multi-path components. The unresolved multi-path components result in additional error in the TDOA measurements. The effective multi-path delay spread is given by the square root of:

$$\tau_{\text{effective-spread}}^2 = \sum_i \tau_i^2 |A_i|^2 \text{sinc}^2 x - \left(\sum_i \tau_i |A_i|^2 \text{sinc}^2 x \right)^2$$

where A_i is the voltage amplitude of the i^{th} multi-path component, $x = \pi B \tau_i$, and B is the signal bandwidth.

The larger the signal bandwidth the more multi-path components can be resolved and the smaller the effective multi-path delay spread. This is illustrated more clearly for TDMA and GSM in the following section. In most AMPS, IS-136 TDMA (hereafter just TDMA) and GSM environments the error caused by unresolved multi-path components dominates location accuracy. TruePosition has developed sophisticated super-resolution techniques to help mitigate the effects of the unresolved multi-path. The performance of these techniques is dependent upon signal bandwidth, coherent integration time and SNR.

A.3. Comparison of GSM Versus TDMA

From a location accuracy perspective the significant difference between GSM and TDMA is signal bandwidth. Figure 1 shows the ideal cross correlation of the reference signal with one from a cooperating site. This was computed by convolving the transmit wave-shaping filter with itself for each of the air-interfaces. The wave-shaping filter for TDMA is a “35% excess bandwidth, root cosine filter” with a 3 dB bandwidth of 24.3 kHz (the symbol rate). The GMSK waveform used for GSM has an approximate bandwidth of 120 kHz.

This approximately 5:1 difference in bandwidth and the resulting time spread of the signals makes GSM significantly more immune to multi-path than TDMA. Because of this, any multi-path components more than a few μs from the main path (typically line-of-site) will not effect the TDOA measurement for GSM. However, as can be seen from the figure, multi-path components tens of μs from the main path will effect TDOA measurements for TDMA. These farther out multi-path components also cause greater errors in the TDMA measurement since the error introduced is proportional to the delay given constant relative amplitude.

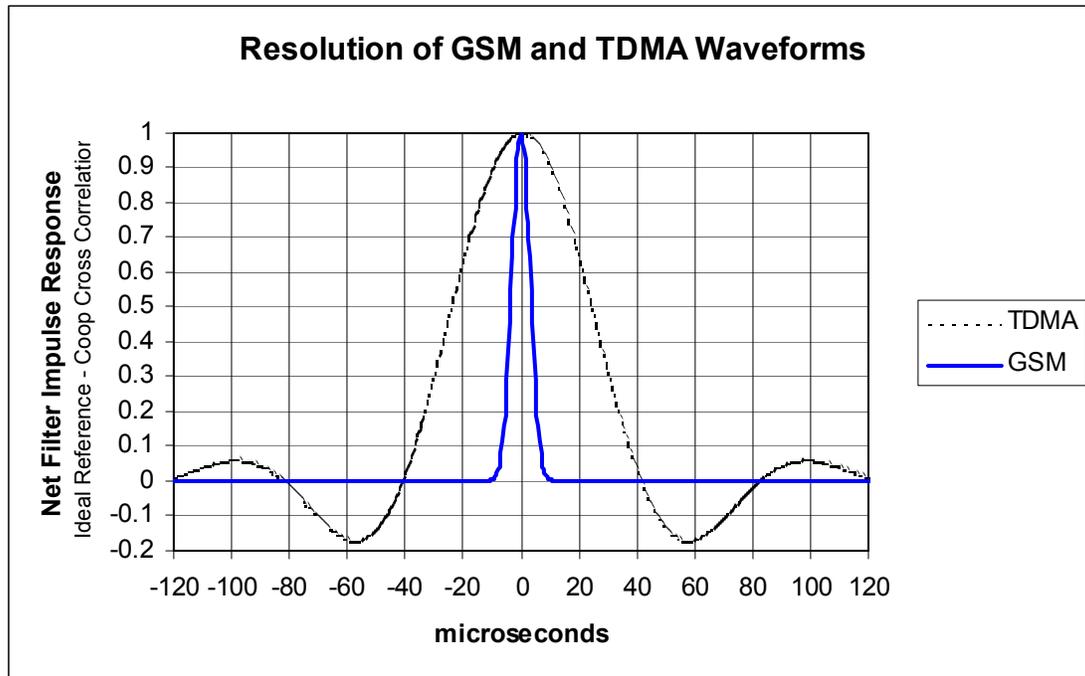


Figure 1- Resolution of GSM and TDA Waveforms

To illustrate the general effect of the smearing of multi-path components into the correlation peak of the main component, one can convolve a set of impulses with the relative amplitudes and delays representing the main path followed by a number of multi-path components. A simple model for the multi-path has components spaced at $2 \mu\text{s}$ intervals with amplitudes proportional to $\tau^{-\alpha}$ where τ is multi-path delay of each component and α is a constant. Larger values of α cause the more-delayed components to have smaller relative amplitudes. The overall multi-path spread is usually described as the RMS time spread of the power of all the multi-path components including the main component.

Figure 2 and Figure 3 show the effect of 10 multi-path components using a $\alpha=1.5$ which results in a multi-path spread of just over $1 \mu\text{s}$. This might be considered a typical multi-path environment.

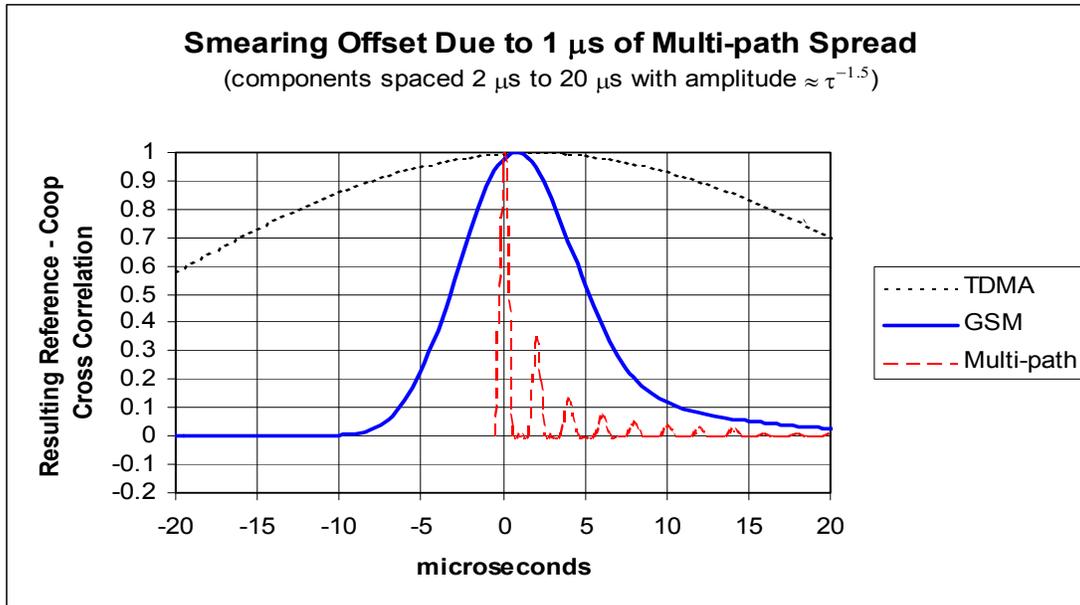


Figure 2 - The Effect of Typical Multi-path on TDOA Measurements

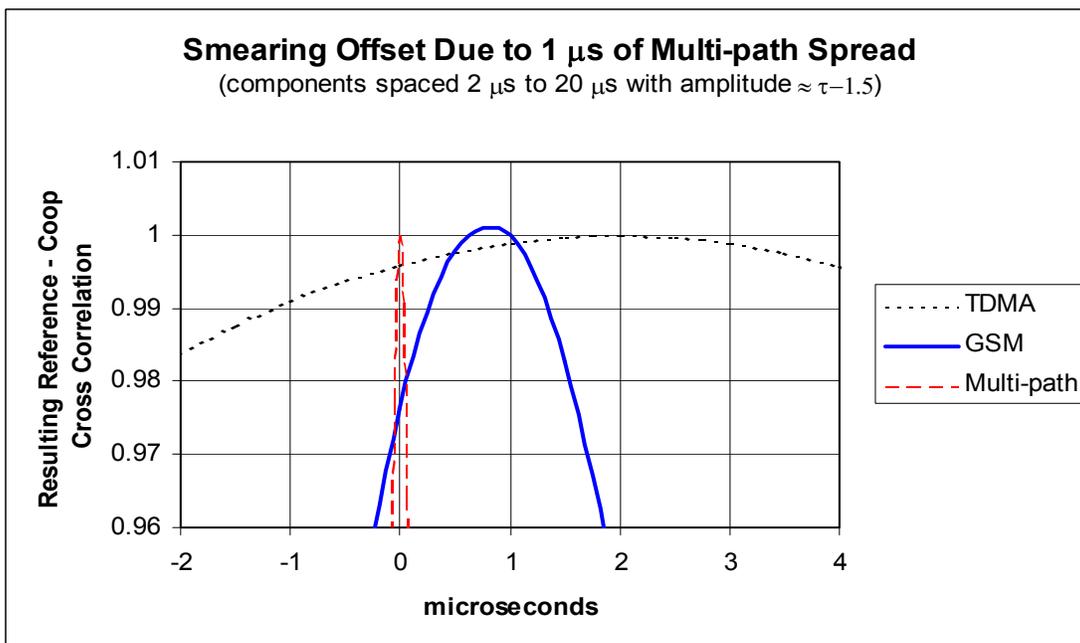


Figure 3 - The Effect of Typical Multi-Path on TDOA Measurements (Zoomed In)

As can be seen in Figure 3, the peak of the correlation for GSM is shifted by approximately 800 ns, while the peak for TDMA is shifted nearly 2000 ns (each ns is approximately one foot). The very broad peak of the TDMA correlation also makes it more sensitive to noise corruption.

Figure 4 and Figure 5 show the effect of 20 multi-path components using a $\alpha=1.0$ which results in a multi-path spread of 3 μs . This might be considered a severe multi-path environment.

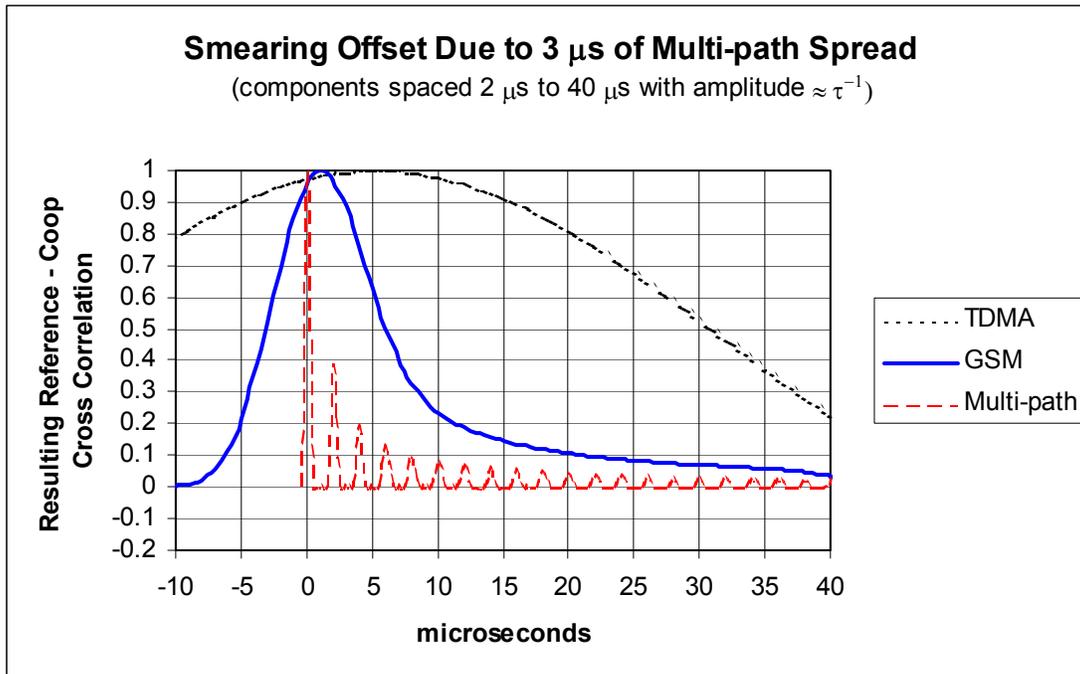


Figure 4 - The Effect of Severe Multi-Path on TDOA Measurements

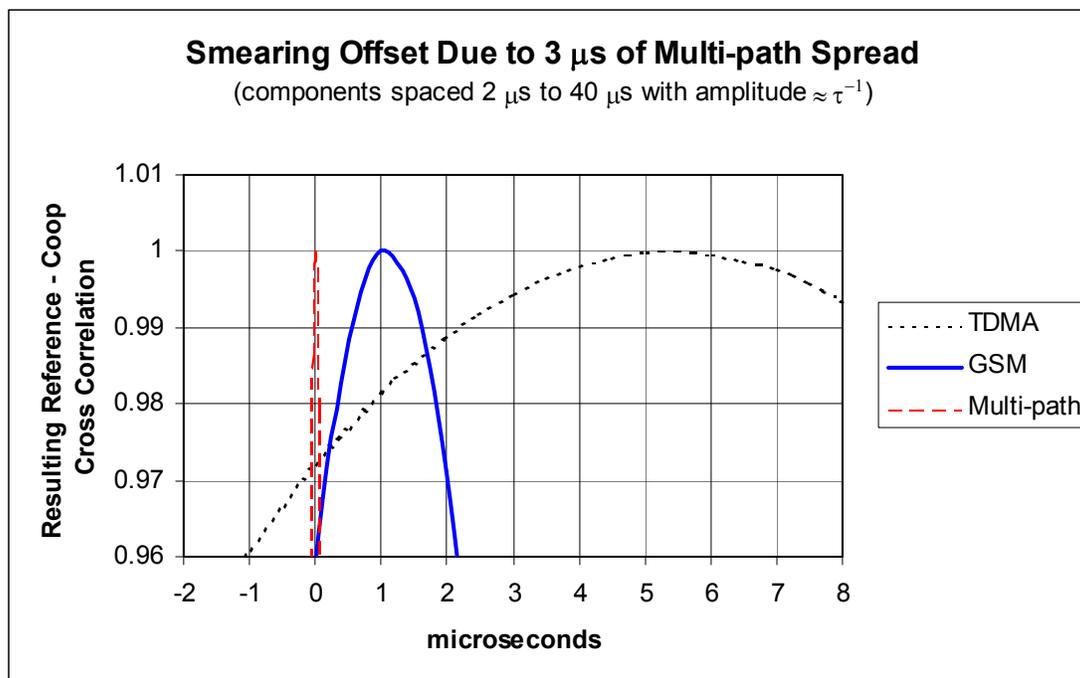


Figure 5 - The Effect of Severe Multi-path on TDOA Measurements (Zoomed In)

As can be seen in Figure 5, the peak of the correlation for GSM is shifted by approximately 1000 ns, while the peak for TDMA is shifted over 5000 ns. TruePosition utilizes super-resolution techniques to correct for large errors such as these in order to attain the location accuracy demonstrated in numerous deployments.

