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GLOBAL SYSTEM FOR
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3GPP

Postal address

3GPP support office address

650 Route des Lucioles - Sophia Antipolis
Valbonne - FRANCE
Tel.: +33 4 92 94 42 00 Fax: +33 4 93 65 47 16

Internet

http://www.3gpp.org

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Foreword

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Introduction

Over the past ten years several organizations within the wireless telecommunications industry have invested significant time and resources in studying wireless location technologies. Of the technologies that have been investigated to date all have proven to have certain strengths and weaknesses. As of yet 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 significant live field deployments to date location technologies based on uplink time difference of arrival (U-TDOA) techniques have proven to provide excellent performance in urban, suburban and indoor environments. The U-TDOA technologies do not require modifications to handsets, so performance for existing mobile stations has proven to be excellent in these same environments. In some rural environments where cell site densities and coverage are very limited the performance of U-TDOA has proven to degrade without the assistance of other location methods.

The A-GPS and E-OTD location technologies currently supported in the GERAN standard have significant capabilities. They also have weaknesses that can be mitigated by complementing them with U-TDOA. For example, in urban and indoor environments where reception of GPS signals becomes very difficult and sometimes impossible the performance of A-GPS technologies degrades significantly. In these same urban and indoor environments U-TDOA technologies have proven to perform well because the SNR of uplink channels remains high and cell site densities are most dense. Additionally, in urban and dense suburban environments where higher accuracies become more valuable but the effects of multipath become more significant, the performance of E-OTD technologies is limited by their inability to mitigate the effects of multipath. In these same urban and dense suburban environments U-TDOA technologies have proven to perform well due to their ability to utilize advanced super-resolution techniques to mitigate the effects of multipath. Finally, U-TDOA is able to cover 100% of existing mobile stations today, while A-GPS and E-OTD location methods depend on the subscriber purchasing new location capable mobile stations.

It is desirable to have support for U-TDOA in the GERAN standards in order to facilitate a location technology that complements the current standardized A-GPS and E-OTD technologies. Products that support all of these technologies will provide a more robust location solution that will enable the widest and most valuable set of applications and services. By standardizing U-TDOA this technology will be able to achieve significant performance improvements through integration with the network infrastructure making it a very viable and attractive technology for manufacturers and operators.

1 Scope

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

2 References

The following documents contain provisions which, through reference in this text, constitute provisions of the present document.

- References are either specific (identified by date of publication, edition number, version number, etc.) or non-specific.
- For a specific reference, subsequent revisions do not apply.
- For a non-specific reference, the latest version applies. In the case of a reference to a 3GPP document (including a GSM document), a non-specific reference implicitly refers to the latest version of that document *in the same Release as the present document*.

[1] 3GPP TS 43.059: "Functional Stage 2 description of Location Services (LCS) in GERAN"

[2] 3GPP TS 44.071: "Location Services (LCS); Mobile Radio Interface Layer 3 Location Services (LCS) specification".

[3] 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".

[4] 3GPP TS 48.018: "General Packet Radio Service (GPRS); Base Station System (BSS) - Serving GPRS Support Node (SGSN); BSS GPRS Protocol (BSSGP)".

[5] 3GPP TS 48.071: "Serving Mobile Location Center – Base Station System (SMLC-BSS) interface; Layer 3 specification".

[6] 3GPP TS 49.031: "Location Services (LCS); Base Station System Application Part - LCS Extension (BSSAP-LE)".

[7] 3GPP TS 23.871: "Enhanced support for privacy in Location Services (LCS)".

3 Abbreviations

3.1 Abbreviations

For the purposes of the present document, the following abbreviations apply:

BSC/PCU	Base Station Controller/ Packet Control Unit
BSSAP-LE	Base Station System Application Part – LCS Extension
GPRS	General Packet Radio Service
LCS	LoCation Services
LLP	LMU LCS Protocol
LMU	Location Measurement Unit
RMS	Root Mean Square
SMLC	Serving Mobile Location Center
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunications System
U-TDOA	Uplink – Time Difference Of Arrival

4 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 [1] (3GPP TS 43.059 (Functional Stage 2 Description of Location Services in GERAN)). Limited modifications to LCS protocol message formats and functional/logical enhancements in the BSC/PCU network node are necessary.

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.

4.1 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 for the target MS (frequency, timeslot, allocated blocks, etc.). This information is generated by the PCU. In order 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 appropriately to include U-TDOA functionality for LCS at this interface.

For a MS in the middle of an uplink data transfer, with enough remaining data to allow the appropriate U-TDOA set-up time (approximately 250 mSec), no additional location-specific transmissions are required. 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 set-up time and 4 to 20 subsequent data Blocks (depending on the QoS requirement and MS transmit power level).

For mobiles not currently active in the uplink direction, it is necessary to cause the MS to transmit for a range of 4-20 blocks; depending on the QoS requirement and resulting MS transmit power level. The method proposed 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 to determine an accurate 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 using Timing Advance Polling is proposed 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 is currently 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 that the repeated execution (4-20, depending on the required location QoS and MS transmit power level) of the PACKET_POLLING_REQUEST message could be used 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.

4.1.1 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 set-up signalling 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 set-up 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.

4.1.2 UMTS

U-TDOA is particularly suited to UMTS. The wide bandwidth and potentially high bit rates (low spreading factors) make even higher levels of accuracy achievable. 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 provides this higher level of accuracy because more LMUs can participate in the location effort. As always, U-TDOA does not require any additional resource or 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.

4.2 Block Diagram

The following diagram 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.

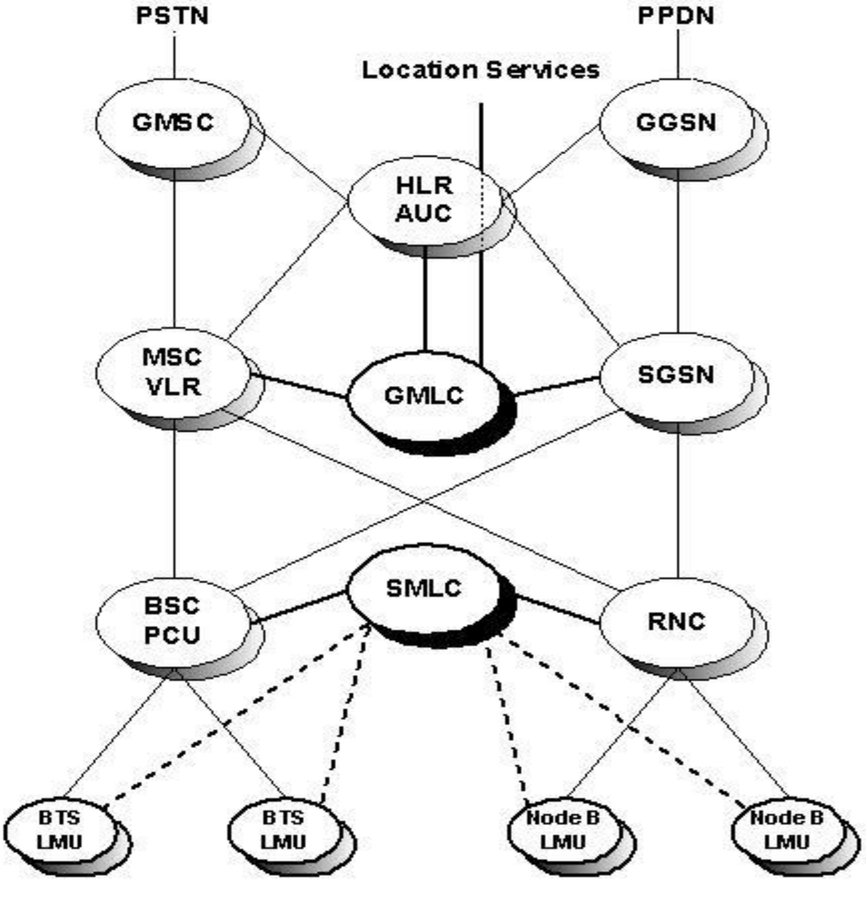


Figure 1: System Block Diagram

5 U-TDOA: Performance Analysis

5.1 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.

5.2 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 multipath, is given by the Cramer-Rao bound:

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

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:

$$\text{Location rms} \approx \text{TDOA}_{\text{rms}}\ \text{P}^{-1/2}\ \text{N}^{-1/2}\ \text{GDOP}_{\text{c}}$$

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 centre of a circular N-station configuration. From this 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 multipath components. The unresolved multipath components result in additional error in the TDOA measurements. The effective multipath delay spread is given by the square root of:

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

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

The larger the signal bandwidth the more multipath components can be resolved and the smaller the effective multipath 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 multipath components dominates location accuracy. Sophisticated super-resolution techniques have been developed to help mitigate the effects of the unresolved multipath. The performance of these techniques is dependent upon signal bandwidth, coherent integration time and SNR.

5.3 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 multipath than TDMA. The effects of this increased bandwidth on multipath spread are illustrated in the more detailed document in Annex A.

The illustrations in Annex A only show the general effect of multipath 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 modelling 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 multipath model. For each TDOA measurement this model generated independent Rayleigh-distributed amplitudes and random phases for each of the multipath 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 multipath case.

Based on this analysis of the effect of signal bandwidth, and the fact that integrated SNR for GSM and TDMA are effectively equivalent, RMS TDOA errors for GSM are predicted to 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 U-TDOA in deployed networks. Both TDMA and GSM performance were modelled using a predictive modelling 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 analysed. A more detailed presentation of this material can be found in Annex 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 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).

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

5.4 Modelling Methodology

The methodology used in this analysis is to configure the modelling tool such that the results conform to observed data in Wilmington, Delaware (USA) and Houston, Texas (USA). On a cell-by-cell basis the power law and the multipath delay spread are modified until the modelling results match the observed data in that cell. This approach provides more accurate results than having a general urban, suburban and rural model.

The Wilmington, Delaware and Houston, Texas systems include dense urban, suburban and moderate density rural environments. The data was captured by making thousands of calls at known locations while inside buildings, vehicles and in a pedestrian environment. Cell spacing in these locations ranges from approximately 0.5 km to 10 km as illustrated in Figures 8 and 26 in Annex A. Additional information about the modelling technique is provided in Annex B.

Table 1

Network	Air Interface	LMU Deployment Density	67% Performance (meters)	95% Performance (meters)	Figure
Wilmington (Trial Results)	TDMA	100%	81	190	N.A.
Wilmington	TDMA	100%	81	137	7
Wilmington	GSM (CS) GPRS (80 burst) GPRS (16 burst)	100%	42 48 55	71 81 94	8 9 10
Wilmington	GSM (CS) GPRS (80 burst) GPRS (16 burst)	50%	57 65 73	100 113 129	11 12 13
Houston (850 MHz)	TDMA	100%	84	143	16
Houston (850 MHz)	GSM (CS) GPRS (80 burst) GPRS (16 burst)	100%	44 49 55	74 84 94	17 18 19
Houston (850 MHz)	GSM (CS) GPRS (80 burst) GPRS (16 burst)	50%	50 57 65	86 98 112	20 21 22
Houston (1900 MHz)	GSM (CS) GPRS (80 burst) GPRS (16 burst)	100%	56 65 76	100 116 139	25 26 27
Houston (1900 MHz)	GSM (CS) GPRS (80 burst) GPRS (16 burst)	50%	66 79 100	117 142 185	28 29 30

5.5 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 multipath than TDMA. A comprehensive analysis showed a 2:1 ratio of TDMA-to-GSM errors for the typical multipath 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 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 the effects of multipath. Also, they do not take into account more aggressive techniques for mitigating the effects of multipath in a GSM environment that are currently under development. These techniques for super-resolving multipath 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.