The above illustrations only show the general effect of multi-path since the phase of these components is not included. To verify that the differences shown by these simple illustrations will also be seen in real GSM deployments, a sophisticated simulation that utilizes the actual TruePosition location algorithms was modified to support the GSM signal bandwidth. Signals representative of both TDMA and GSM were generated and passed through a random multi-path simulation model. For each TDOA measurement this model generated independent Rayleigh distributed amplitudes and random phases for each of the multi-path components along with Gaussian noise added to the output. The results averaged over many TDOA measurements showed a 2:1 ratio of TDMA to GSM errors for the typical multi-path case shown in Figure 3, and nearly a 4:1 ratio for the severe case shown in Figure 5.

Coherent integration time and SNR also affect the accuracy of TDOA measurements. In a typical 3-second data collection period the TruePosition LMUs collect 375 milliseconds of data (650 bursts) from a GSM mobile transmitting at a power level of two watts, compared to 1 second of data (150 bursts) from a TDMA mobile transmitting at a power level of 0.6 watts. This means the integrated SNR for GSM and TDMA are effectively equivalent.

Based on this analysis of the effect of signal bandwidth, and the fact that integrated SNR for GSM and TDMA are effectively equivalent, TruePosition is confident that the RMS TDOA errors for GSM will be approximately half of those for TDMA. Given that in similar network deployments

the number of receive antennas, number of receive sites, and the geometry of the receive sites will be the same, the accuracy for GSM should be at least twice that of TDMA.

To verify this conclusion an analysis was conducted to determine the expected performance of the TruePosition WLS in deployed networks. Both TDMA and GSM performance were modeled using TruePosition's predictive modeling tool. An 18-site 850 MHz TDMA trial network location in Wilmington, Delaware was used to establish a frame of reference with actual measured TDMA performance. In addition, a 172-site 850 MHz TDMA network covering the portion of Houston, Texas inside the Sam Houston Parkway was used to provide a more comprehensive test. Finally, an example 1900 MHz GSM network covering the same portion of Houston, Texas was used to provide insight into the effects of the different propagation environment, cell site density, antenna configurations, etc. GSM performance for both 100% and 50% LMU deployment densities were analyzed. Refer to Appendix B for a description of the predictive modeling tool and the methodology used to make these predictions.

Figure 6, Figure 15 and Figure 24 identify the network designs used for the three networks. In the 100% LMU deployment density cases LMUs were modeled at all sites. In the 50% LMU deployment density cases LMUs were modeled only at the sites displayed in green.

Additional analysis was done to evaluate the location accuracy of TruePosition's proposed approach for GPRS. Packet polling requests would be used to initiate transmission from the MS. A range of 4 to 20 requests, resulting in the transmission of 16 to 80 bursts, has been considered. Analysis was therefore done for both the 16 and 80 burst cases to compare with the 650 burst GSM voice mode results. Note that the 80-burst performance would also be applicable to locations performed for GSM during the Circuit Switched Idle Mode through use of a commanded handover to the same channel (the total amount of signal contained in 145 access bursts is approximately the same as 80 normal bursts).

Network	Air Interface	LMU Deployment Density	67% Performance (meters)	95% Performance (meters)	Figure
<i>Wilmington (Trial Results)</i>	<i>TDMA</i>	<i>100%</i>	<i>81.2</i>	<i>189.9</i>	N.A.
Wilmington	TDMA	100%	81	137	7
Wilmington	GSM	100%	42	71	8
	GPRS (80 burst)		48	81	9
	GPRS (16 burst)		55	94	10
Wilmington	GSM	50%	57	100	11
	GPRS (80 burst)		65	113	12
	GPRS (16 burst)		73	129	13
Wilmington	EOTD	N.A.	76	128	14
Houston (850 MHz)	TDMA	100%	84	143	16
Houston (850 MHz)	GSM	100%	44	74	17
	GPRS (80 burst)		49	84	18
	GPRS (16 burst)		55	94	19
Houston (850 MHz)	GSM	50%	50	86	20
	GPRS (80 burst)		57	98	21
	GPRS (16 burst)		65	112	22
Houston (850 MHz)	EOTD	N.A.	88	152	23
Houston (1900 MHz)	GSM	100%	56	100	25
	GPRS (80 burst)		65	116	26
	GPRS (16 burst)		76	139	27
Houston (1900 MHz)	GSM	50%	66	117	28
	GPRS (80 burst)		79	142	29
	GPRS (16 burst)		100	185	30
Houston (1900 MHz)	EOTD	N.A.	120	218	31

Table 7-1 - Predicted Location Accuracy Performance

Each plot in the accuracy prediction figures has a polygon that defines the region over which the 67% and 95% predictions were computed. The accuracy contours are only shown for this region inside the polygon. Cell sites without LMUs are shown by thin outlines of their antenna sectors. Even though no LMUs for sites outside the Sam Houston Parkway were included in the performance predictions shown in Figures 11 through 16, they are shown on the plots to put the deployed sites in context.

Although the predicted 67% performance is consistent with actual measured performance, the predicted 95% performance is slightly better than the actual measured performance. This is due to the fact that the predictive model tends to underestimate the effect of some outlier cases caused by third order anomalies (e.g. cell sites temporarily off line, interference, etc.)

This analysis verifies the location accuracy of the TruePosition WLS in a GSM environment is approximately twice that of TDMA. In addition, the TruePosition WLS should be able to achieve reasonable accuracy in most GSM networks when LMUs are deployed at only 50% of the cell sites.

Wilmington Analysis

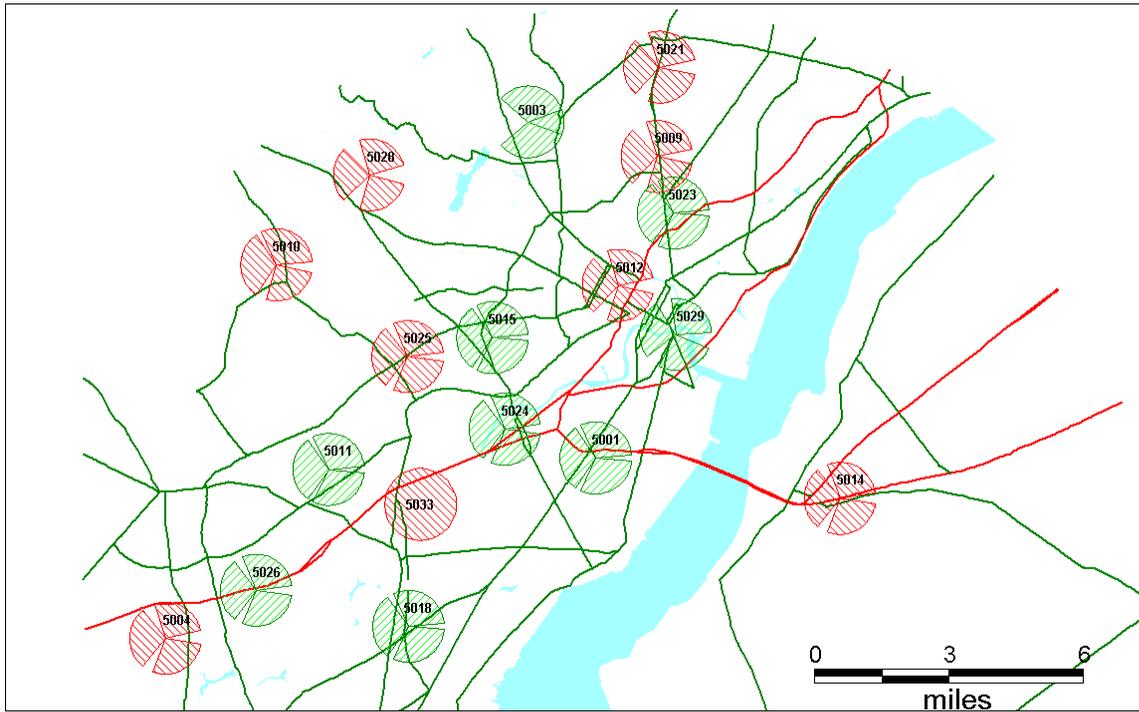
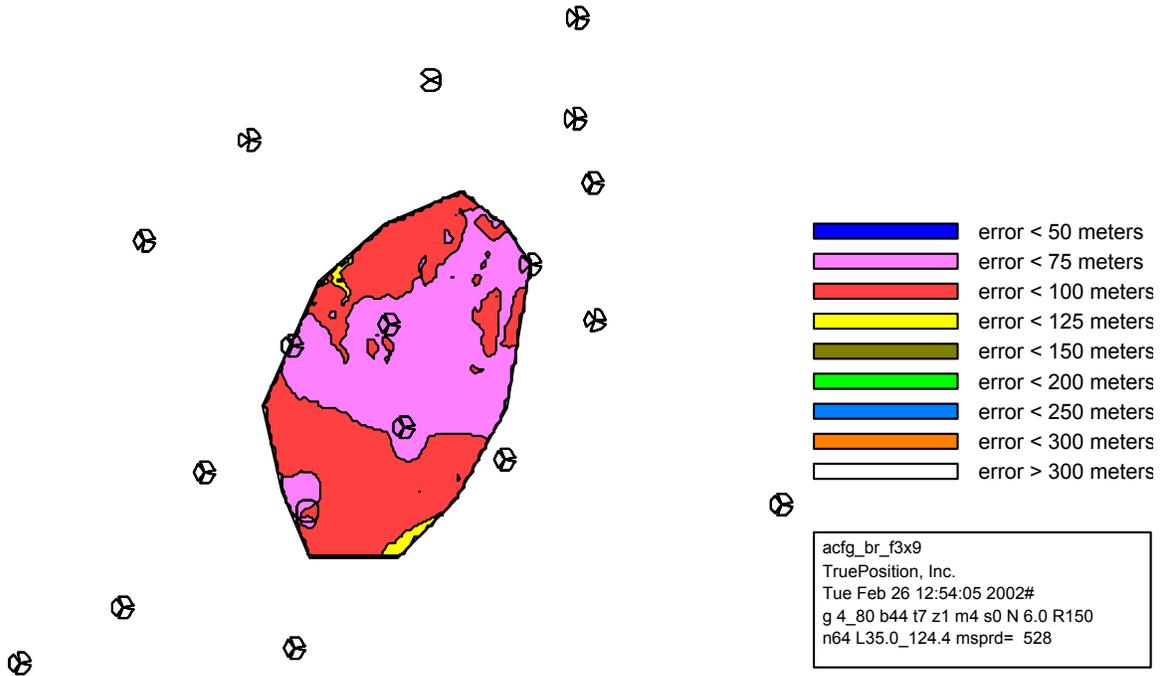