6 U-TDOA: System Impacts

6.1 Protocol Impacts

6.1.1 GSM

Call Control

No impact.

Mobility Management

No impact.

Radio Resource Management

No impact.

Short Message Service

No impact.

Supplementary Services

No impact.

6.1.2 GPRS

GPRS Mobility Management (GMM)

No impact.

Session Management (SM)

No impact.

GPRS Short Message Service

No impact.

BSSGP

Modification of BSSGP is not required. However, a simple extension of one information element (IE) of the **Perform_Location_Request** message will add the capability for the location application to select the preferred location methodology. This is appropriate when multiple location methods are available and location service providers are billed differently for each method.

The **Location Type** IE in the **Perform_Location_Request** message may 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 [4] (3GTS 48.018 (BSSGP)) which points to Paragraph 10.18 (**Location Type** IE) of [6] (3GTS 49.031 (BSSAP-LE)). New values could 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.

6.1.3 Common Protocols for Location Services

BSSAP-LE

Modification of BSSAP-LE is not required. As in BSSGP (Paragraph 6.1.2.4 above), the **Location Type** IE in the **Perform_Location_Request** message could 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 information transfer between the SMLC and the PCU have to be specified.

LLP

In addition to the already-defined messages, new messages that support 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.

6.2 Impacts to Existing Nodes

6.2.1 BTS

None.

6.2.2 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 Section 7.2 of this document.

6.2.3 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 Section 7.1 of this document.

6.2.4 MSC/VLR

None.

6.2.5 SGSN

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

6.2.6 SMLC

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

6.2.7 LMU

- Implement logic and messaging for U-TDOA

6.2.8 MS

None.

6.3 Network Capacity Impacts

The impact of U-TDOA on the GSM/GPRS network depends on the SMLC and BSC control architectures. In general the amount of additional message traffic imposed by U-TDOA depends on whether existing functionalities in the BSC/PCU are repetitively executed by the SMLC or whether the BSC/PCU is modified to execute new procedures that have been created specifically for U-TDOA LCS. The following are examples of possible control architectures:

1. The SMLC sequentially and individually executes mobile interrogations (i.e., Packet Polling Requests) as many times as necessary to achieve the indicated QoS. The SMLC also sequentially and individually tasks each LMU involved in a particular location determination for each execution of the mobile interrogation. This requires the least modification to the BSC/PCU but results in a high level of messaging traffic between the SMLC, BSC/PCU and LMU.

2. The SMLC tasks the BSC/PCU with executing the mobile interrogation a specific number of times and the BSC/PCU attempts to execute all of the mobile interrogations within a fixed period of time (1-2 seconds). If it is unable to do so it will return a specific Cause Value and the SMLC will reinitiate the location determination. This will minimize the SMLC to BSC/PCU messaging traffic and also minimize the SMLC to LMU traffic by enabling the SMLC to task the LMU once for each series of mobile interrogations made for a particular location determination. This technique does impose significant processing burden on the LMU to search throughout the archived RF data and correlate to the MS transmission of interest.

3. The SMLC tasks the BSC/PCU with executing the mobile interrogation a specific number of times on the beacon frequency (f_0) and the BSC/PCU reports to the SMLC the initial frame number (as acquired from the BTS) of the mobile interrogations. This information would then be included in the LMU tasking messages sent to all of the cooperating LMUs. This technique reduces the processing burden on the LMU by providing accurate information about when the mobile interrogations and responses will begin.

4. The SMLC tasks the BSC/PCU with executing the mobile interrogation a specific number of times. The BSC/PCU will indicate the frame number of each mobile interrogation, and the SMLC will use it to task the LMUs for each mobile interrogation. This reduces the SMLC to BSC/PCU messaging traffic but does not reduce the SMLC to LMU traffic.

5. The BSC/PCU processing and message handling load can be significantly reduced for SMLC to LMU traffic by taking advantage of the packet routing architecture of the BSC. By assigning the LMU a LAPD TEI (as if it were a TRX module) and allowing the SMLC access to the packet routing functionality of the BSC, it is possible to transport SMLC to LMU traffic with little or no additional processing burden. In this approach the SMLC would structure the messages to the LMU (LLP) into the TRAU frame format with the LAPD address of the desired LMU.

6.3.1 Network Assumptions

- One (1) LMU at each BTS
- 100 BTS per BSC
- 16 LMUs involved with each Location Estimation, 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

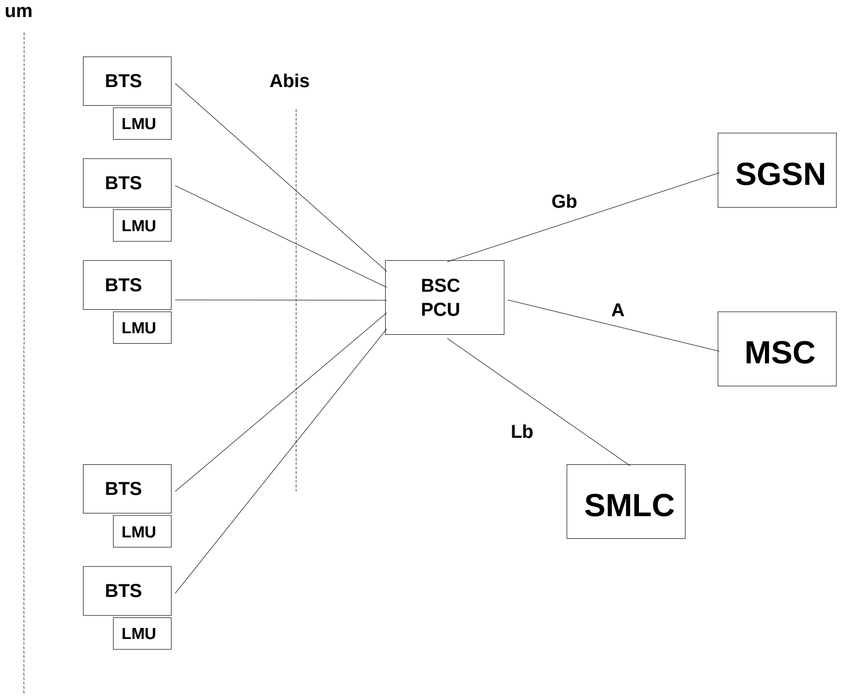


Figure 2: Network Assumptions

6.3.2 Um and Abis Interfaces

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 single location estimates 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.

The traffic on the Abis interface, for location activity in a particular cell/sector is analogous to the traffic on the Um 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_Request** 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).

In addition to the BSC-to-MS messaging on the Abis interface, the SMLC-to-LMU tasking and response information is also present. This traffic consists of the LMU tasking for the resident 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 15 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 is 160 tasking messages or 160 PCU frames per minute (2.67 frames per second) per Abis link.

6.3.3 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 messaging traffic associated with the initiation and reporting of a location request is the same for all of the proposed location methodologies and will not be discussed. The volume of the SMLC to BSC messaging associated with initiating the U-TDOA mobile interrogations depends on the control architecture as discussed in the introductory paragraph above. This traffic will be included in the analysis of the individual control architectures described in the following paragraphs.

LMU tasking and response traffic represents the vast majority of the traffic in U-TDOA. For each location estimation, up to 30 LMUs may be tasked to capture the resulting RF energy while a more typical number is 16. The control architecture discussed in paragraph number 5 above discusses how the impact of this traffic can be minimized. This traffic will be included in the analysis of the individual control architectures described in the following paragraphs.

The RLC/MAC control message (mobile interrogation) and U-TDOA associated data messages (LMU tasking/response) require 250 bits each in the following analysis. Only the mature case of ten (10) locations per second per cell/sector is shown.

Control Architecture #1 – Minimum modifications to the BSC

For each location determination:	Forward	Reverse
- Location Request	1 x 250 bits	0.25 Kbits
- Eight mobile interrogations	8 x 250 bits	2 Kbits
- Eight RLC/MAC messages sent to BTS	8 x 250 bits	2 Kbits
- Tasking, 16 LMU		
Per mobile interrogation 16 x 250 bits = 4 000 bits		
For 8 interrogations	8 x 4000 bits	32 Kbits
- Response, 16 LMU		
For 8 interrogations	8 x 4000 bits	32 Kbits
- Location Response	1 x 250 bits	0.25 Kbits
Total (per location)	34.5 Kbits	34.5 Kbits

Traffic per BSC-SMLC link

- 100 cell/sectors per BSC x 10 locations per minute = 1000 locations per minute/BSC

  = 16.67 locations per second/BSC

- Total BSC-SMLC traffic = 575.011 Kbits/second

Control Architecture #2 – BSC modified for multiple mobile interrogations on a predefined ARFCN and within a defined time interval

For each location determination:	Forward	Reverse
- Location Request	1 x 250 bits	0.25 Kbits
- Mobile interrogation request	1 x 250 bits	0.25 Kbits
- Initial frame number	1 x 250 bits	0.25 Kbits
- Tasking, 16 LMU	16 x 250 bits	4.00 Kbits
- Response, 16 LMU	16 x 250 bits	4.00 Kbits
- Location Response	1 x 250 bits	0.25 Kbits
Total (per location)	4.50 Kbits	4.50 Kbits

Traffic per BSC-SMLC link

- 100 cell/sectors per BSC x 10 locations per minute = 1000 locations per minute/BSC

  = 16.67 locations per second/BSC

- Total BSC to SMLC traffic = 75.00 Kbits/second

Control Architecture #3 – BSC modified for multiple mobile interrogations on a predefined ARFCN and the provision of the frame number of the first mobile interrogation

For each location determination:	Forward	Reverse
- Location Request	1 x 250 bits	0.25 Kbits
- Mobile interrogation request	1 x 250 bits	0.25 Kbits
- Initial frame number	1 x 250 bits	0.25 Kbits
- Tasking, 16 LMU (Includes init. frame number)	16 x 250 bits	4.00 Kbits
- Response, 16 LMU	16 x 250 bits	4.00 Kbits
- Location Response	1 x 250 bits	0.25 Kbits
Total (per location)	4.50 Kbits	4.50 Kbits

Traffic per BSC-SMLC link

- 100 cell/sectors per BSC x 10 locations per minute = 1000 locations per minute/BSC

  = 16.67 locations per second/BSC

- Total BSC to SMLC traffic = 75.00 Kbits/second

Control Architecture #4 – BSC modified for multiple mobile interrogations on a predefined ARFCN and the provision of all frame numbers of mobile interrogations

For each location determination:	Forward	Reverse
- Location Request	1 x 250 bits	0.25 Kbits
- Mobile interrogation request	1 x 250 bits	0.25 Kbits
- Frame numbers for 8 mobile interrogations	1 x 250 bits	0.25 Kbits
- BSC to SMLC		
- Tasking 16 LMU		
Tasking 16 LMU	16 x 250 bits	4.00 Kbits
Mobile interrogation frame numbers to LMU	16 x 250 bits	4.00 Kbits
- Response, 16 LMU	16 x 250 bits	4.00 Kbits
- Location Response	1 x 250 bits	0.25 Kbits
Total (per location)	4.50 Kbits	8.50 Kbits

Traffic per BSC-SMLC link

- 100 cell/sectors per BSC x 10 locations per minute = 1000 locations per minute/BSC

  = 16.67 locations per second/BSC

- Total BSC to SMLC traffic (higher value) = 141.67 Kbits/second (reverse)

Control Architecture #5 – Implementation of a direct SMLC to LMU packet switching capability

NOTE: This architecture assumes that SMLC to LMU traffic is "automatically" routed in the BSC and BTS in the same manner as TRAU frames. Only messaging traffic that the BSC must analyse and act upon are listed.

Actionable message traffic for each location determination	Forward	Reverse
- Location Request	1 x 250 bits	0.25 Kbits
- Mobile interrogation request	1 x 250 bits	0.25 Kbits
- Frame numbers for 8 mobile interrogations	1 x 250 bits	0.25 Kbits
- BSC to SMLC		
- Location Response	1 x 250 bits	0.25 Kbits
Total (per location)	0.50k bits	0.50 Kbits

Traffic per BSC-SMLC link

- 100 cell/sectors per BSC x 10 locations per minute = 1000 locations per minute/BSC
  = 16.67 locations per second/BSC
- Total BSC to SMLC traffic (actionable) = 8.33 Kbits/second

6.3.4 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.

6.3.5 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.

6.4 Impact on Specifications

6.4.1 3GPP TS 48.018: BSSGP

It is not necessary to modify this specification to implement U-TDOA. As discussed in 6.1.2.4, 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) may be extended. New values could be specified for U-TDOA in Octet 3 (**Coding of location information**) and Octet 4 (**Positioning method**).

6.4.2 3GPP TS 49.031: BSSAP-LE

It is not necessary to modify this specification to implement U-TDOA. As discussed in 6.1.2.4, the IE specified in Paragraph 10.18 (**Location Type** IE) of 3GTS 49.031 (BSSAP-LE) may be extended. New values could be specified for U-TDOA in Octet 3 (**Coding of location information**) and Octet 4 (**Positioning method**).

6.4.3 3GPP TS 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 already defined messages new messages supporting information transfer between the SMLC and the LMU have to be specified.

6.4.4 3GPP TS 44.071: LLP

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

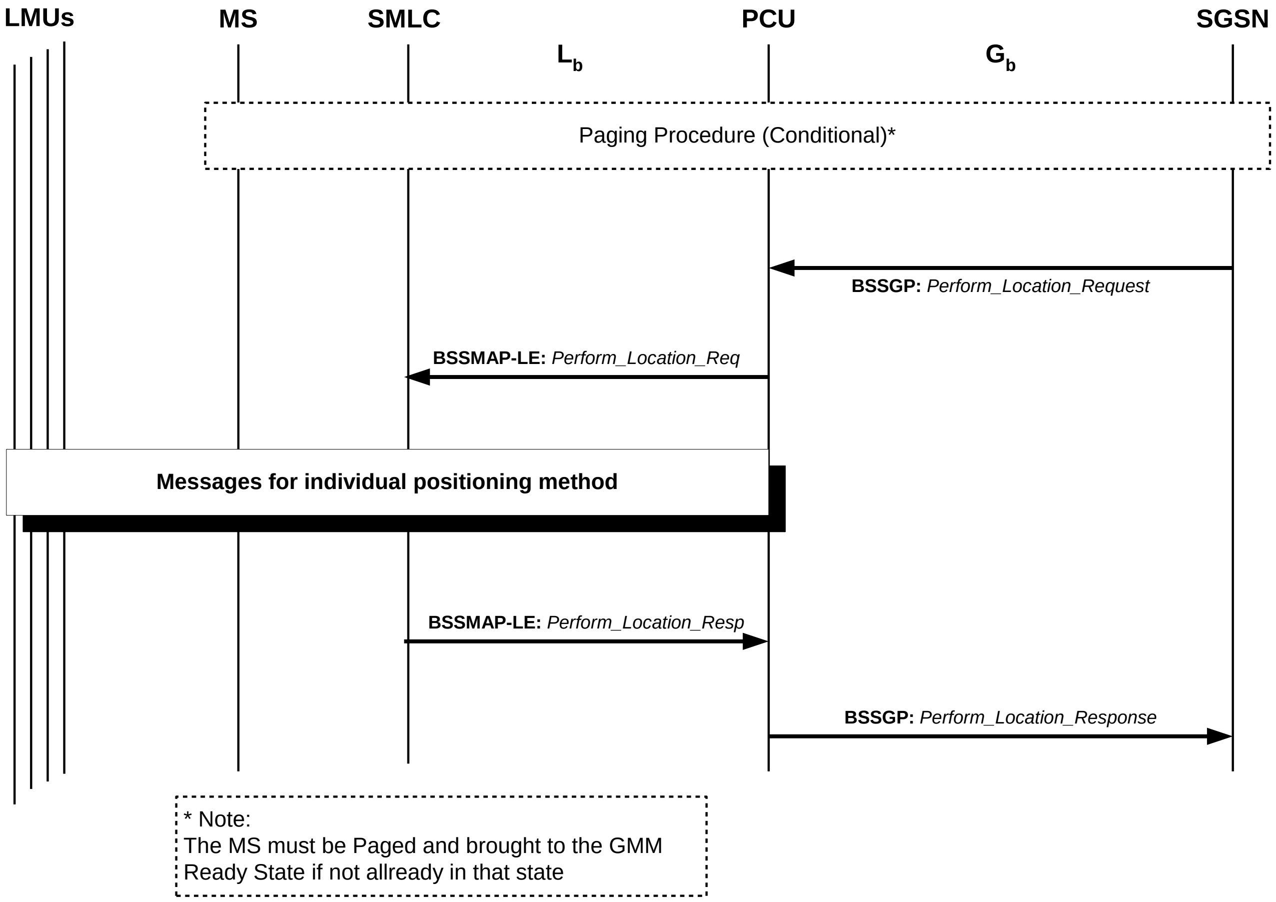
6.4.5 3GPP TS 43.059: LCS Stage 2 Document