Figure 6 - Wilmington 850 MHz AMPS/TDMA Network

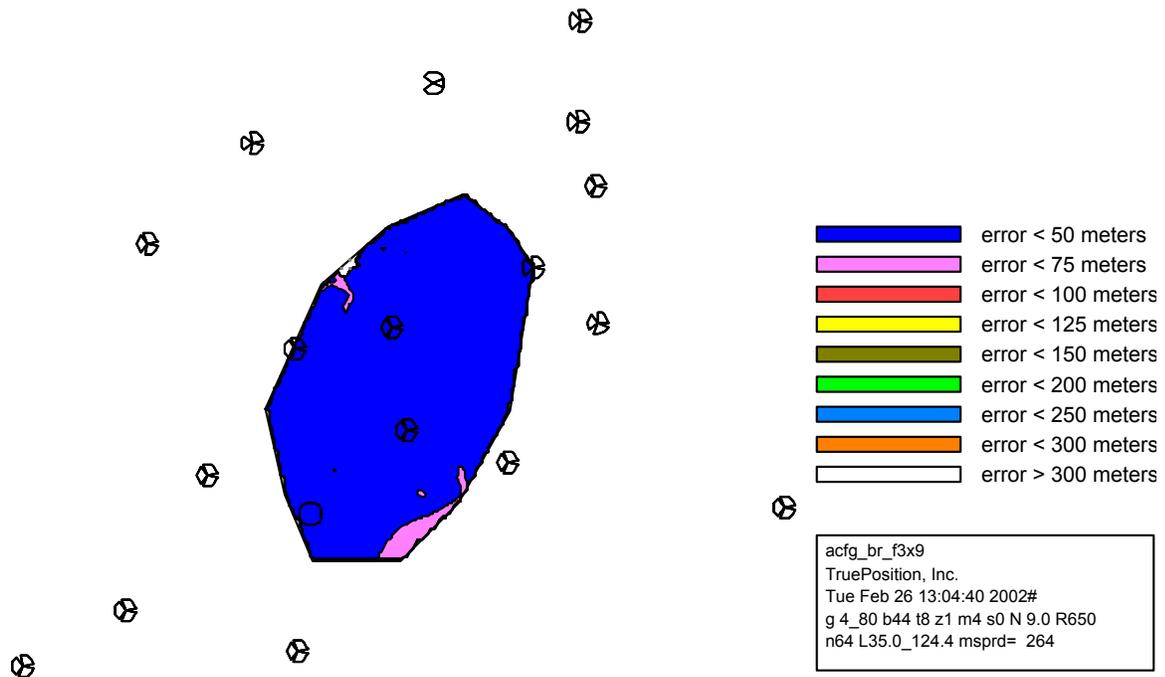
scale 1.0 mile



TruePositionTM Sysid: 10018 overall rms= 78 p67= 81 p95= 137 meters

Figure 7 – Wilmington 850 MHz TDMA Performance

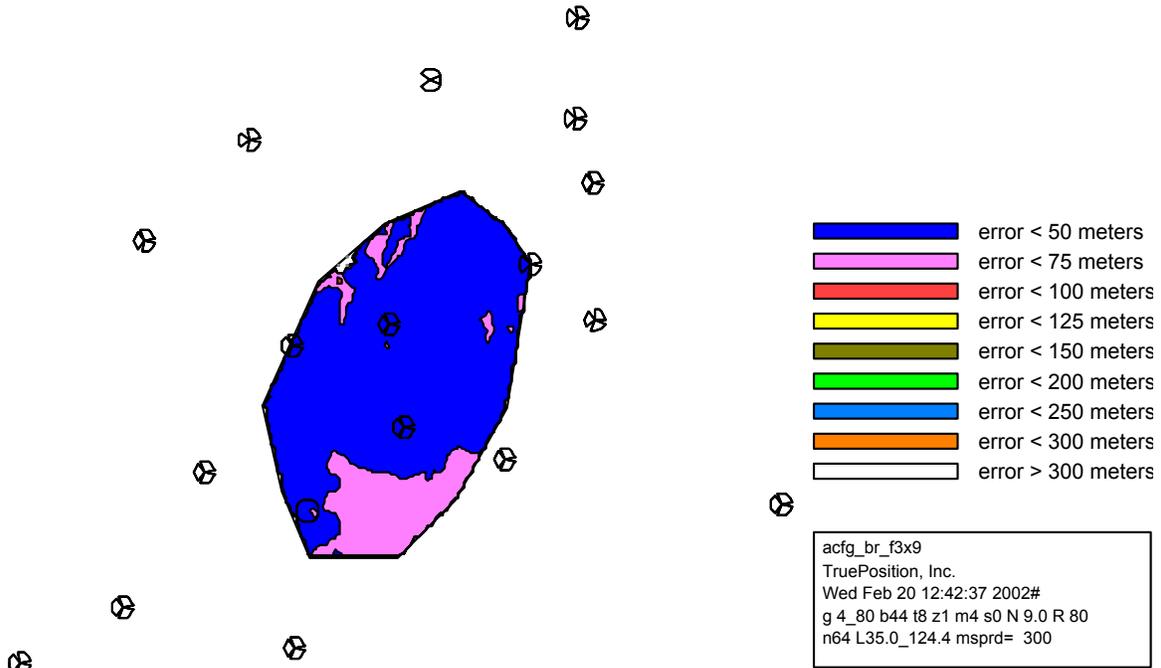
scale 1.0 mile



TruePositionTM Sysid: 10018 overall rms= 41 p67= 42 p95= 71 meters

Figure 8 - Wilmington 850 MHz GSM Performance (100% LMU Density)

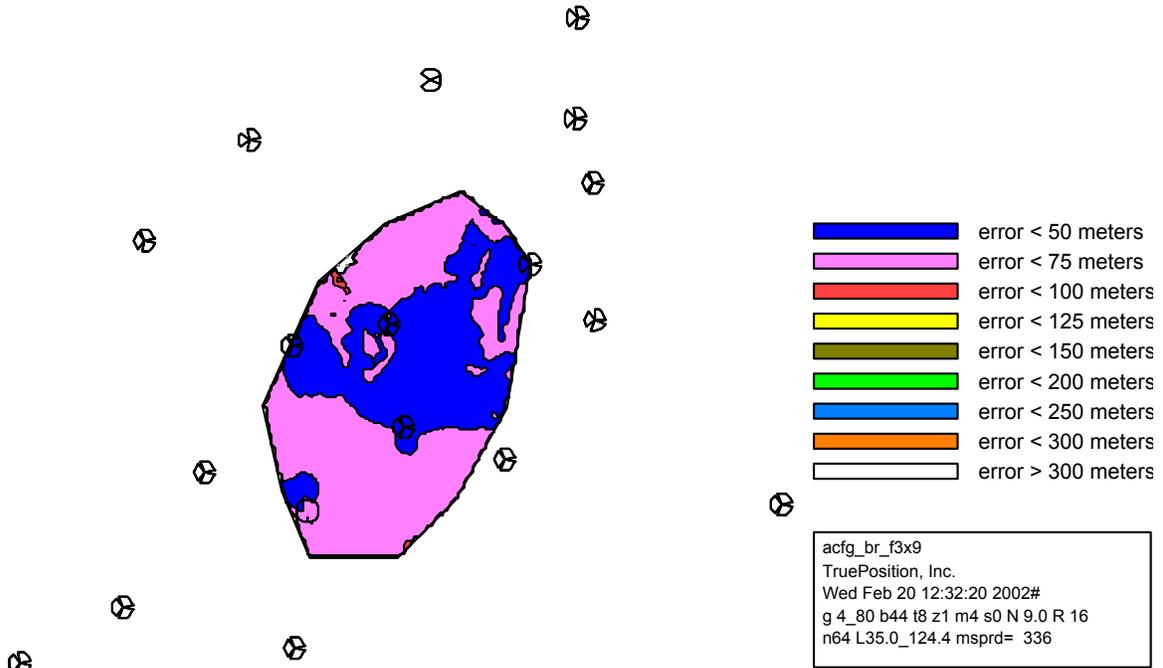
scale 1.0 mile



TruePositionTM Sysid: 10018 overall rms= 46 p67= 48 p95= 81 meters

Figure 9 - Wilmington 850 MHz GPRS 80 Burst Performance (100% LMU Density)

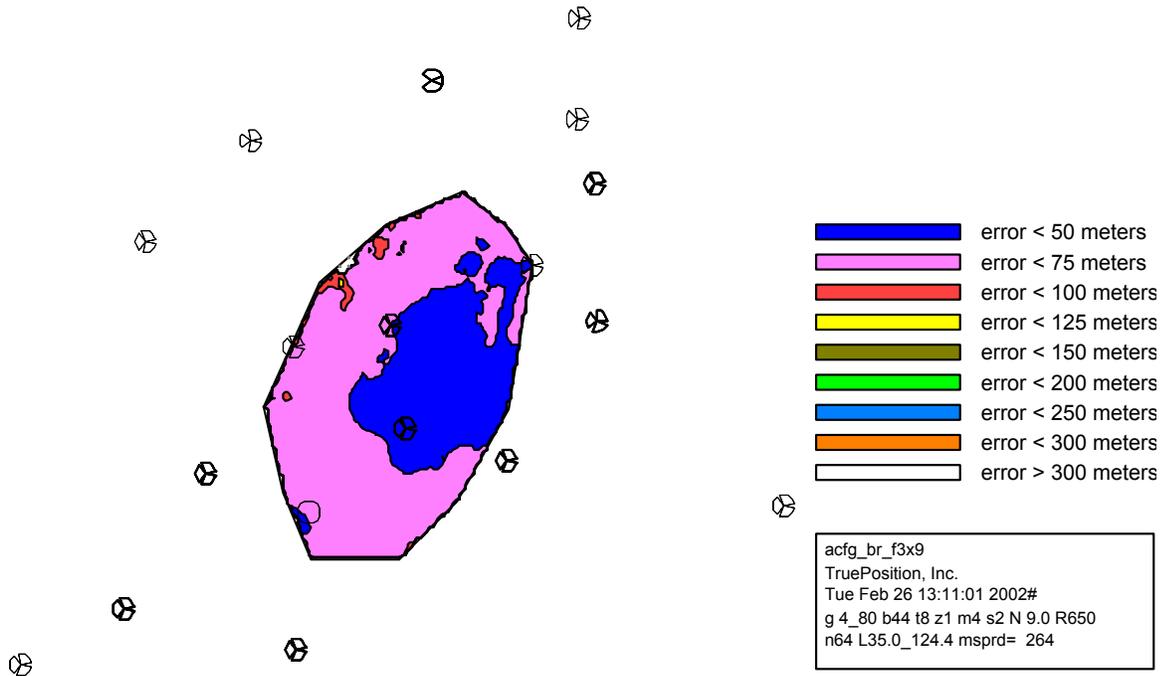
scale 1.0 mile



TruePositionTM Sysid: 10018 overall rms= 53 p67= 55 p95= 94 meters

Figure 10 - Wilmington 850 MHz GPRS 16 Burst Performance (100% LMU Density)

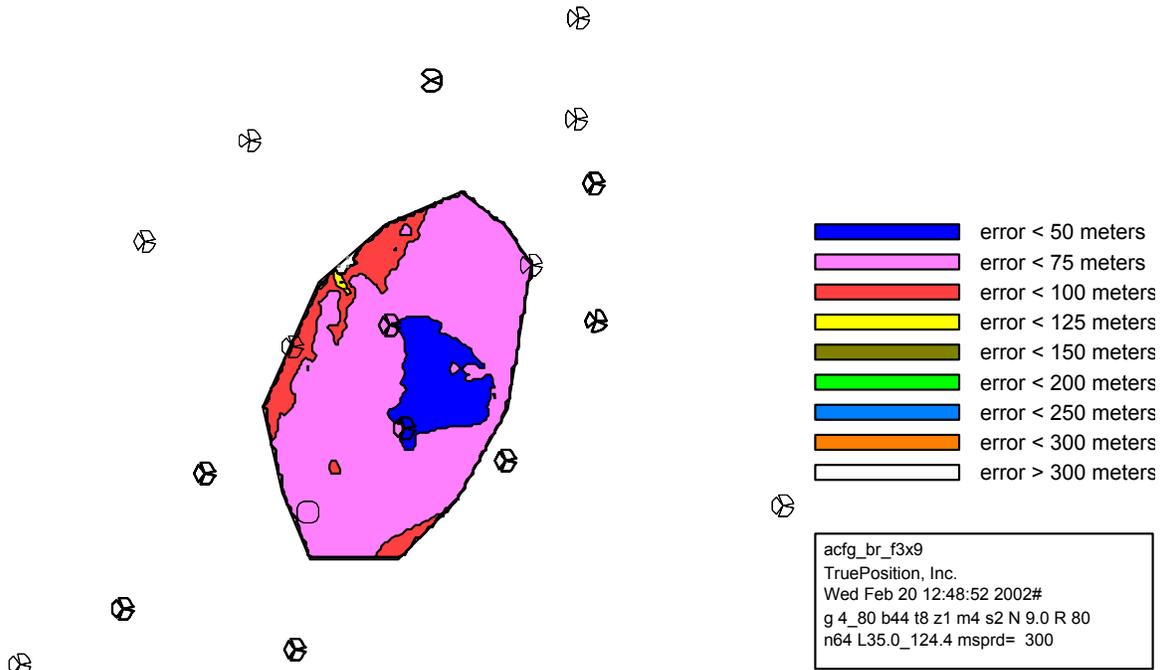
scale 1.0 mile



TruePosition™ Sysid: 50018 overall rms= 55 p67= 57 p95= 100 meters

Figure 11 - Wilmington 850 MHz GSM Performance (50% LMU Density)

scale 1.0 mile

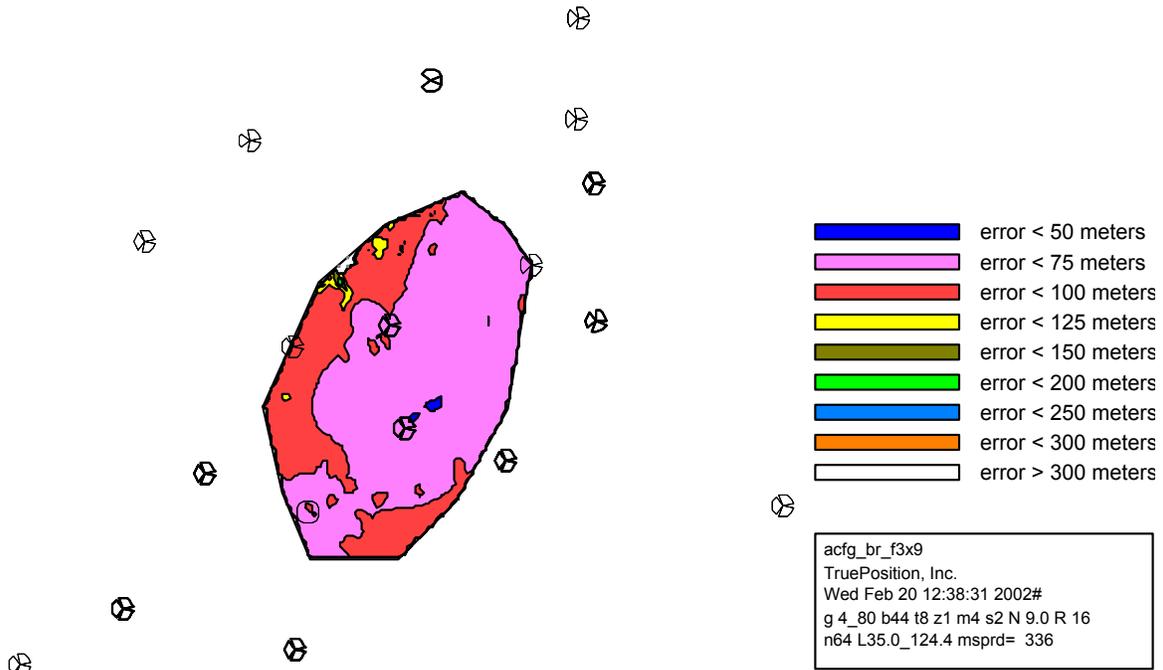


TruePosition™

Sysid: 50018 overall rms= 63 p67= 65 p95= 113 meters

Figure 12 - Wilmington 850 MHz GPRS 80 Burst Performance (50% LMU Density)