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

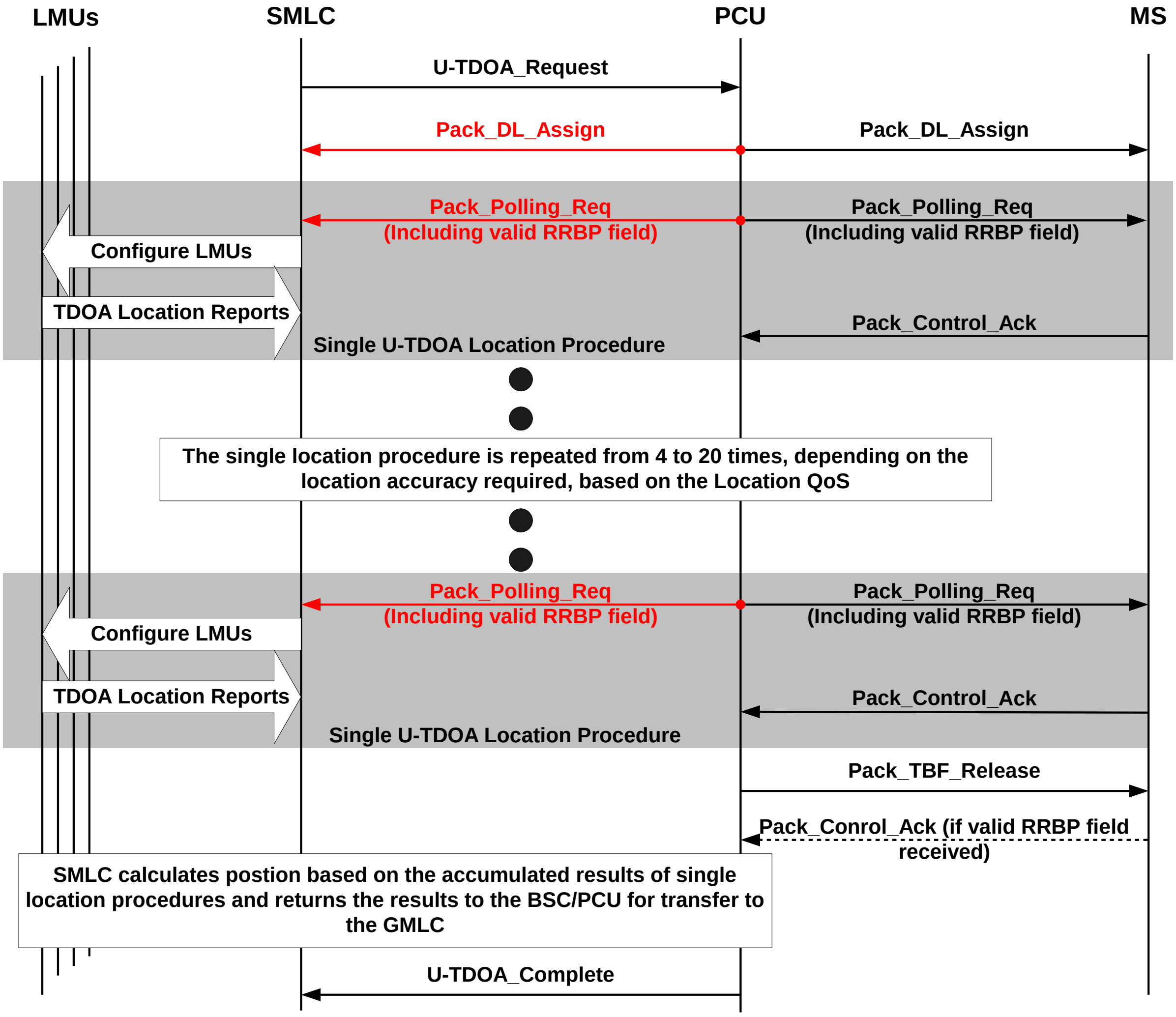
7 U-TDOA Call Flows

7.1 Packet Switched

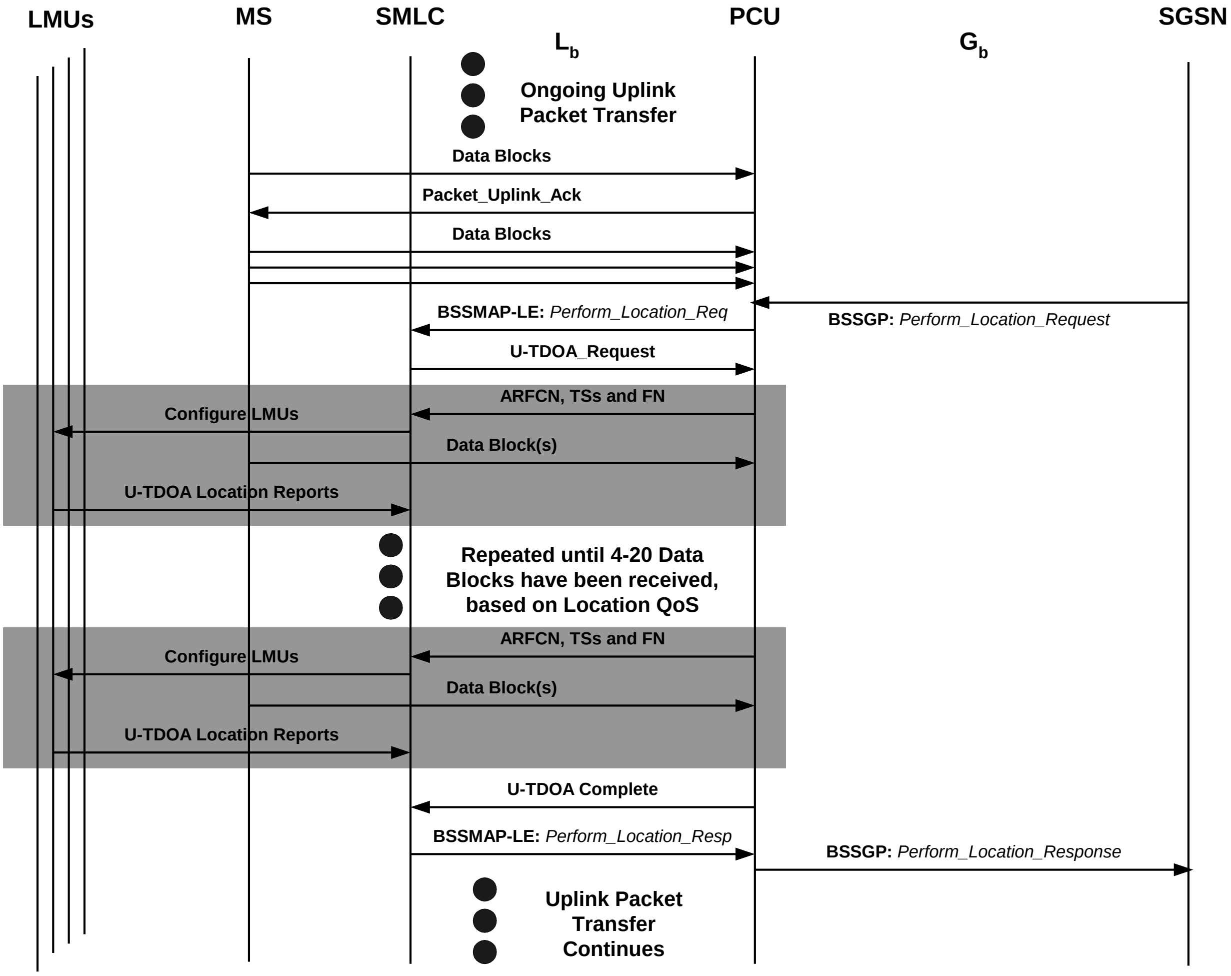
7.1.1 General Location Procedure



7.1.2 PS U-TDOA, Packet Idle Mode

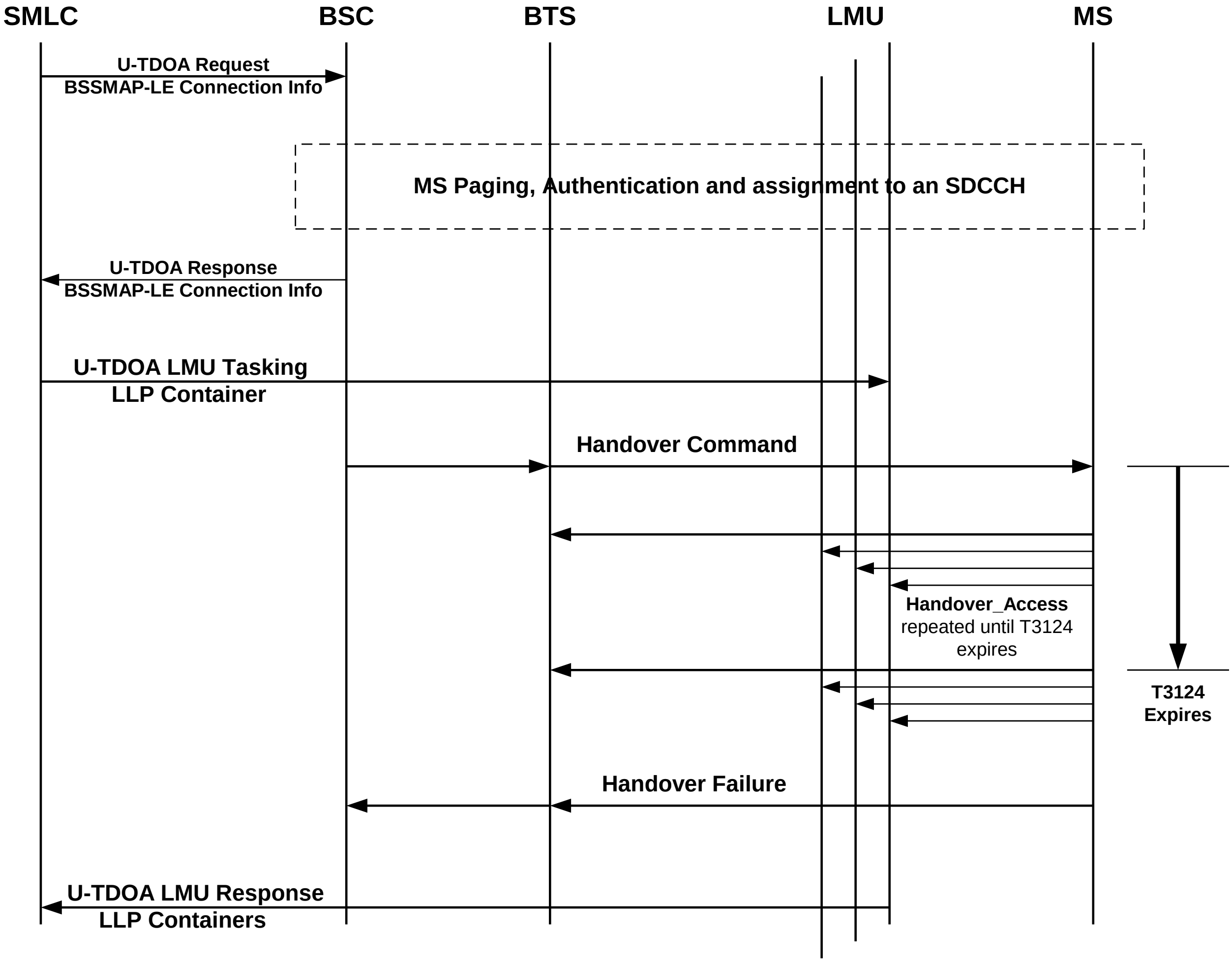


7.1.3 PS U-TDOA, Ready State, Uplink data transfer in progress

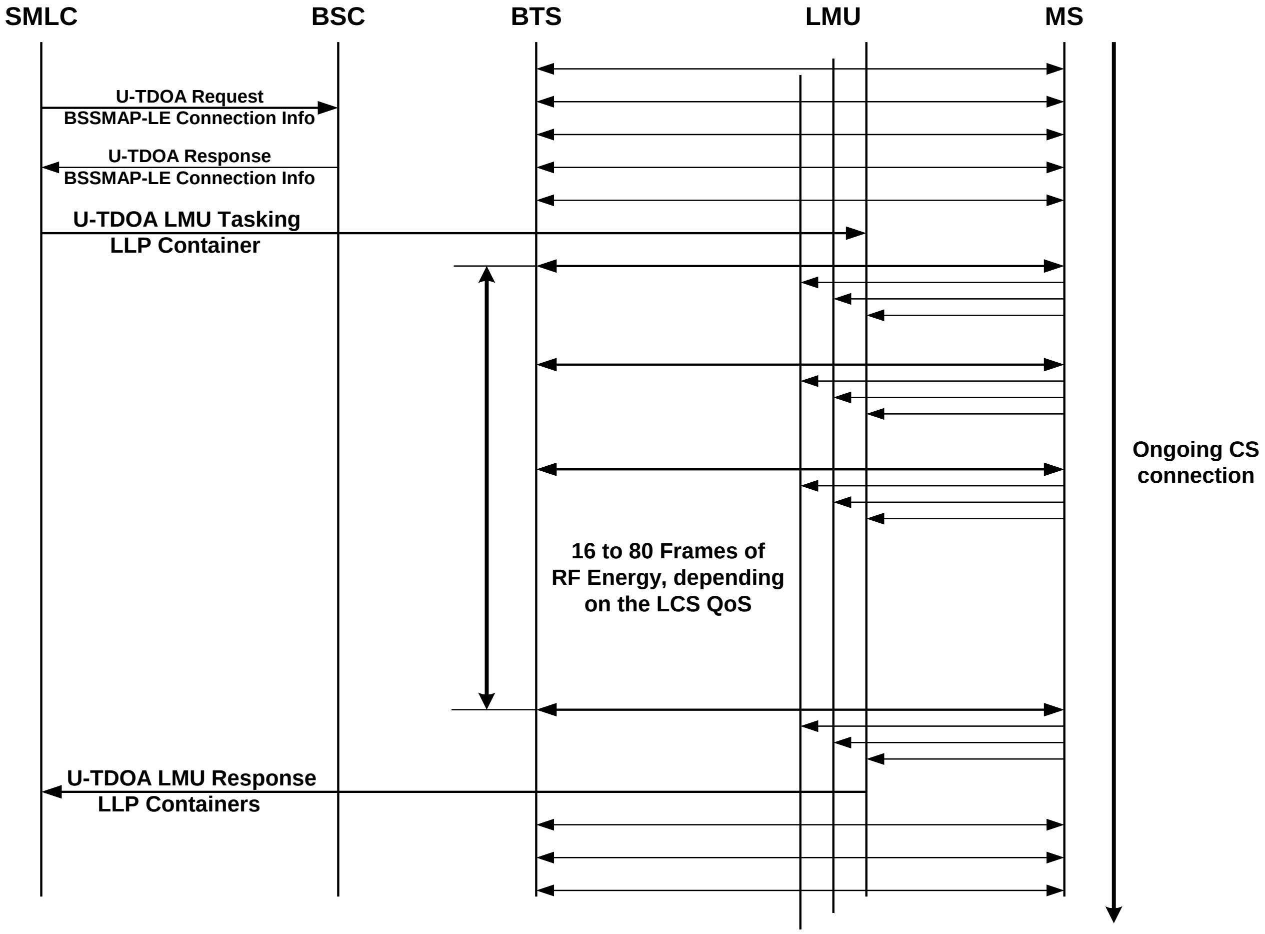


7.2 Circuit Switched

7.2.1 CS, Idle Mode



7.2.2 CS, Dedicated Mode



8 Implementation Considerations

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

8.1 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.

8.1.1 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, this may require an overlay interconnect to the SMLC that is a separate logical and possibly physical interconnect architecture.

8.1.2 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. This LMU implementation would support specification-compliant LMU-to-SMLC interconnect that would be integrated with the BTS and BSC/PCU.

8.1.3 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.

8.2 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. Very little latency could be tolerated from receipt of the connection-oriented information (frequency, timeslot, etc.) to the tasking of the LMU to capture the RF signal information if LMU tasking were to be done in “real time”. Severe delay (latency) restrictions would be imposed on the BSC and BTS for the transport of LLP (SMLC to LMU) messages. In the GPRS domain, there is 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 frequency(s). These bursts may have been transmitted significantly before this 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 difference of arrival information to the SMLC, which then calculates the MS location. Based upon resource availability (RF and message transport capabilities) this process can be allowed to take many seconds (if necessary and allowable) without placing severe resource assignment and transport latency restrictions on the network infrastructure.

8.3 Synchronization

All U-TDOA capable LMUs are synchronized to an externally derived and very accurate clock. Periodically (every few minutes) the LMU 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 optimise the collection of a particular MS signal in the cache memory at a remote LMU. The remote LMU is subsequently given the frequency(s) and system time at which to extract the relevant RF signal from the cache memory to begin the location calculation process.

8.4 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.

8.5 MS Power Control

The affect of MS power control on U-TDOA depends on the environment in which the location determination occurs. In general, location accuracy is constrained by two factors; the multipath characteristics and the Signal-to-Noise Ratio (SNR) of the received signal(s).

In an environment dominated by multipath, location accuracy is typically limited by the receiver's ability to resolve the earliest arriving signal component and not SNR. Additional power or longer integration times do not provide a dramatic increase in location accuracy in multipath dominated environments. This situation is typically encountered in urban and suburban environments where cell sizes are relatively small and it is reasonable to involve many LMUs in a given location determination without increasing the MS power or significantly increasing the integration time

Location accuracy is typically limited by SNR in open environments with larger cell spacing where a majority of the active mobiles are transmitting at a relatively high power level. These environments tend to be less constrained by the availability of RF resources or limited by co-channel interference. In this case it is more reasonable to either increase the mobile power, increase the integration time or both for that relatively low percentage of mobiles that are close enough to the serving cell site to have significantly reduced transmit power.

8.6 Operation with Repeaters

The LMU in the vicinity of repeaters will be modified to recognize and report multiple location solutions. One of the location solutions may correspond to the repeater itself. The SMLC must recognize the possibility of multiple location solutions and, knowing the precise physical location of the repeater, disregard the repeater location unless it is the only solution derived. In the later case the MS is actually located in the immediate vicinity of the repeater.

For a variety of reasons, it is not practical, although possible, to locate phones accurately if an LMU is not deployed at the repeater.

LMUs located at primary cell sites would receive similar signals, separated in time, from both the repeater antenna and the MS. Without additional processing, it would not be possible to determine the actual source of the signal, and the calculated location would be significantly different.

Calls initiated at the repeater site would have an insufficient SNR to allow neighbouring LMUs to create an adequate reference signal for location. The result would be degraded or blocked location.

Since a repeater initiates signals into the wireless network, it is important to identify, isolate and remove these signals from the remainder of the location processing. Therefore an LMU needs to be located at the repeater to provide timing of signal departing the repeater. Knowing the distance between the repeater and surrounding cell sites (with their own LMU’s) will allow the system to identify and remove the “extra” repeater transmissions.

For an F1:F1 repeater, the LMU must be located at the site to allow the LMU at the primary site to differentiate between the original (MS) signal and the repeater signal. This information will be passed to the TLP so that repeater initiated signals can be screened from location processing.

For an F1:F2 repeater, the LMU must be located at the site to detect incoming (F1) signals that will be converted to “false” outgoing (F2) signals. The “false” signal information would be passed to the TLP so that they can be screened from location processing.

For an LMU installed at the repeater site, some form of backhaul must be provided to bring the data back to the TLP/SMLC. Several options are available, including:

- DS0
- Microwave communication
- Dedicated 64 Kbps POTS line

It is assumed that repeaters which are not located on the periphery of a cell are not intended to extend the range of that cell are intended to provide localized service and will use low transmit power; i.e., subway stations, building interiors, tunnels, etc. In the case of repeaters intended to provide service in a small area it may be acceptable to locate the MS at the physical location of the repeater. Location determination in long tunnels can be accomplished by locating an LMU at both ends of the tunnel.

8.7 Privacy

For future MS, privacy can be implemented consistent with specification [7] (TS 23.871: Enhanced support for privacy in Location Services (LCS)). For legacy MS, subscriber management of location privacy will be implemented using one or more of the following methods:

- Circuit Switched connection to the MSC or SMLC and location activation/deactivation via DTMF response or voice prompts
- MSC based feature activation/deactivation
- For GPRS capable MS, personal computer based interaction with the SMLC and/or individual location application for activation/deactivation of location services.

9 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.

9.1 Advantages of U-TDOA

9.1.1 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.

9.1.2 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.

9.1.3 Scalable Accuracy

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 level of effort while permitting incremental upgrades that improve accuracy as market opportunities mature. For example, a U-TDOA location solution can be deployed initially in only 50% of cell sites to achieve sub-100m accuracy, and in the future as applications and accuracy requirements change the density can be increased up to 100% to achieve 50m accuracy.

U-TDOA also optimises utilization of system resources. Location applications require varying degrees of accuracy and U-TDOA enables a selectable level of accuracy by varying the number of bits (bursts) required for a given location determination. Less RF and signalling resources are used to make a less accurate location determination.

9.1.4 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.

9.1.5 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, no additional system resource is used for location determination when using U-TDOA. U-TDOA technology locates mobile stations using the energy associated with the existing traffic and control information.

9.1.6 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.

9.1.7 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. These deployments have included dense urban, suburban, rural, and indoor environments. Millions of location estimates collected over thousands of square kilometers have been analysed and used to improve the performance and operability of the technology to a very mature level.

9.2 Disadvantages of U-TDOA

9.2.1 U-TDOA is currently perceived as being prohibitively complicated

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 complicated stand-alone overlay configurations. The LMU and BTS network elements have not been able to share common equipment or communications interconnect. The efficiencies possible from integration with the network infrastructure have not yet been realized.

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

9.2.2 Accuracy of U-TDOA degrades in some rural areas

U-TDOA by itself requires time difference measurements from at least three sites distributed in a reasonable geometry around the transmitting mobile station in order to provide accurate position estimates. 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 achieved and accuracy of U-TDOA degrades.

Typically, these very rural environments where lower cell densities and limited geometries occur are sparsely populated and require less accuracy to satisfy applications. U-TDOA typically provides adequate accuracy in these environments. In cases where additional accuracy is required a hybrid U-TDOA system solution can provide excellent performance.

10 Conclusion

U-TDOA is technically feasible in GSM and GPRS systems.

Annex A: Analysis of GSM and GPRS Uplink Time Difference of Arrival (U-TDOA)

A.1 Introduction

Over the past nine years comprehensive knowledge about the capabilities and performance of Uplink Time Difference of Arrival (U-TDOA) based wireless location systems has been developed. This knowledge was developed through extensive research, analysis and field deployments. Although a U-TDOA-based wireless location system has not yet been deployed 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 in a GSM environment. The goal is to provide insight into the theoretical aspects of the performance 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 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 proposed system estimates the position of a mobile station by measuring the time-difference-of-arrival (U-TDOA) between the signal received at the serving cell site and the same transmission received at other surrounding cell sites. The error in these U-TDOA measurements, not including the effect of multipath, is given by the Cramer-Rao bound:

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

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:

$$\text{Location rms} \approx \text{TDOA}_{rms}\ \text{P}^{-1/2}\ \text{N}^{-1/2}\ \text{GDOP}_c$$

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 centre 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 multipath components. The unresolved multipath components result in additional error in the U-TDOA measurements. The effective multipath delay spread is given by the square root of:

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

where A_i is the voltage amplitude of the ith multipath component, $x = \pi B$, and B is the signal bandwidth.

The larger the signal bandwidth the more multipath components can be resolved and the smaller the effective multipath 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 multipath components dominates location accuracy. Sophisticated super-resolution techniques have been developed to help mitigate the effects of the unresolved multipath. 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 3 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 multipath than TDMA. Because of this, any multipath components more than a few µs from the main path (typically line-of-site) will not effect the U-TDOA measurement for GSM. However, as can be seen from the figure, multipath components tens of µs from the main path will effect U-TDOA measurements for TDMA. These farther out multipath components also cause greater errors in the TDMA measurement since the error introduced is proportional to the delay given constant relative amplitude.

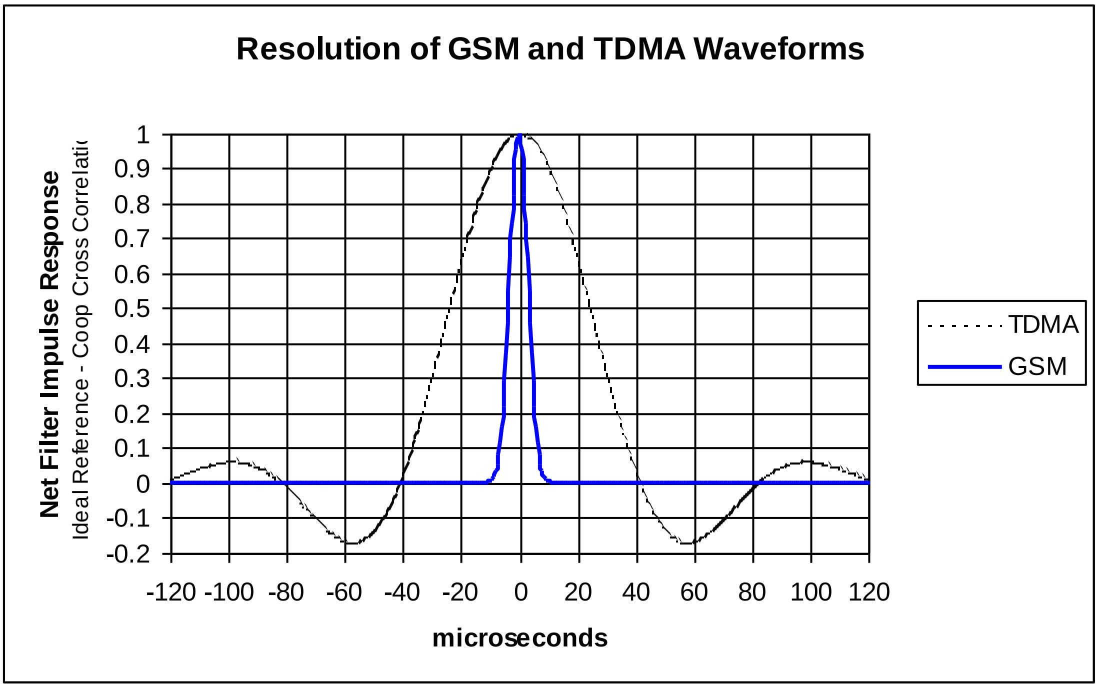


Figure 3: Resolution of GSM and TDMA Waveforms

To illustrate the general effect of the smearing of multipath 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 multipath components. A simple model for the multipath has components spaced at 2 µs intervals with amplitudes proportional to $\tau^{-\alpha}$ where τ is multipath 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 multipath spread is usually described as the RMS time spread of the power of all the multipath components including the main component.

Figure 4 and Figure 5 show the effect of 10 multipath components using a α=1.5 which results in a multipath spread of just over 1 µs. This might be considered a typical multipath environment.