scale 1.0 mile

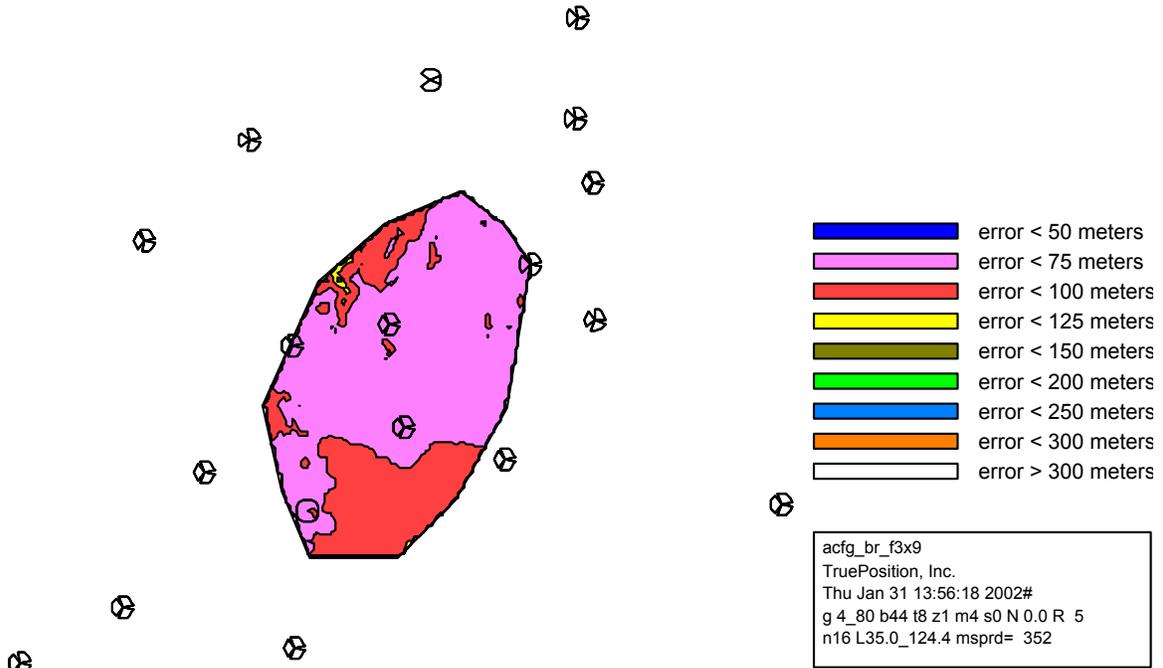


TruePosition™

Sysid: 50018 overall rms= 71 p67= 73 p95= 129 meters

Figure 13 - Wilmington 850 MHz GPRS 16 Burst Performance (50% LMU Density)

scale 1.0 mile



TruePositionTM Sysid: 10018 overall rms= 73 p67= 76 p95= 128 meters

Figure 14 - Wilmington 850 MHz E-OTD Performance

Houston Analysis

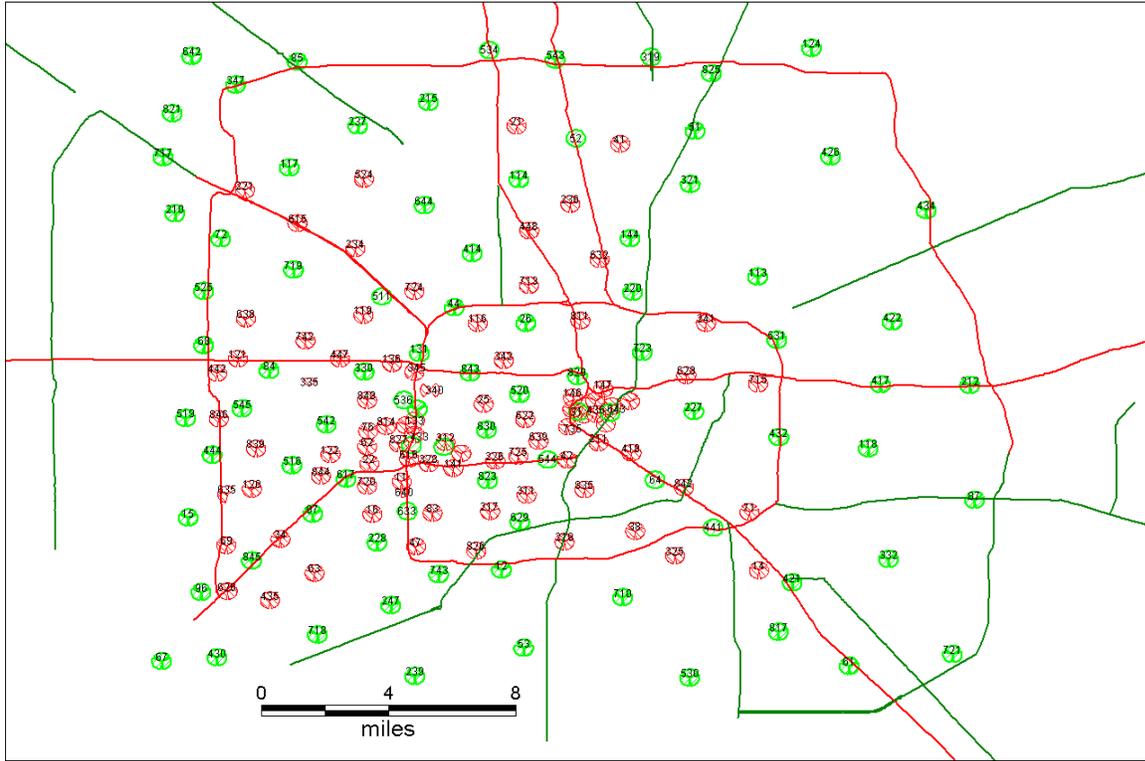
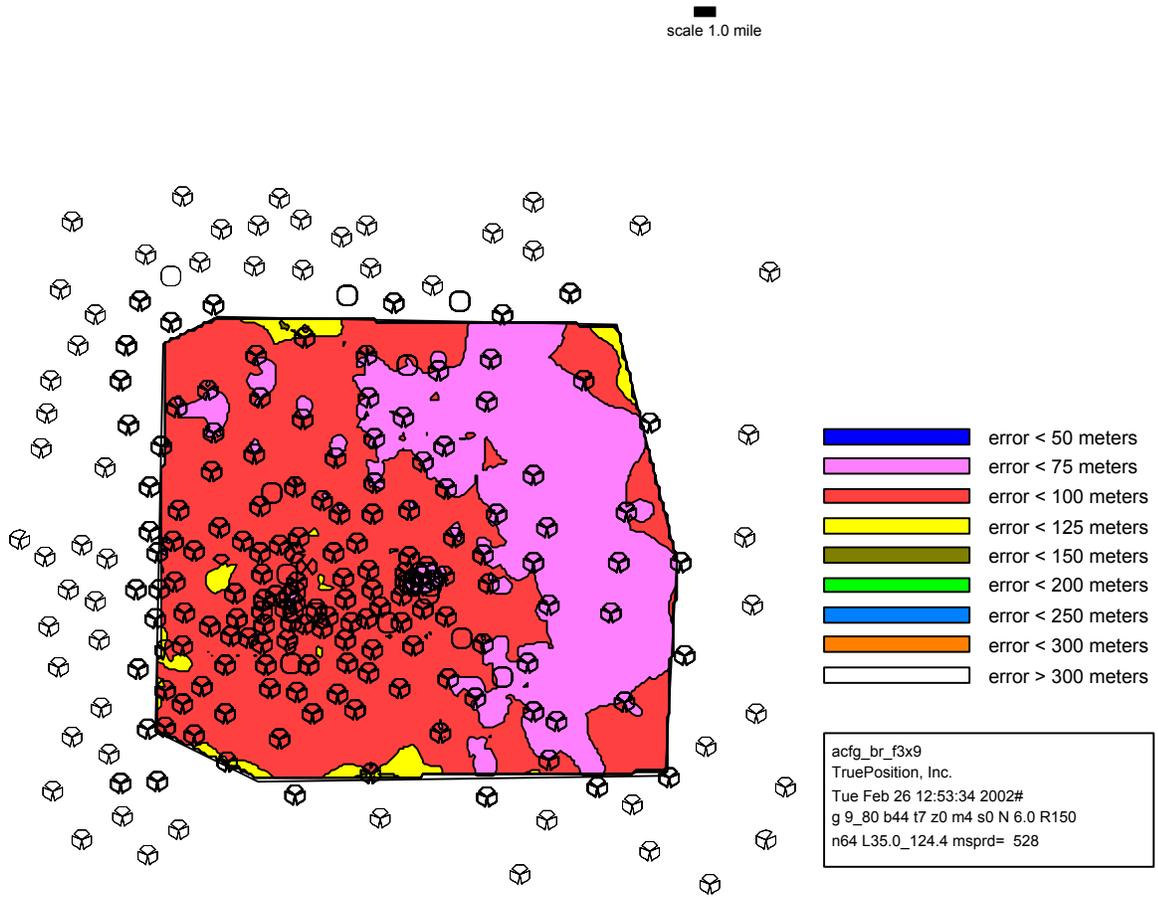


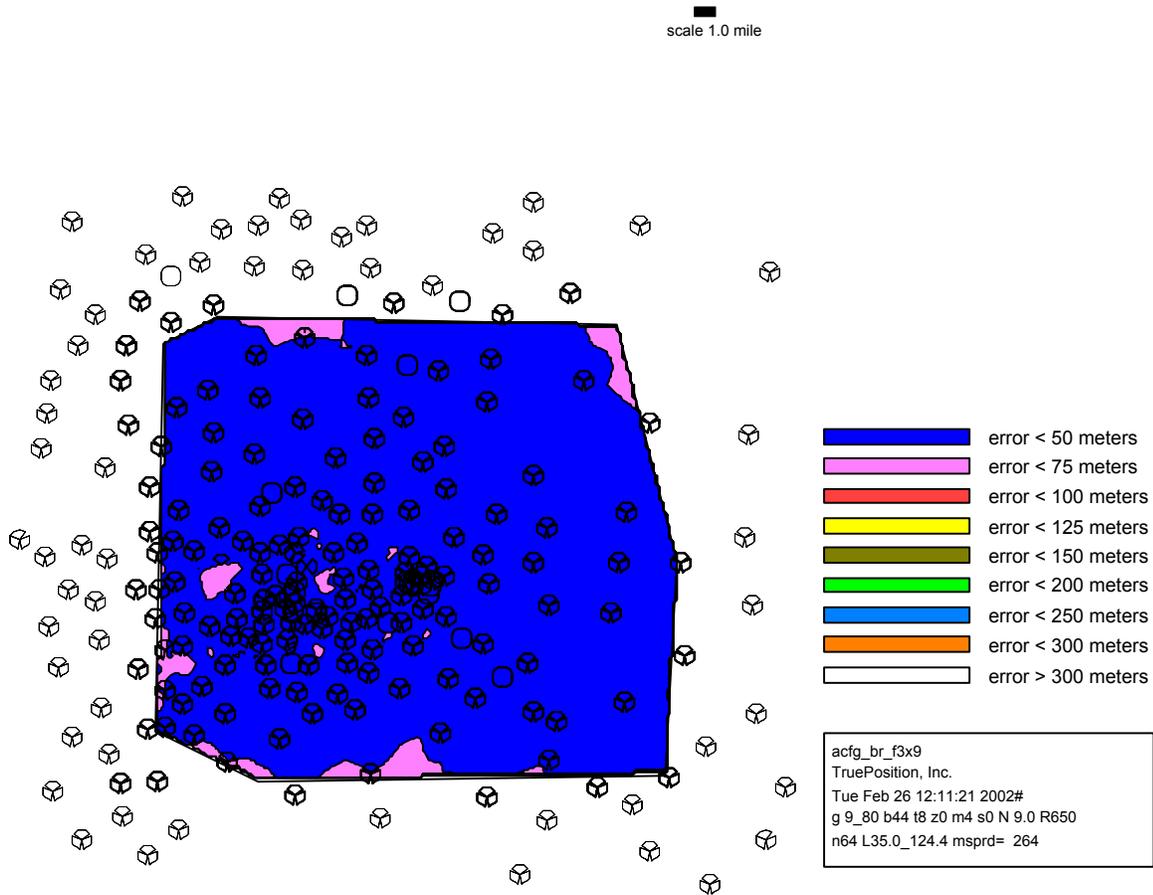
Figure 15 - Houston 850 MHz AMPS/TDMA Network



TruePosition™

Sysid: 10229 overall rms= 81 p67= 84 p95= 143 meters

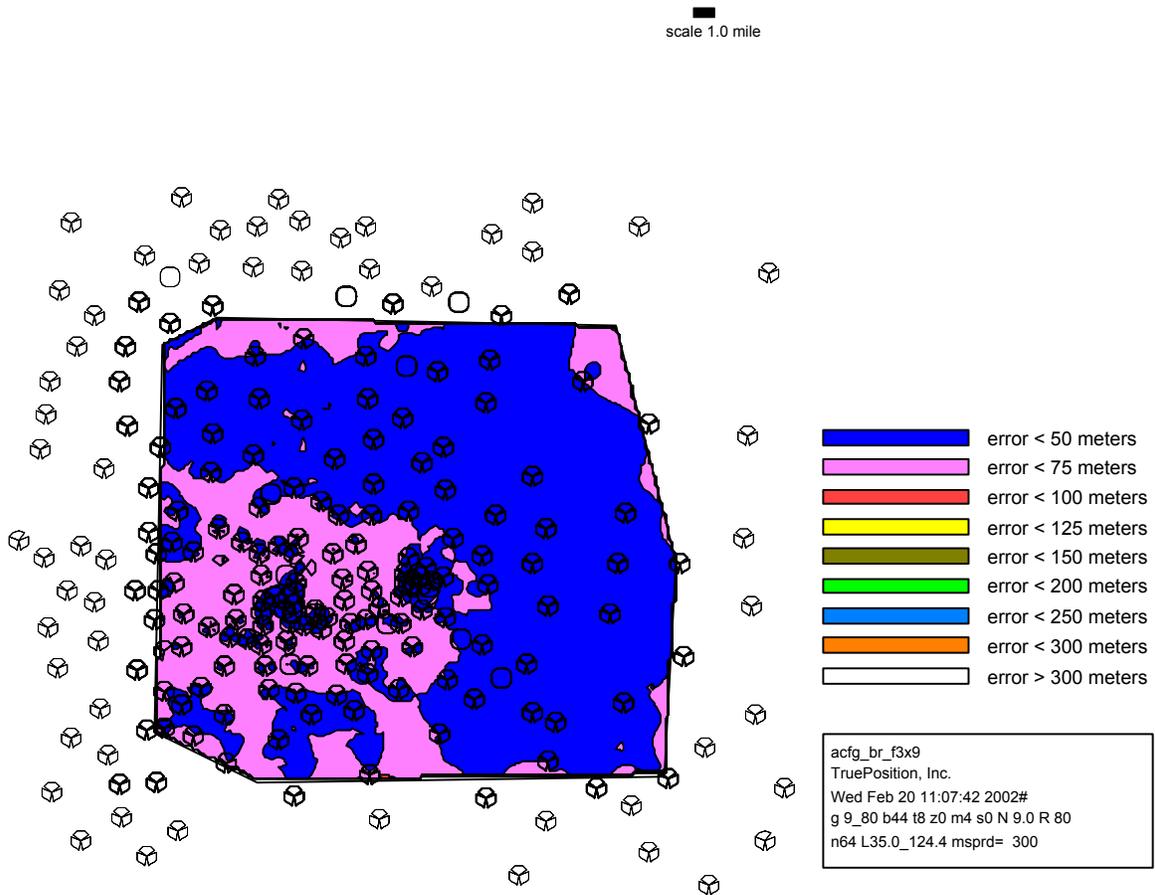
Figure 16 - Houston 850 MHz TDMA Performance