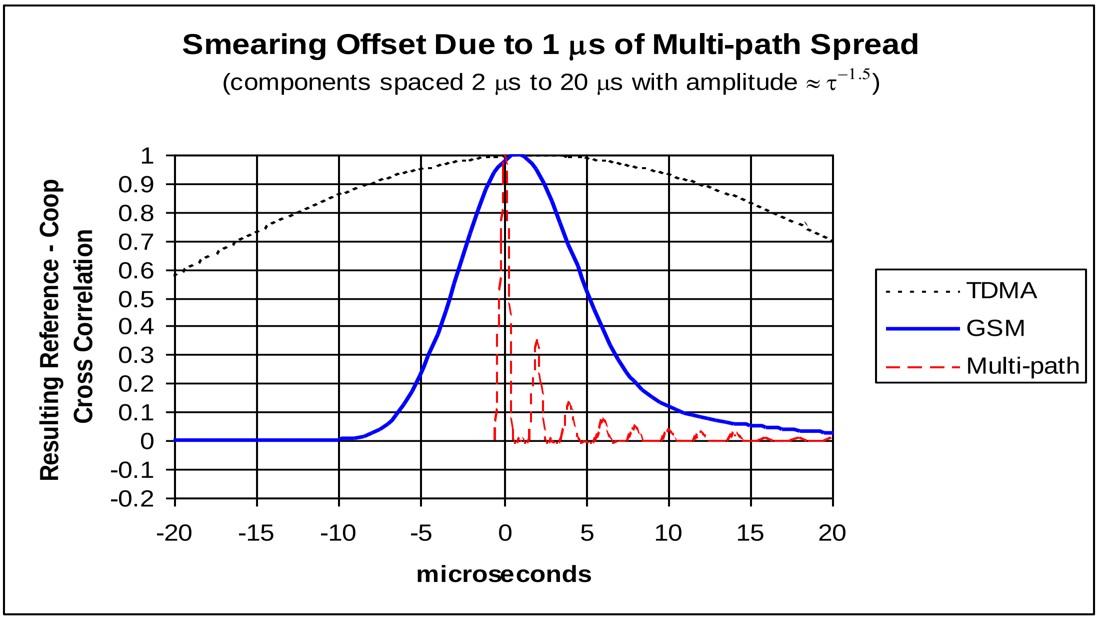


Figure 4: The Effect of Typical Multipath on U-TDOA Measurements

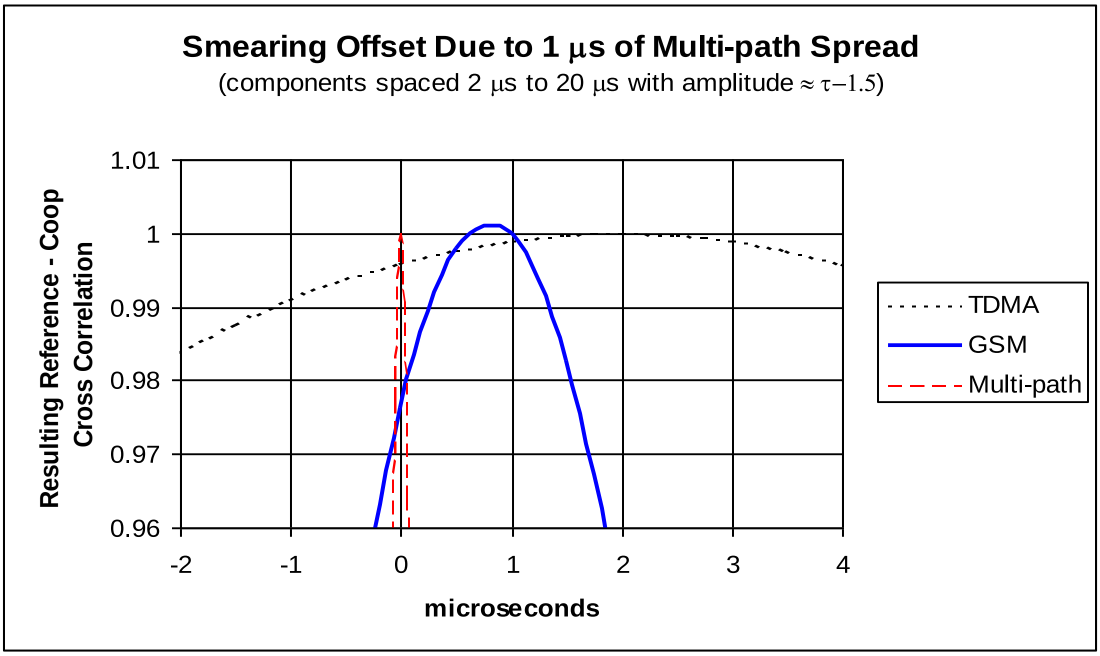


Figure 5: The Effect of Typical Multipath on U-TDOA Measurements (Zoomed In)

As can be seen in Figure 4, 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 5and Figure 6 show the effect of 20 multipath components using a α=1.0 which results in a multipath spread of 3 μs. This might be considered a severe multipath environment.

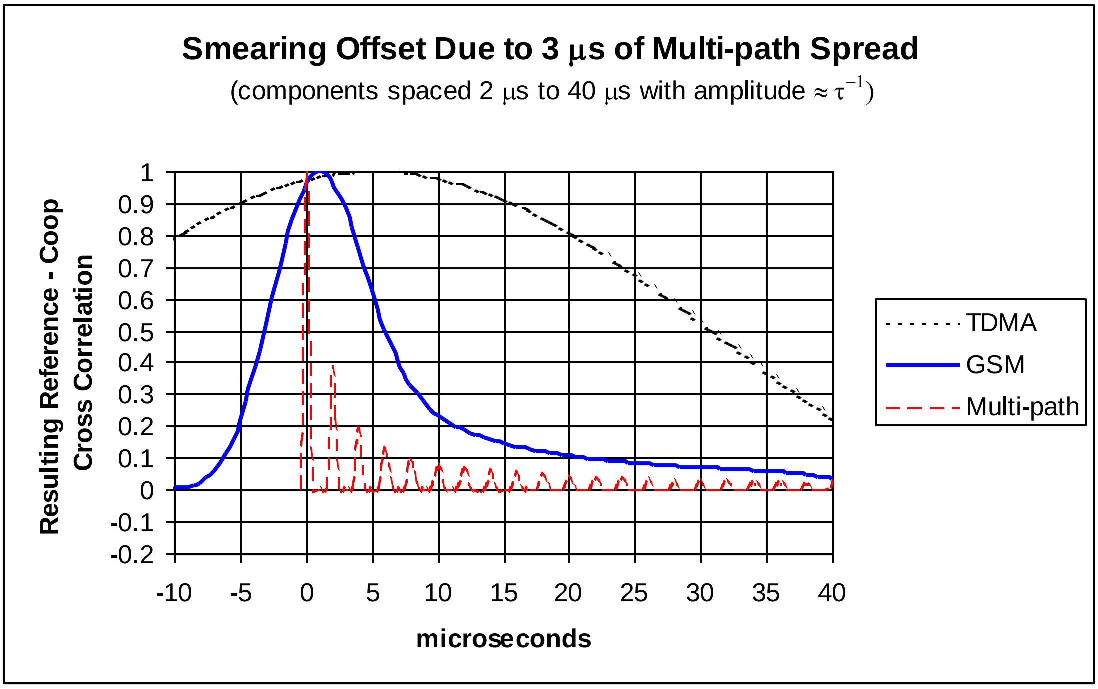


Figure 6: The Effect of Severe Multipath on U-TDOA Measurements

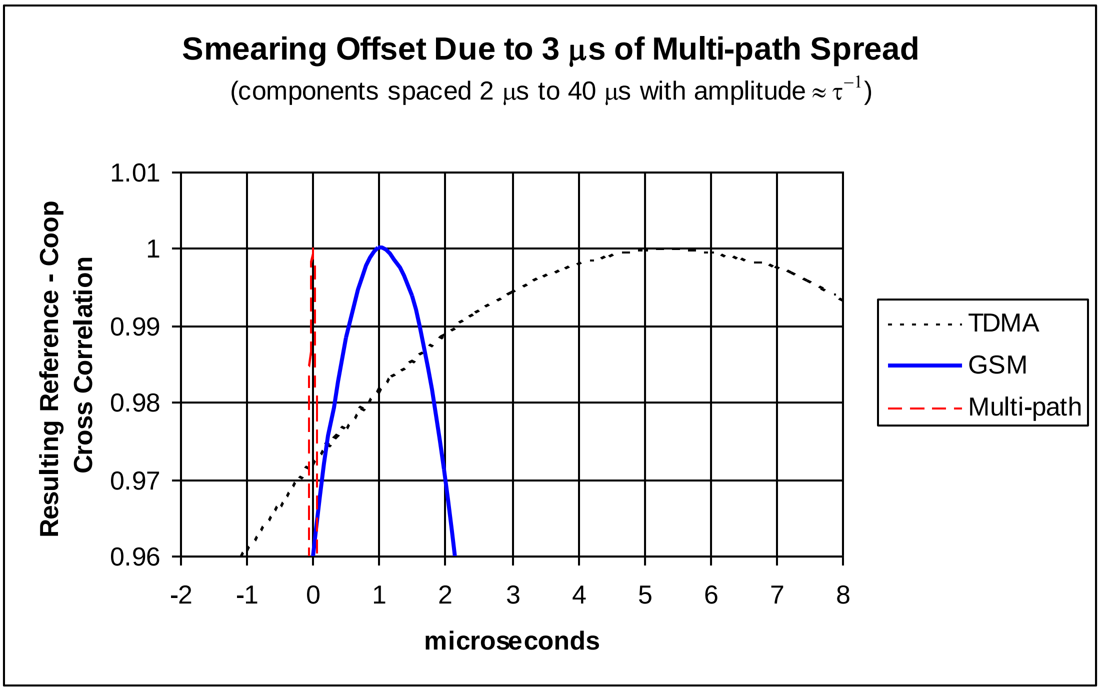


Figure 7: The Effect of Severe Multipath on U-TDOA Measurements (Zoomed In)

As can be seen in Figure 6, the peak of the correlation for GSM is shifted by approximately 1000 ns, while the peak for TDMA is shifted over 5000 ns. The proposed system can utilize 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 multipath 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 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 multipath simulation model. For each U-TDOA measurement this model generated independent Rayleigh distributed amplitudes and random phases for each of the multipath components along with Gaussian noise added to the output. The results averaged over many U-TDOA measurements showed a 2:1 ratio of TDMA to GSM errors for the typical multipath case shown in Figure 4, and nearly a 4:1 ratio for the severe case shown in Figure 6.

Coherent integration time and SNR also affect the accuracy of U-TDOA measurements. In a typical 3-second data collection period the LMUs collects 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, it can be confidently concluded that the RMS U-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 in deployed networks. Both TDMA and GSM performance were modelled using a predictive modelling 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 analysed. Refer to Annex B for a description of the predictive modelling tool and the methodology used to make these predictions.

Figure 8, Figure 17 and Figure 26 identify the network designs used for the three networks. In the 100% LMU deployment density cases LMUs were modelled at all sites. In the 50% LMU deployment density cases LMUs were modelled only at the sites displayed in green.

Additional analysis was done to evaluate the location accuracy of the 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).

Table 2: Predicted Location Accuracy Performance

Network	Air Interface	LMU Deployment Density	67% Performance (meters)	95% Performance (meters)	Figure
Wilmington (Trial Results)	TDMA	100%	81	190	N.A.
Wilmington	TDMA	100%	81	137	7
Wilmington	GSM GPRS (80 burst) GPRS (16 burst)	100%	42 48 55	71 81 94	8 9 10
Wilmington	GSM GPRS (80 burst) GPRS (16 burst)	50%	57 65 73	100 113 129	11 12 13
Wilmington	EOTD	N.A.	76	128	14
Houston (850 MHz)	TDMA	100%	84	143	16
Houston (850 MHz)	GSM GPRS (80 burst) GPRS (16 burst)	100%	44 49 55	74 84 94	17 18 19
Houston (850 MHz)	GSM GPRS (80 burst) GPRS (16 burst)	50%	50 57 65	86 98 112	20 21 22
Houston (850 MHz)	EOTD	N.A.	88	152	23
Houston (1900 MHz)	GSM GPRS (80 burst) GPRS (16 burst)	100%	56 65 76	100 116 139	25 26 27
Houston (1900 MHz)	GSM GPRS (80 burst) GPRS (16 burst)	50%	66 79 100	117 142 185	28 29 30
Houston (1900 MHz)	EOTD	N.A.	120	218	31

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 though 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 proposed approach in a GSM environment is approximately twice that of TDMA. In addition, the proposed system should be able to achieve reasonable accuracy in most GSM networks when LMUs are deployed at only 50% of the cell sites.