TruePosition™

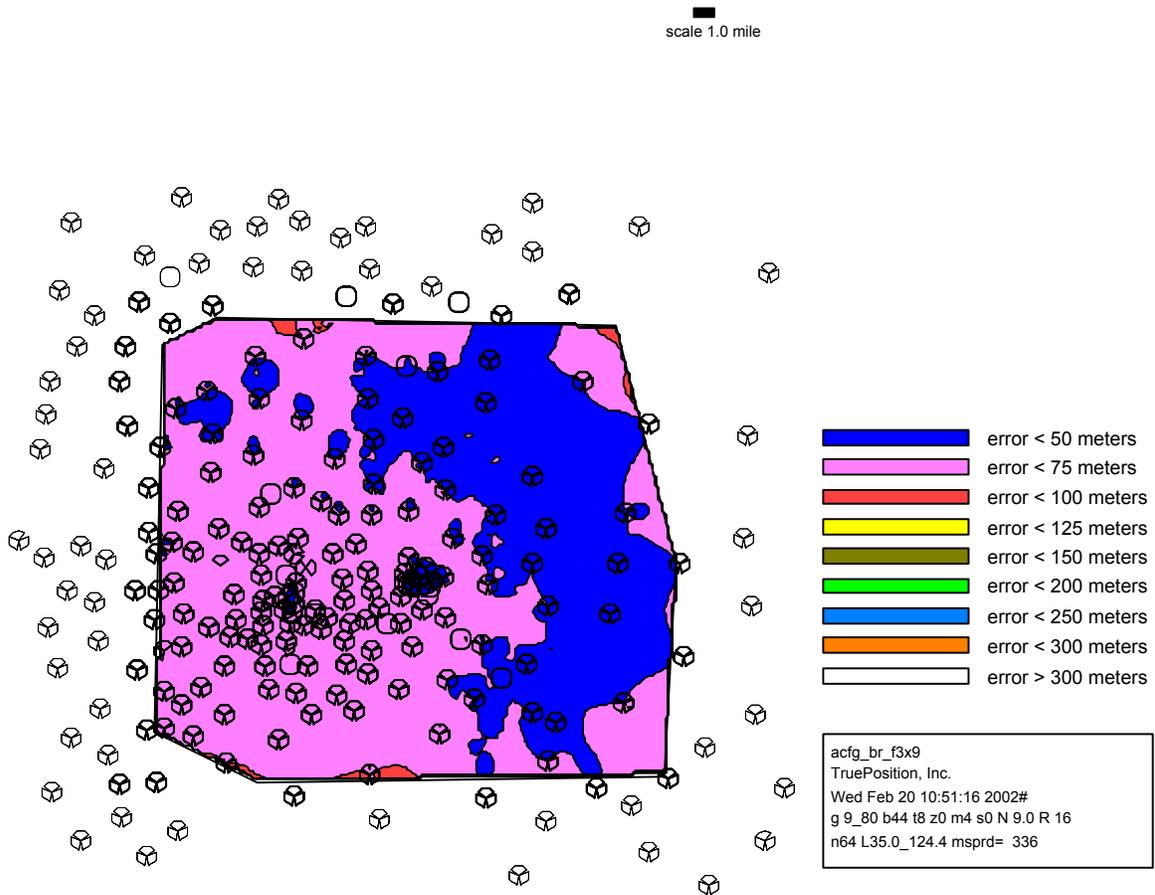
Sysid: 10229 overall rms= 42 p67= 44 p95= 74 meters

Figure 17 - Houston 850 MHz GSM Performance (100% LMU Density)



TruePosition™ Sysid: 10229 overall rms= 47 p67= 49 p95= 84 meters

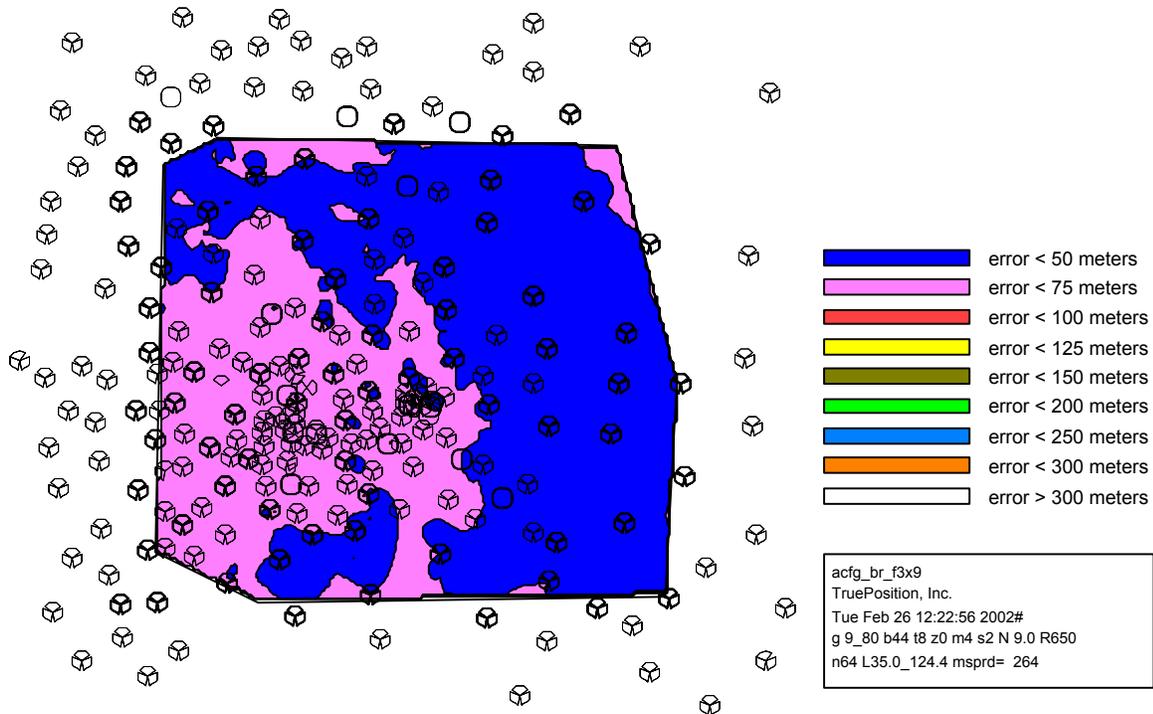
Figure 18 - Houston 850 MHz GPRS 80 Burst Performance (100% LMU Density)



TruePosition™ Sysid: 10229 overall rms= 53 p67= 55 p95= 94 meters

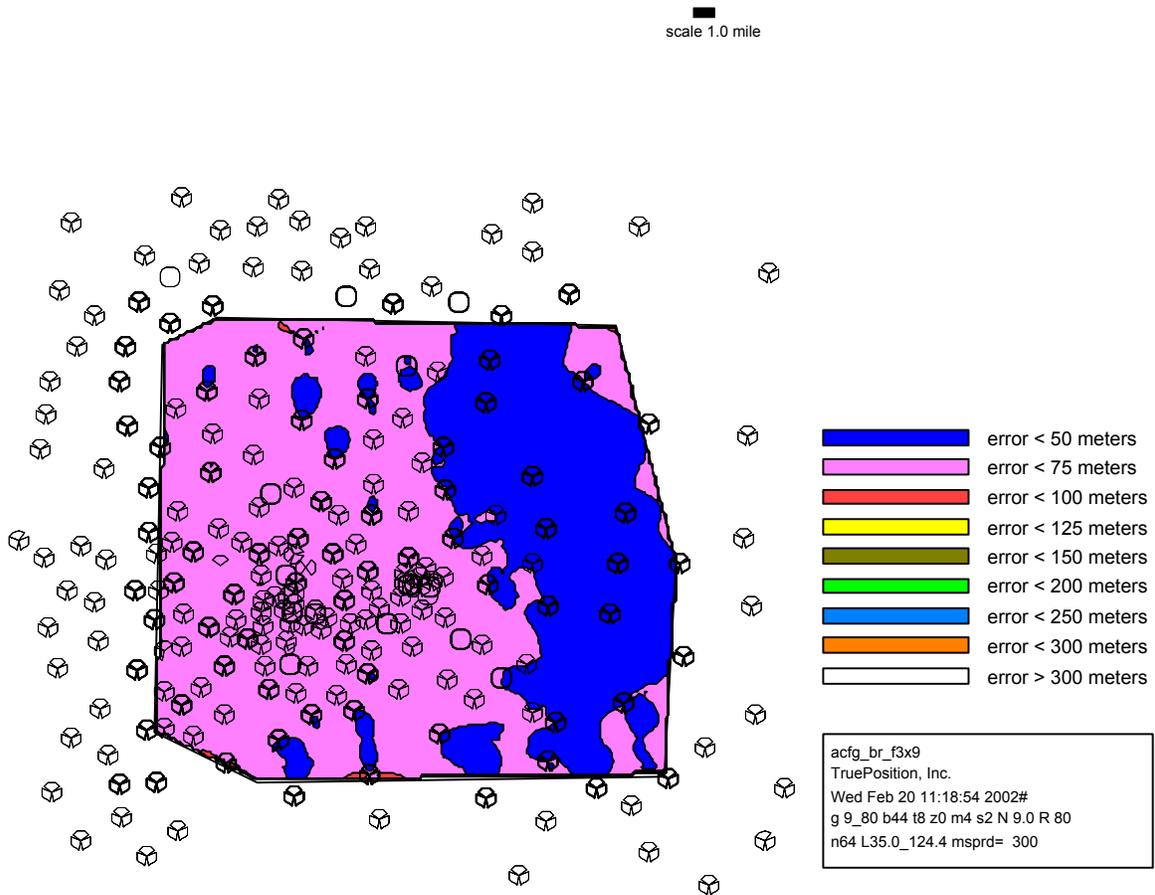
Figure 19 - Houston 850 MHz GPRS 16 Burst Performance (100% LMU Density)

■ scale 1.0 mile



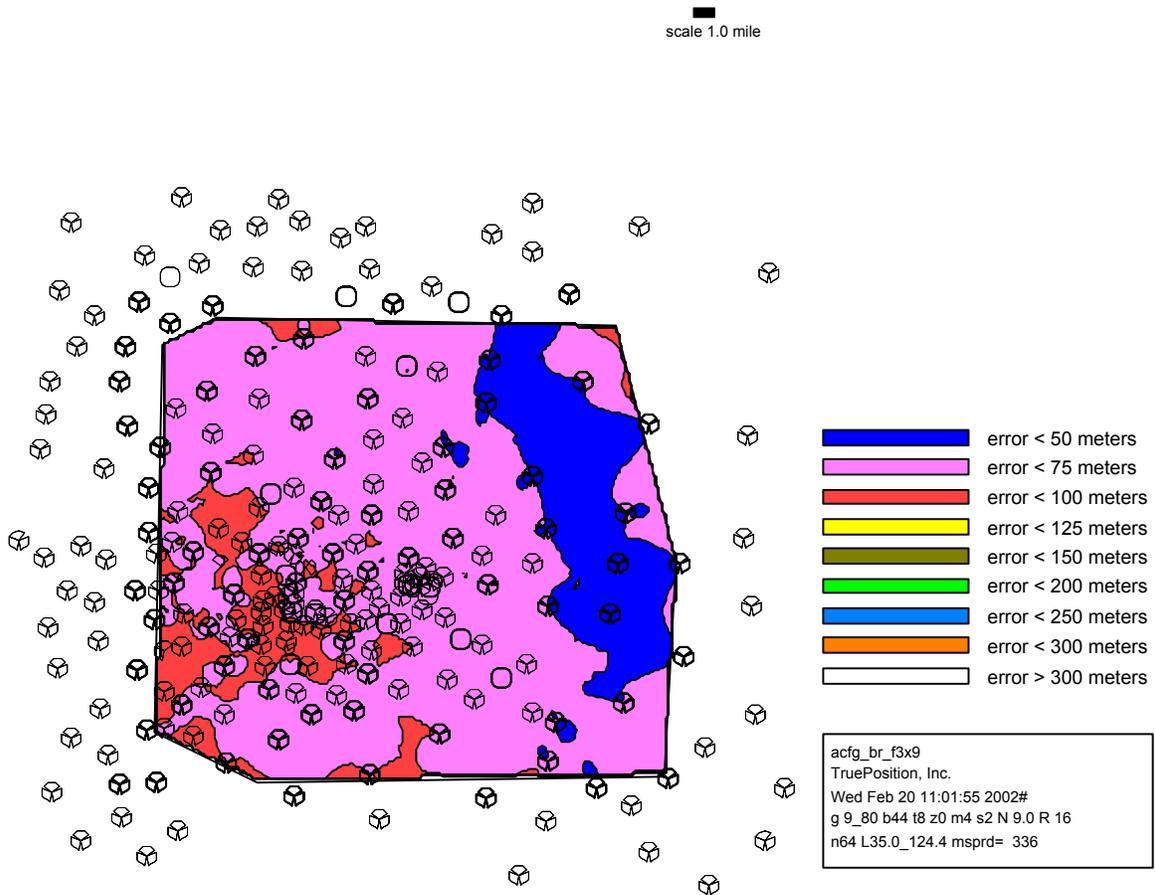
TruePosition™ Sysid: 50229 overall rms= 48 p67= 50 p95= 86 meters