Wilmington Analysis

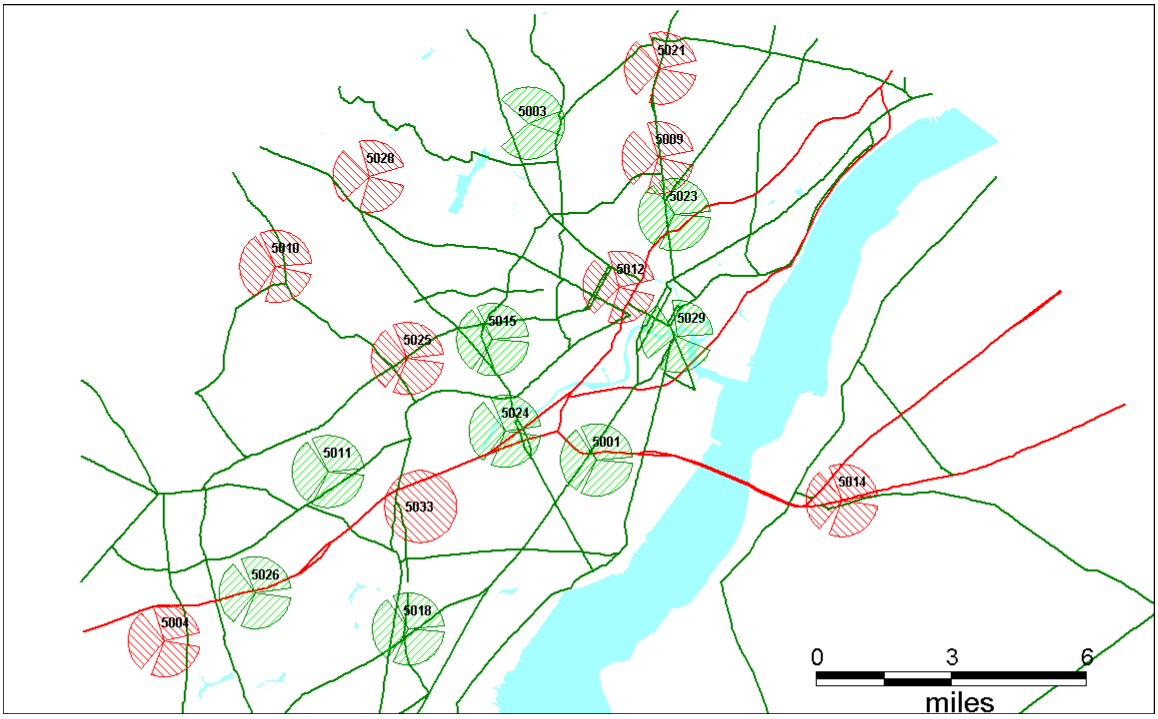
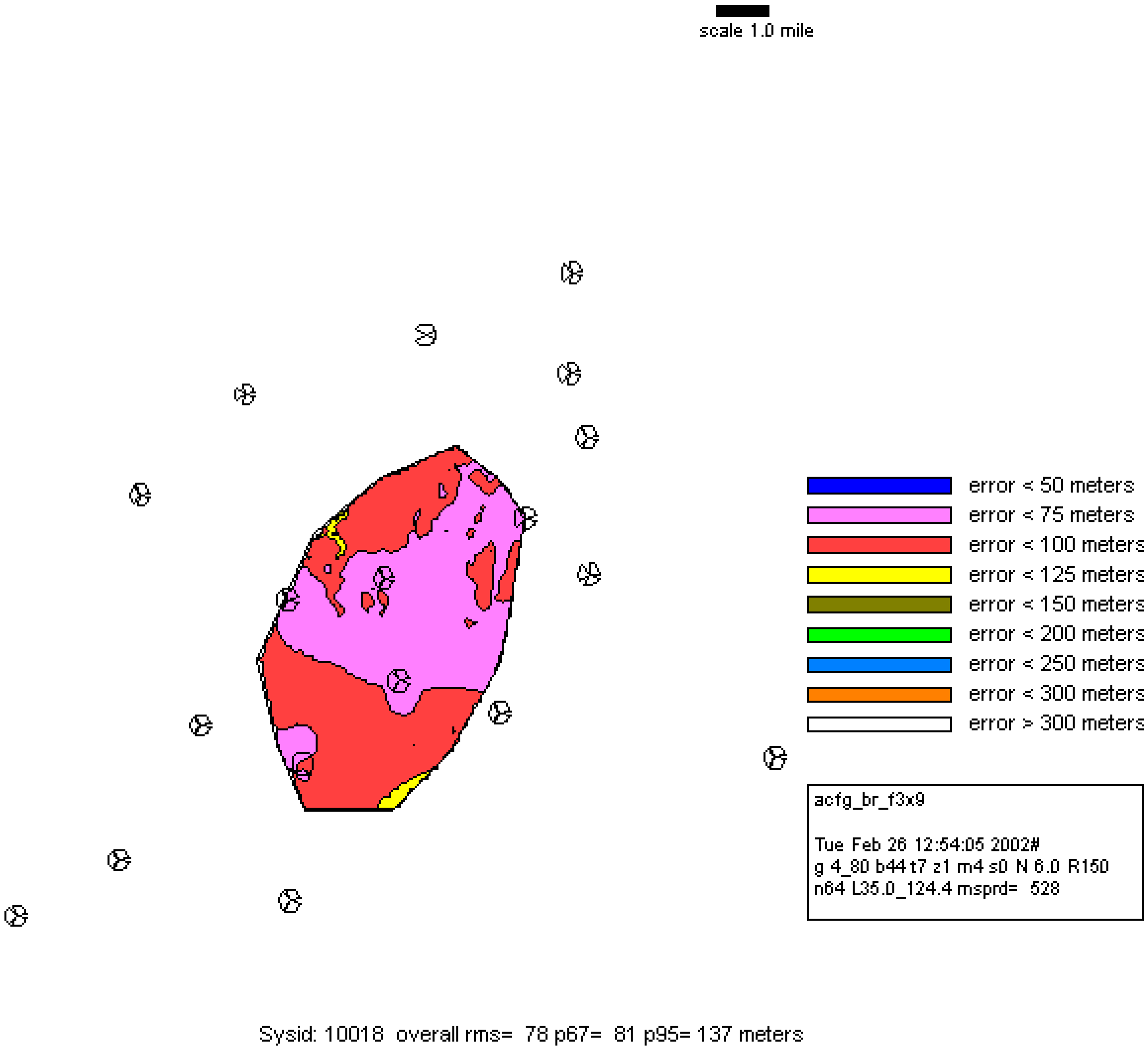


Figure 8: Wilmington 850 MHz AMPS/TDMA Network



```
acfg_br_f3x9

Tue Feb 26 12:54:05 2002#
g 4_80 b44 t7 z1 m4 s0 N 6.0 R150
n64 L35.0_124.4 msprd= 528
```

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

Figure 9: Wilmington 850 MHz TDMA Performance

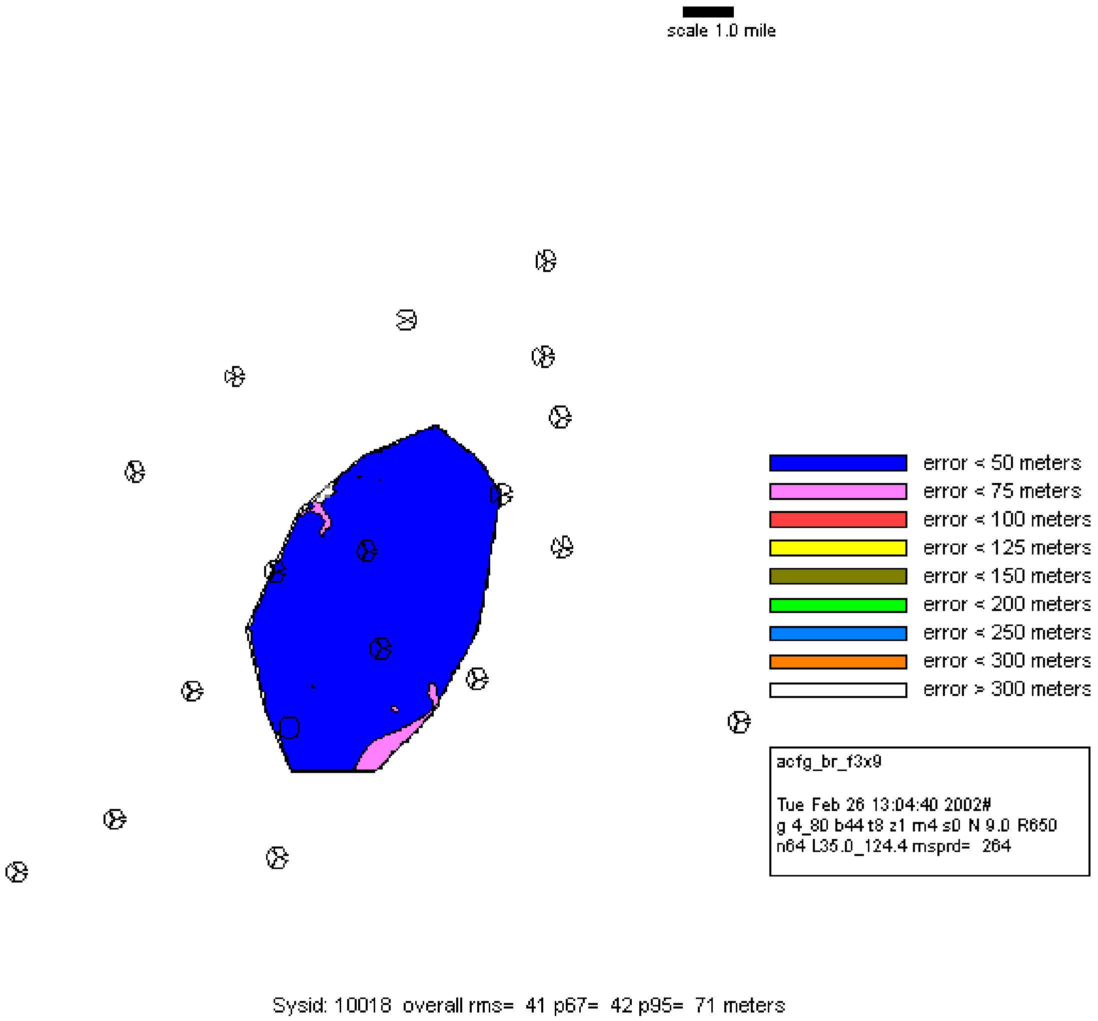
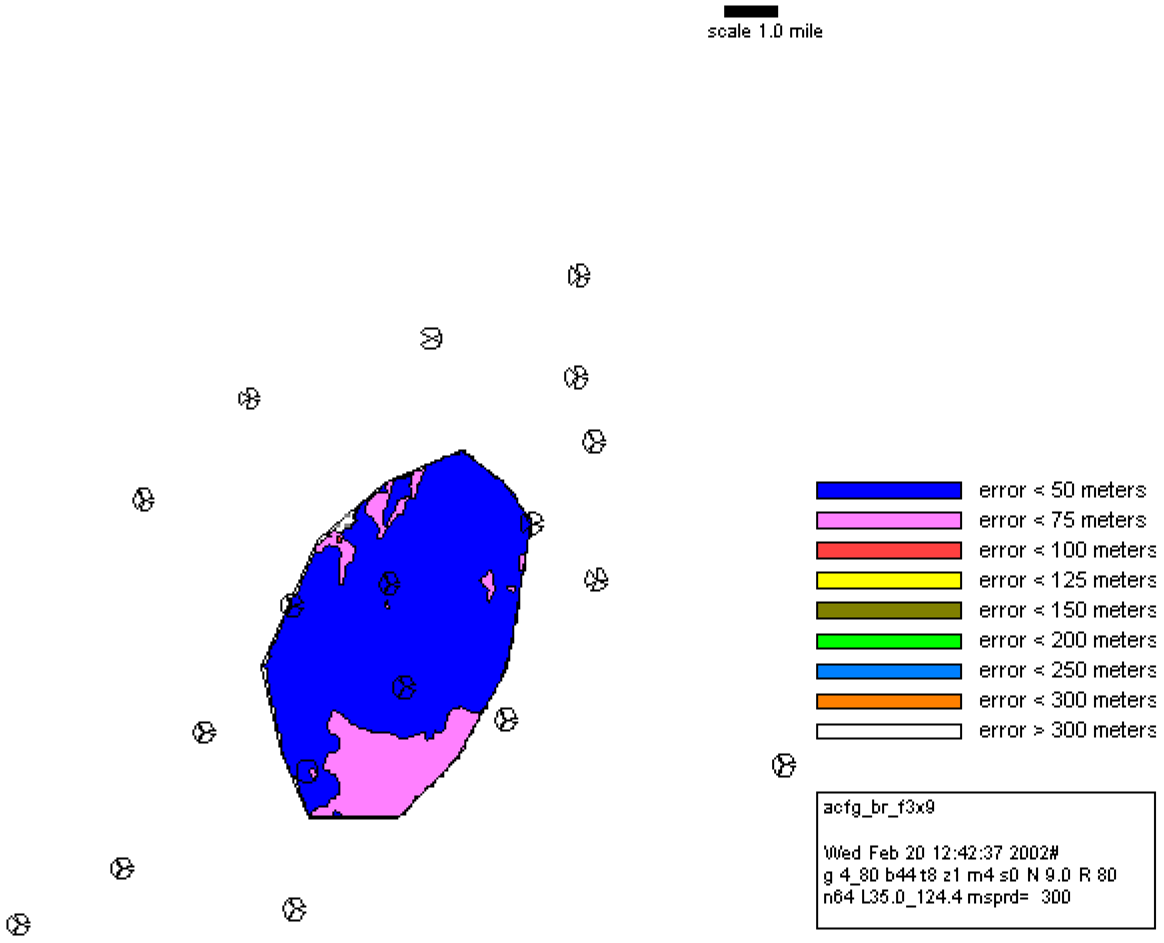