Figure 20 - Houston 850 MHz GSM Performance (50% LMU Density)



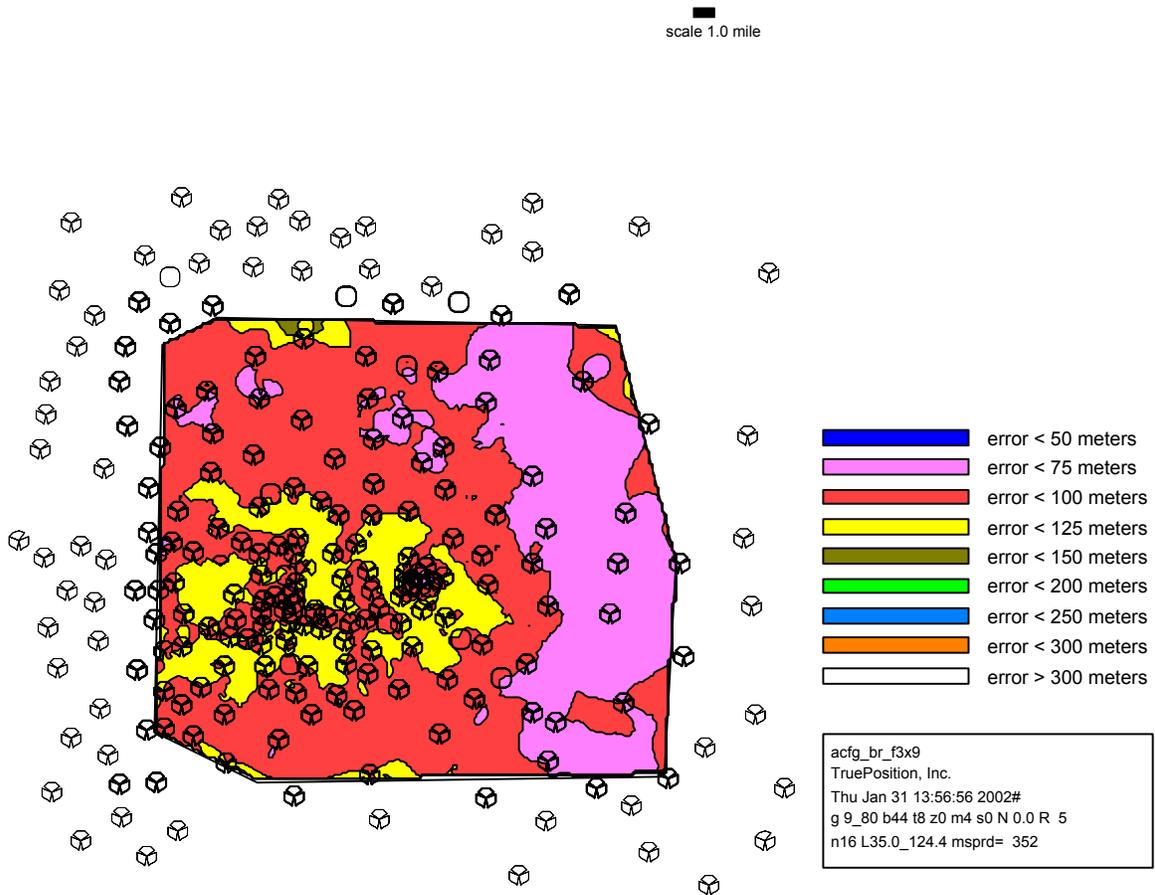
TruePosition™ Sysid: 50229 overall rms= 55 p67= 57 p95= 98 meters

Figure 21 - Houston 850 MHz GPRS 80 Burst Performance (50% LMU Density)



TruePosition™ Sysid: 50229 overall rms= 63 p67= 65 p95= 112 meters

Figure 22 - Houston 850 MHz GPRS 16 Burst Performance (50% LMU Density)



TruePosition™ Sysid: 10229 overall rms= 86 p67= 88 p95= 152 meters

Figure 23 – Houston 850 MHz E-OTD Performance

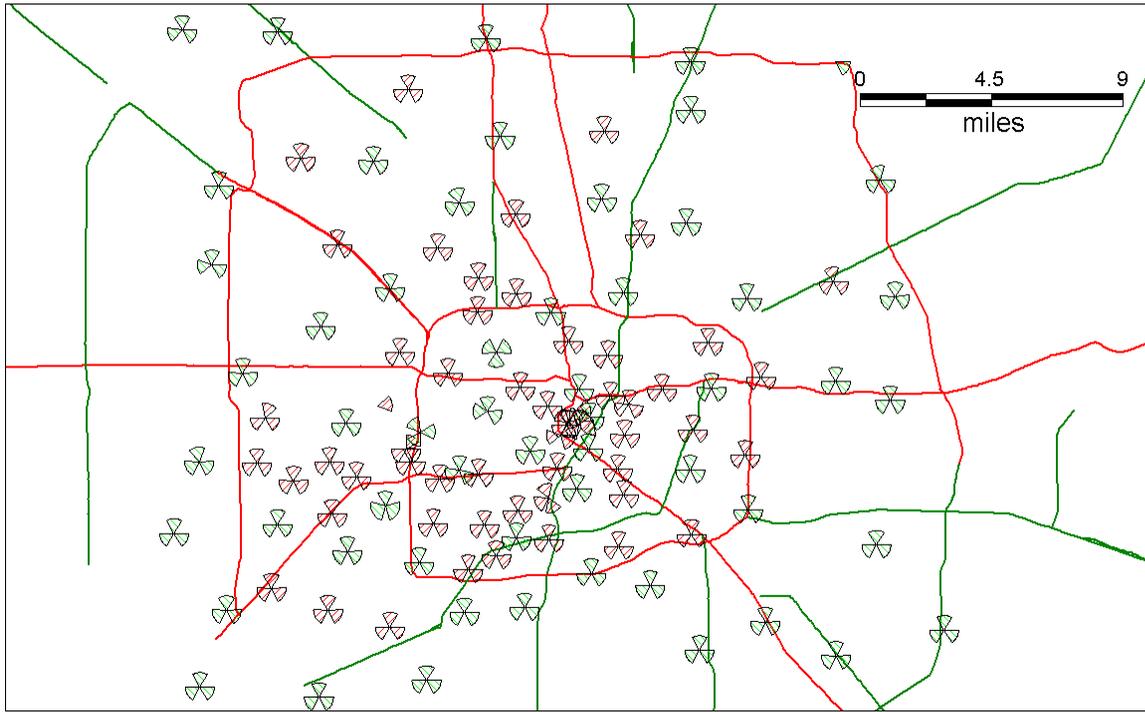
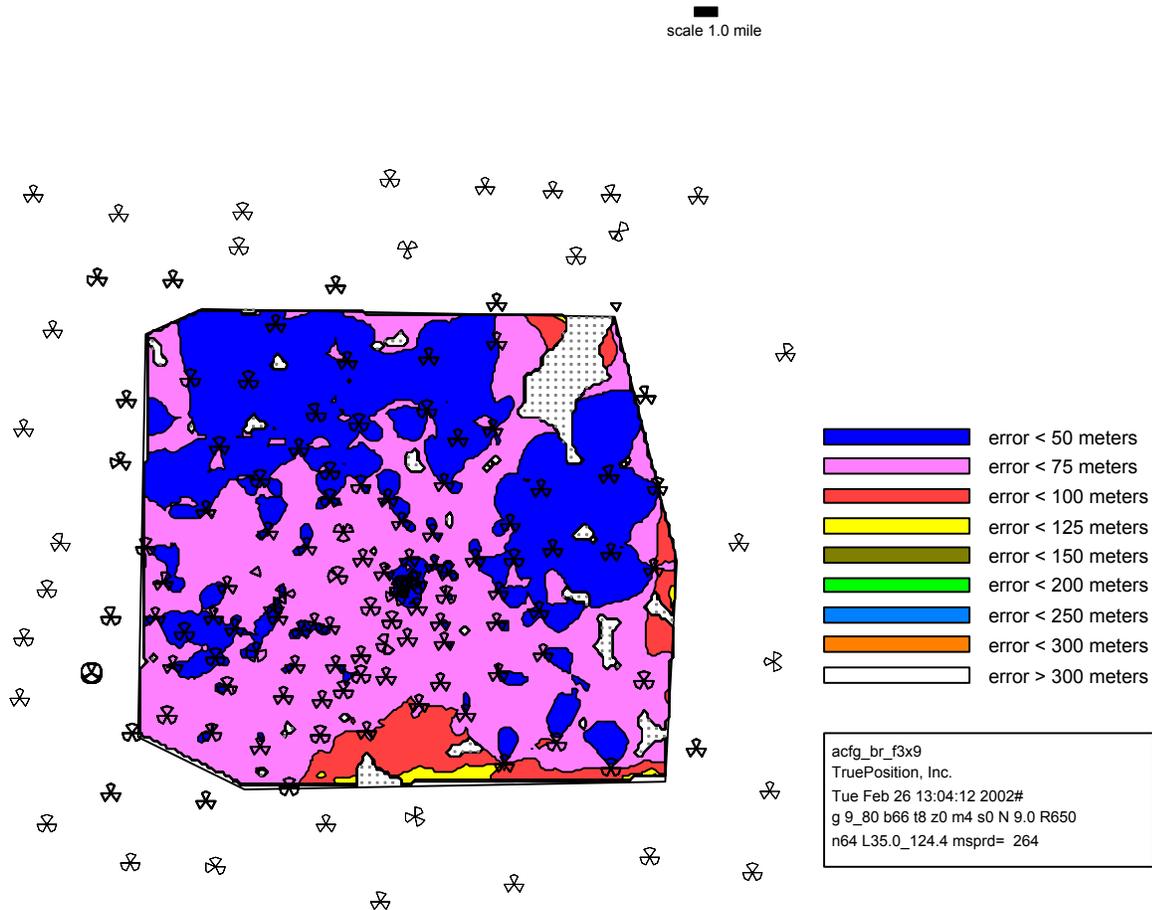
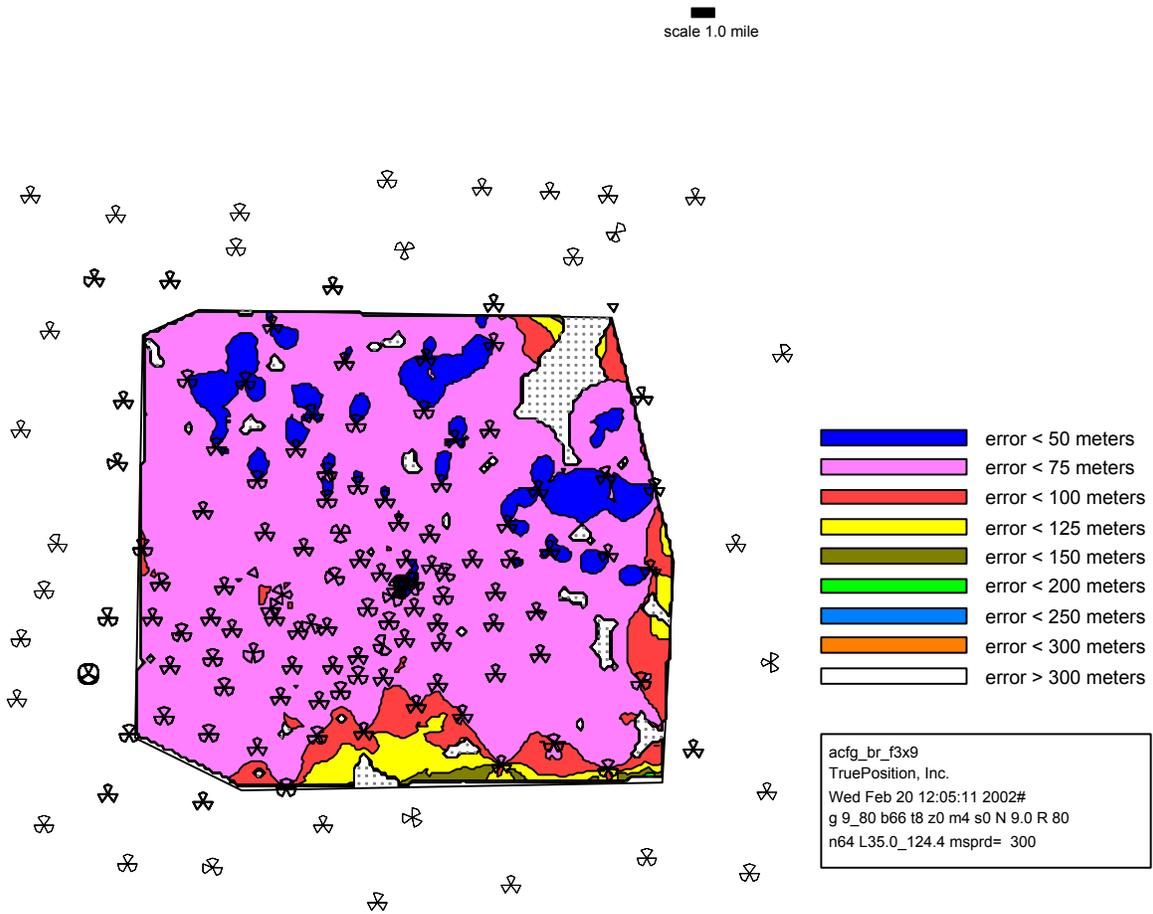


Figure 24 - Houston 1900 MHz GSM Network



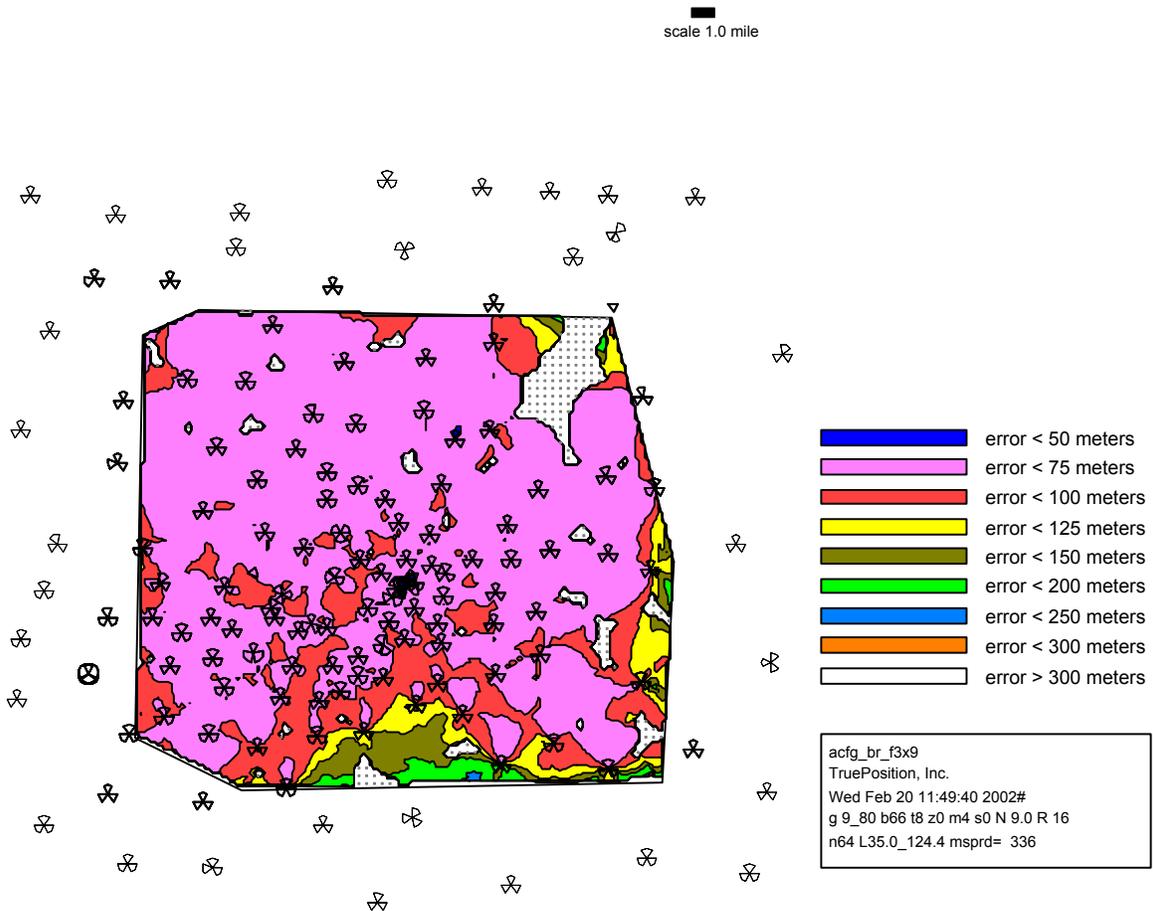
TruePosition™ Sysid: 10144 overall rms= 56 p67= 56 p95= 100 meters

Figure 25 - Houston 1900 MHz GSM Performance (100% LMU Density)



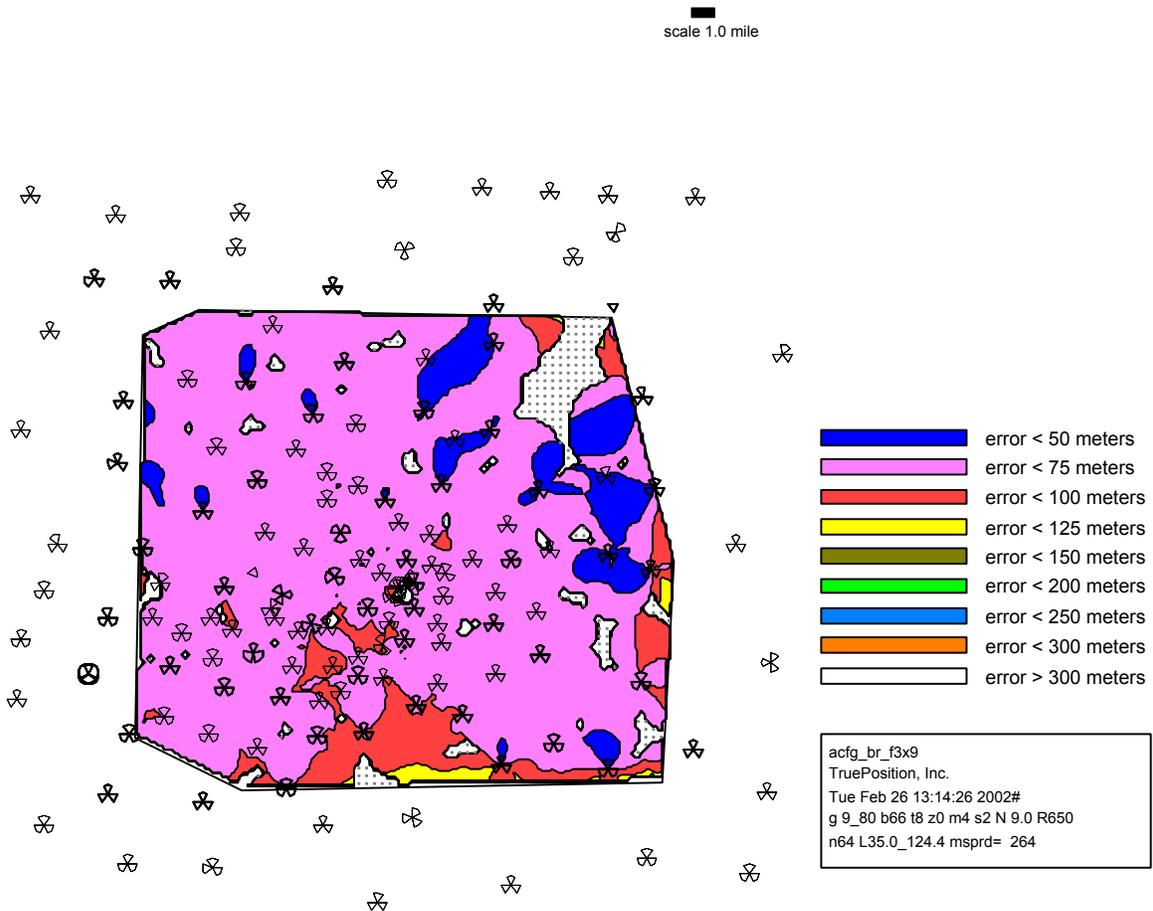
TruePosition™ Sysid: 10144 overall rms= 65 p67= 65 p95= 116 meters

Figure 26 - Houston 1900 MHz GPRS 80 Burst Performance (100% LMU Density)



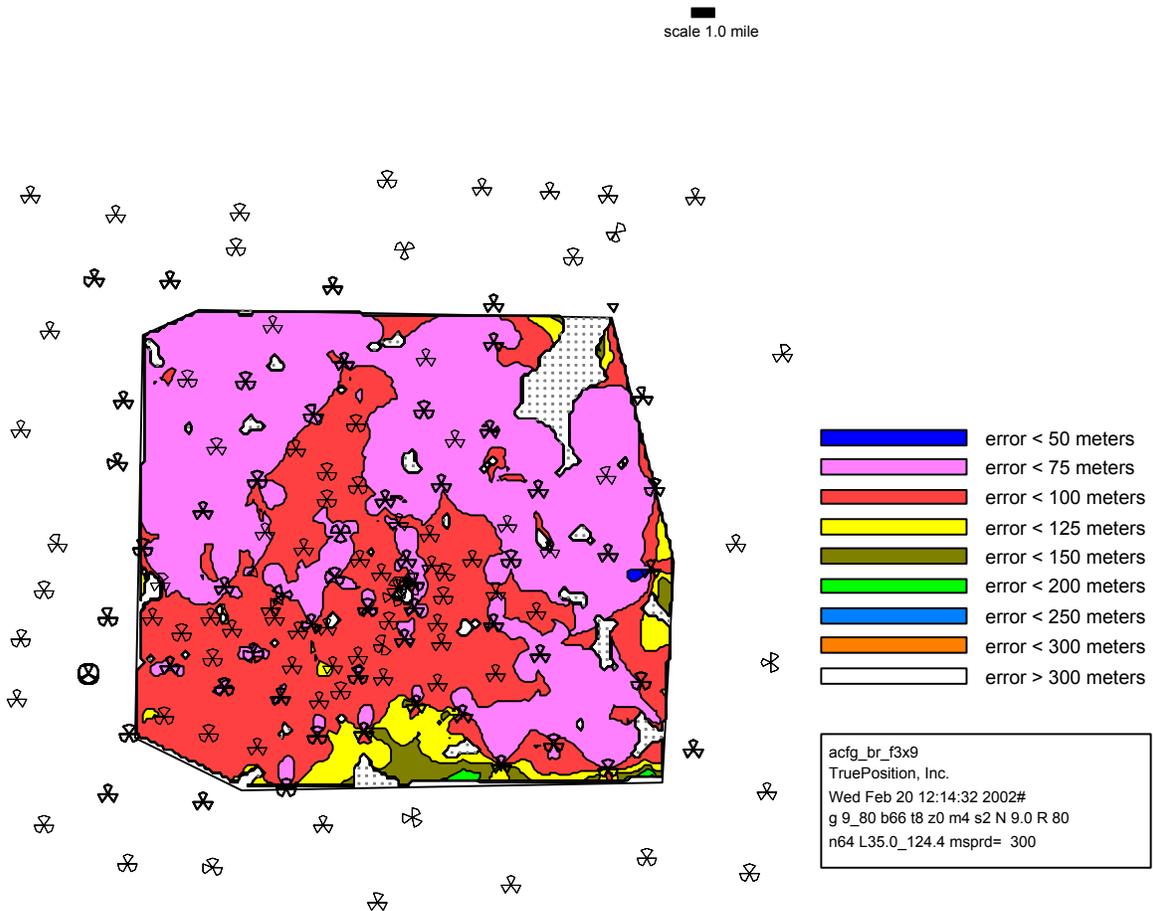
TruePositionTM Sysid: 10144 overall rms= 78 p67= 76 p95= 139 meters

Figure 27 - Houston 1900 MHz GPRS 16 Burst Performance (100% LMU Density)



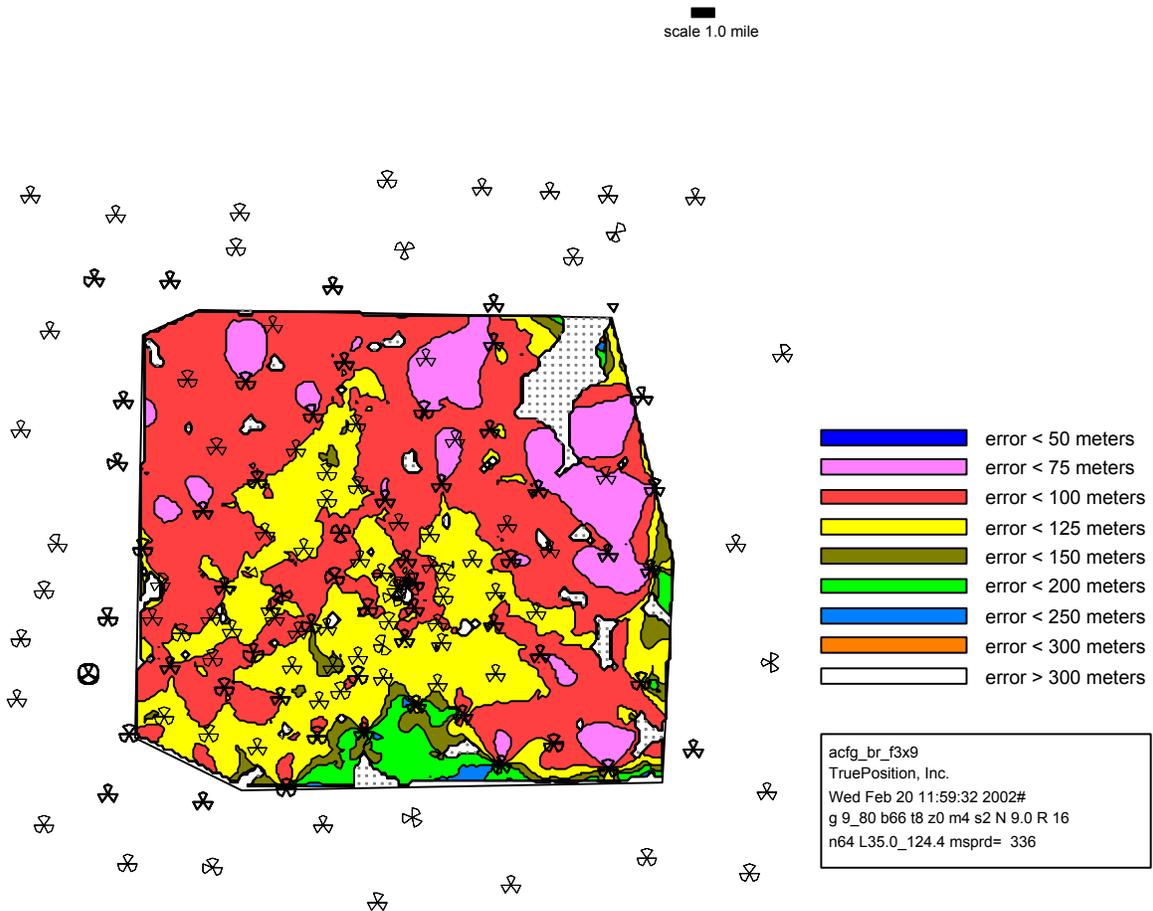
TruePosition™ Sysid: 50144 overall rms= 155 p67= 66 p95= 117 meters

Figure 28 - Houston 1900 MHz GSM Performance (50% LMU Density)



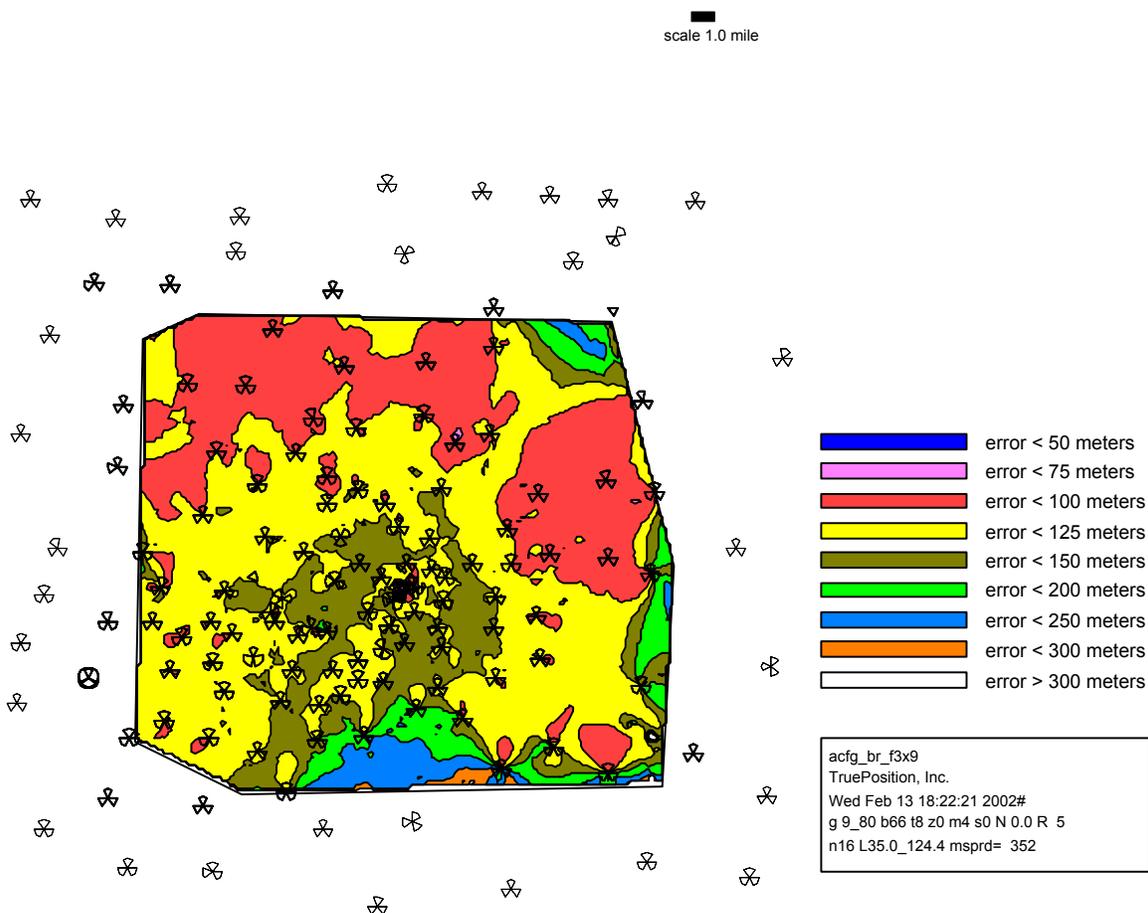
TruePosition™ Sysid: 50144 overall rms= 161 p67= 79 p95= 142 meters

Figure 29 - Houston 1900 MHz GPRS 80 Burst Performance (50% LMU Density)



TruePosition™ Sysid: 50144 overall rms= 173 p67= 100 p95= 185 meters

Figure 30 - Houston 1900 MHz GPRS 16 Burst Performance (50% LMU Density)



TruePosition™ Sysid: 10144 overall rms= 121 p67= 120 p95= 218 meters

Figure 31 – Houston 1900 MHz E-OTD Performance

A.4. Comparison of U-TDOA and E-OTD Performance

The primary advantage U-TDOA has over E-OTD is the ability to make uplink measurements at many sites simultaneously, while the MS with a single receiver can measure only one downlink signal at a time. In the U-TDOA solution integration can occur over all transmitted energy from the MS, while the E-OTD solution can only integrate over known signals, such as the SCH. The ability to integrate over all energy at many sites simultaneously provides 16-21 dB increased processing gain for U-TDOA over E-OTD for the same period of time. Although the downlink has greater

transmit power and provides a net SNR improvement of 6 dB over the uplink, when both transmit power and processing gain are considered, U-TDOA has a 10 – 15 dB SNR advantage over E-OTD. Therefore, signals with 10-15 dB more path loss can be used in an U-TDOA system compared to an E-OTD system.

U-TDOA can use diversity receive antennas, whereas in the E-OTD system the MS does not have diversity receive antenna capability. These additional antennas reduce the effects of fading and provide additional TDOA measurements to improve accuracy over that achievable with an E-OTD system.

The reduced effective SNR and lack of diversity will cause the E-OTD solution to be at best 75% less accurate than U-TDOA.

U-TDOA has significant processing capacity to analyze signal information and compute TDOA measurements. E-OTD is constrained by limited processing capacity in the mobile station. The additional processing power allows U-TDOA to utilize advanced correlation and super-resolution algorithms to mitigate the effects of multi-path and improve the accuracy of TDOA measurements.

The signal transmitted by the MS and measured by the U-TDOA LMU is frequency hopped. The effects of multi-path tend to be independent at different frequencies. Averaging the TDOA measurements over different frequencies provides substantial fading mitigation as well as multi-path reduction. Because multi-path effects dominate location error in any TDOA location system, a frequency-hopped signal will provide a large improvement in accuracy for the U-TDOA system compared to the E-OTD system, in which measurements are made on un-hopped signals.

Because E-OTD does not have the additional benefits of increased processor capability and a frequency hopped waveform, and may also have performance issues within the MS, the performance of E-OTD may be as much as 140% less accurate than U-TDOA.

A.5. Conclusion

From a location accuracy perspective the significant difference between GSM and TDMA is signal bandwidth. The 5:1 difference in bandwidth makes GSM significantly more immune to multi-path than TDMA. A comprehensive analysis showed a 2:1 ratio of TDMA to GSM errors for the typical multi-path case, and nearly a 4:1 ratio for the severe case. Based on this analysis, TruePosition is confident that the RMS TDOA errors for GSM will be approximately half of those for TDMA. As a result, the accuracy of TDOA for GSM should be at least twice that of TDMA. In addition, the TruePosition WLS should be able to achieve a reasonable level of accuracy in most GSM networks when LMUs are deployed at only 50% of the cell sites.

The U-TDOA performance results presented in this analysis are conservative. They only take into account the increased signal bandwidth of GSM. They do not take into account frequency hopping on the uplink channels and the significant benefit this has in reducing multi-path. Also, they do not take into account more aggressive techniques for mitigating the effects of multi-path in a GSM environment that are currently being developed by TruePosition. These techniques for super-resolving multi-path and detecting leading edge components have potential to improve results even

further. TruePosition is confident that the performance of U-TDOA in actual deployments will be more accurate than the results presented in this analysis.

U-TDOA has several performance advantages over E-OTD. These include a 10-15 dB SNR advantage, and the ability to utilize diversity to reduce the effects of fading. In addition, U-TDOA has the ability to use sophisticated super-resolution algorithms and take advantage of frequency hopping on the uplink channels to mitigate the effects of multi-path. These advantages will result in E-OTD being at least 75% less accurate than U-TDOA, and possibly as much as 140% less accurate. This means that E-OTD will not provide high levels of accuracy. In addition, E-OTD will have a difficult time achieving reasonable accuracy for network-based location technologies in demanding environments with severe multi-path or limited cell site coverage.

APPENDIX B. Functional Description of TruePosition Predictive Model

The predicted location accuracies in Appendix A are computed using TruePosition's predictive modeling tool. This tool has been developed and refined for over seven years based upon data gathered during numerous field trials.

This tool takes into account the following characteristics of the system being modeled:

1. The specific characteristics of each cell site antenna sector
 - a. Exact location including latitude, longitude, and height
 - b. Antenna gain and noise figure
 - c. Antenna pattern (horizontal and vertical beamwidths)
 - d. Antenna orientation (azimuth and down-tilt angles)
2. The specific details of the proposed Wireless Location System (WLS) deployment
 - a. The cell sites at which LMUs are to be deployed
 - b. The maximum number of cell sites and sectors that can be used (cooperate) on any single location attempt.
3. The specific waveform (air interface, i.e. AMPS, IS-136, GSM, CDMA, WCDMA, etc.) details
 - a. Carrier frequency
 - b. Signal bandwidth
 - c. Signal power including power control
 - d. Net time duration of the RF signal collected for the location processing
4. The RF signal propagation environment
 - a. Terrain
 - b. Average building height and density in the vicinity of each antenna sector
 - c. Estimated signal loss as a function of distance for each antenna sector.

The operation of TruePosition's predictive modeling tool may be summarized as follows:

1. A set of "grid points" specified by latitude and longitude is selected.

- a. The region covered by these points is specified as the vertices of a polygon.
 - b. The spacing between adjacent points is specified in Arc seconds.
2. The estimated root mean square (rms) accuracy for location attempts at each of these grid points is computed (this is further detailed below).
 3. The 67th and 95th accuracy percentiles for the entire region specified by the polygon are stochastically computed using these rms accuracy estimates to define the Rayleigh probability density function at each grid point.
 4. Accuracy (rms) contours (regions) are generated.

The estimated rms accuracy for locations made from each grid point is computed as follows:

1. The most likely serving sector is determined.
 - a. The received SNR for a phone at this grid point to each of the sector antennas (receivers) in the system is computed using the following data specific to each sector (unless otherwise noted) by the use of well established cell phone propagation models as can be found in Hata (“Emperical formula for propagation loss in Land Mobile radio services,” IEEE Transactions on Vehicular Technology, Vol. 29, No. 3, Aug. 1980) and Turin, et al, (“A statistical model of urban multipath propagation” and “Simulation of urban vehicle-monitoring systems,” IEEE Trans. VT-21, 1972):
 - i. Waveform type and MS transmit signal power (same for all sectors)
 - ii. Noise figure (assumed same for all sectors)
 - iii. Bore-site antenna gain
 - iv. Antenna pattern loss in the direction to the grid point
 - v. Signal loss as function of distance to the grid point
 - vi. Signal loss due to diffraction over terrain from the grid point
 - vii. Signal loss based on average building height.
 - b. The sector with the best SNR is chosen as the serving sector.
 - i. If the SNR to this sector is not sufficient to complete a call, this grid point is marked as a “no coverage” grid point, and no accuracy estimate is computed.
2. The cooperating sectors for a location at this grid point are determined.
 - a. Only sectors from a predetermined list (part of the WLS configuration) for the serving sector are considered.

- b. A cooperating sector must have a received SNR sufficient to permit a TOA measurement to be made.
 - i. The received SNR is adjusted to account for power control if applicable.
 - ii. The minimum SNR is determined based on the total signal energy that will be collected, i.e. integrated over the specified net duration of the RF signal collection.
 - c. Up to “N-1” of the qualifying cooperators with the largest SNRs are selected for computing the estimated location accuracy.
 - i. The value of “N” is specified as part of the WLS configuration used for the analysis.
3. Estimates for the rms TOA measurement errors are computed individually for the serving and cooperating sectors based on the following data through the use of well established models as found in Turin, et al, (referenced above):
- a. The waveform type and bandwidth
 - b. The net duration of the RF signal collection
 - c. The received SNR at the sector (this takes into account many factors as detailed above)
 - d. The average building density in the vicinity of the sector.
4. The rms error weighted HDOP (discussed below) for this grid point is computed from the estimated rms TOAs for each of the sectors (serving sector plus cooperators).
- a. Because this HDOP is weighted by the rms errors, it directly represents the expected rms error for a location at this grid point.

B.1. Calculation of rms error weighted HDOP

In Leick's book on GPS (Alfred Leick, GPS Satellite Surveying, Wiley), Geometrical Dilution of Precision (GDOP) is defined as the square root of the trace of the covariance matrix for determination of directions east, north, vertical, and time. In forming the covariance matrix the data are equally weighted.

For network-based location, the 2-D case, denoted as HDOP (horizontal dilution of precision), is used. Also since the rms TOA errors are not equal, HDOP is calculated from the covariance matrix formed using rms TOA error weighting of the distance partial derivatives from the grid point to each of the N receiving sectors.

B.2. The HDOP calculation

The rms error weighted covariance matrix is defined as $(\mathbf{A}^T \mathbf{w} \mathbf{A})^{-1}$ where

\mathbf{A} is the 2-D (east and north) design matrix whose elements are:

$$A_{i1} = \frac{\partial \tau_i}{\partial x}$$

$$A_{i2} = \frac{\partial \tau_i}{\partial y}$$

and \mathbf{w} is the diagonal matrix with elements

$$w_{ii} = 1/\sigma_{ii}^2 = w_i$$

$$w_{i \neq j} = 0$$

where σ_{ii} is the rms TOA error to the i^{th} sector.

It can then be shown that:

$$\text{HDOP} = (C_{11} + C_{22})^{1/2}$$

where C_{11} and C_{22} are elements of the covariance matrix $(\mathbf{A}^T \mathbf{w} \mathbf{A})^{-1}$. Evaluating the matrix inversion using cofactors and the determinant

$$\text{HDOP} = [(ac + bc - e^2 - f^2) / (abc + 2def - be^2 - af^2 - cd^2)]^{1/2}$$

where

$$a = \sum w_i \left(\frac{\partial \tau_i}{\partial x} \right)^2$$

$$b = \sum w_i \left(\frac{\partial \tau_i}{\partial y} \right)^2$$

$$c = \sum w_i$$

$$d = \sum w_i \frac{\partial \tau_i}{\partial x} \frac{\partial \tau_i}{\partial y}$$

$$e = \sum w_i \frac{\partial \tau_i}{\partial x}$$

$$f = \sum w_i \frac{\partial \tau_i}{\partial y}$$

with the Σ sums over all sectors (primary plus cooperating sectors).

B.3. Calculation of the partial derivatives

Define the location of the phone to be at (0,0) and the i^{th} sector to be at (x_i, y_i) where the units of x_i and y_i are time delay. If the delay (τ_i) from the phone at (0,0) to the i^{th} sector at (x_i, y_i) is assumed to be only that for a straight-line distance, then:

$$\tau_i = (x_i^2 + y_i^2)^{1/2}$$

and thus the partial derivatives are dimensionless and equal to:

$$\frac{\partial \tau_i}{\partial x} = x_i / (x_i^2 + y_i^2)^{1/2}$$

$$\frac{\partial \tau_i}{\partial y} = y_i / (x_i^2 + y_i^2)^{1/2}$$

Note that a, b, etc. in the HDOP calculation each have units of $1/(\text{rms time error})^2$ and thus HDOP can be seen to have units of “rms time error”.