Figure 10: Wilmington 850 MHz GSM Performance (100% LMU Density)



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

Figure 11: Wilmington 850 MHz GPRS 80 Burst Performance (100% LMU Density)

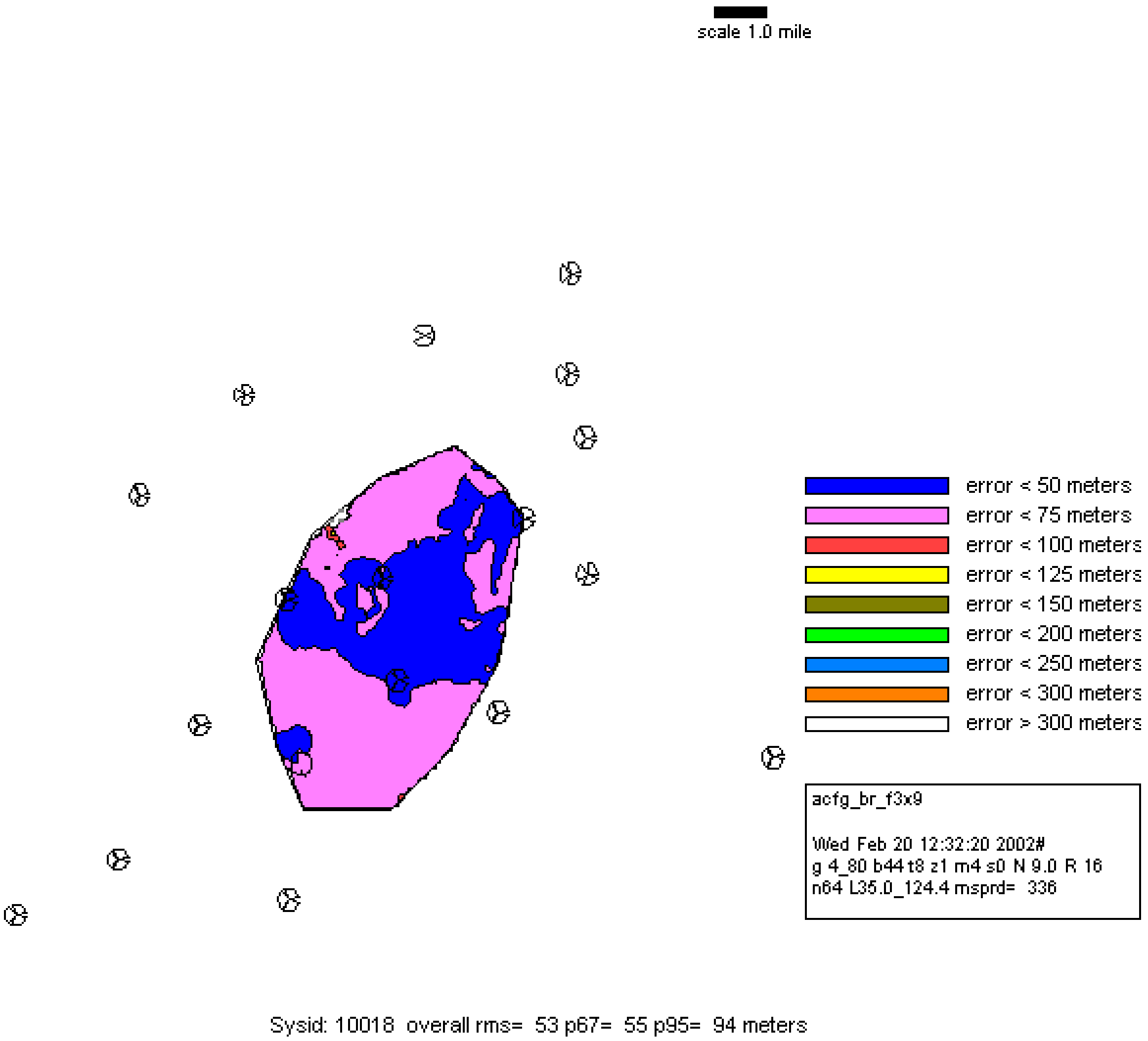


Figure 12: Wilmington 850 MHz GPRS 16 Burst Performance (100% LMU Density)

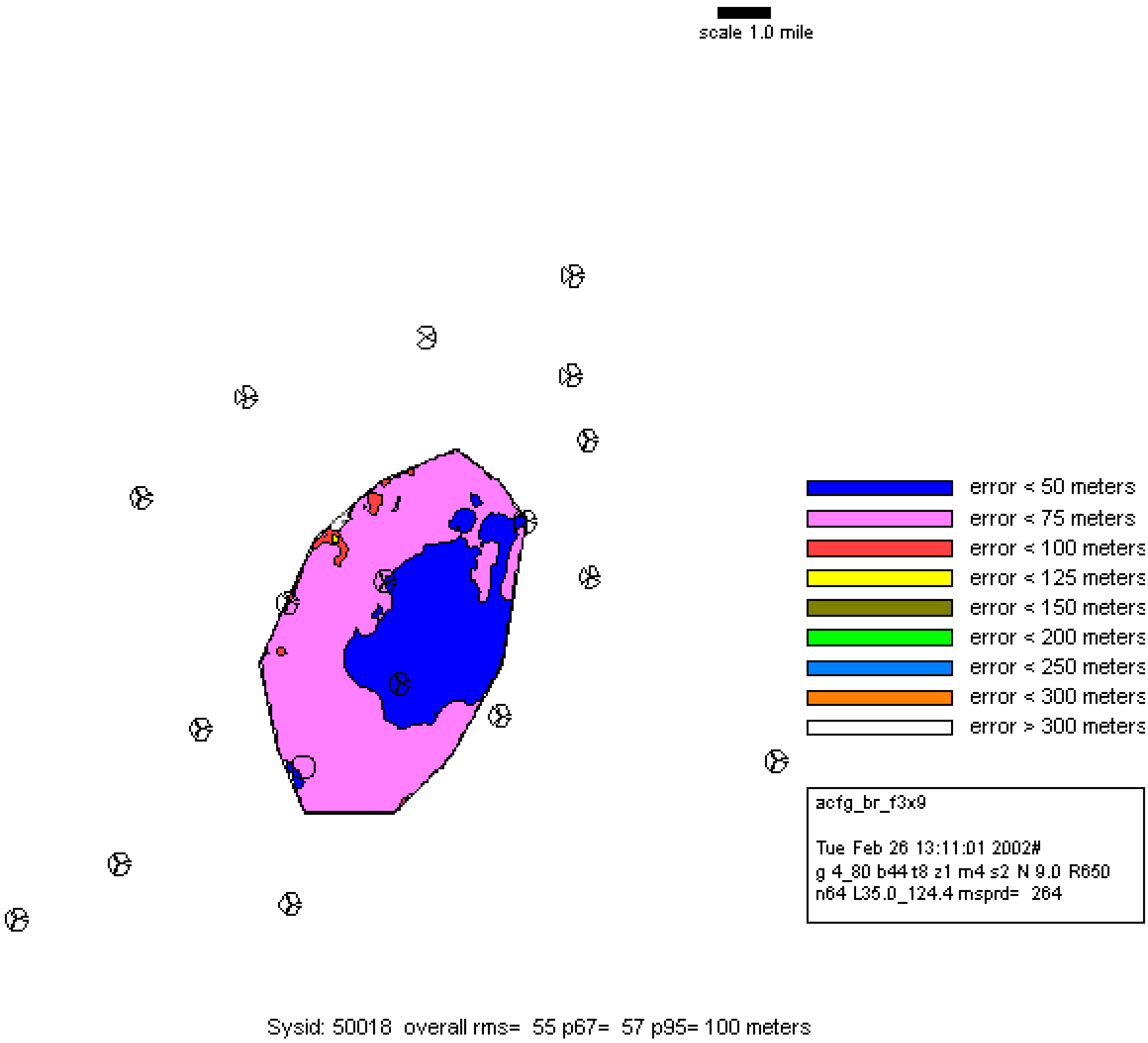


Figure 13: Wilmington 850 MHz GSM Performance (50% LMU Density)

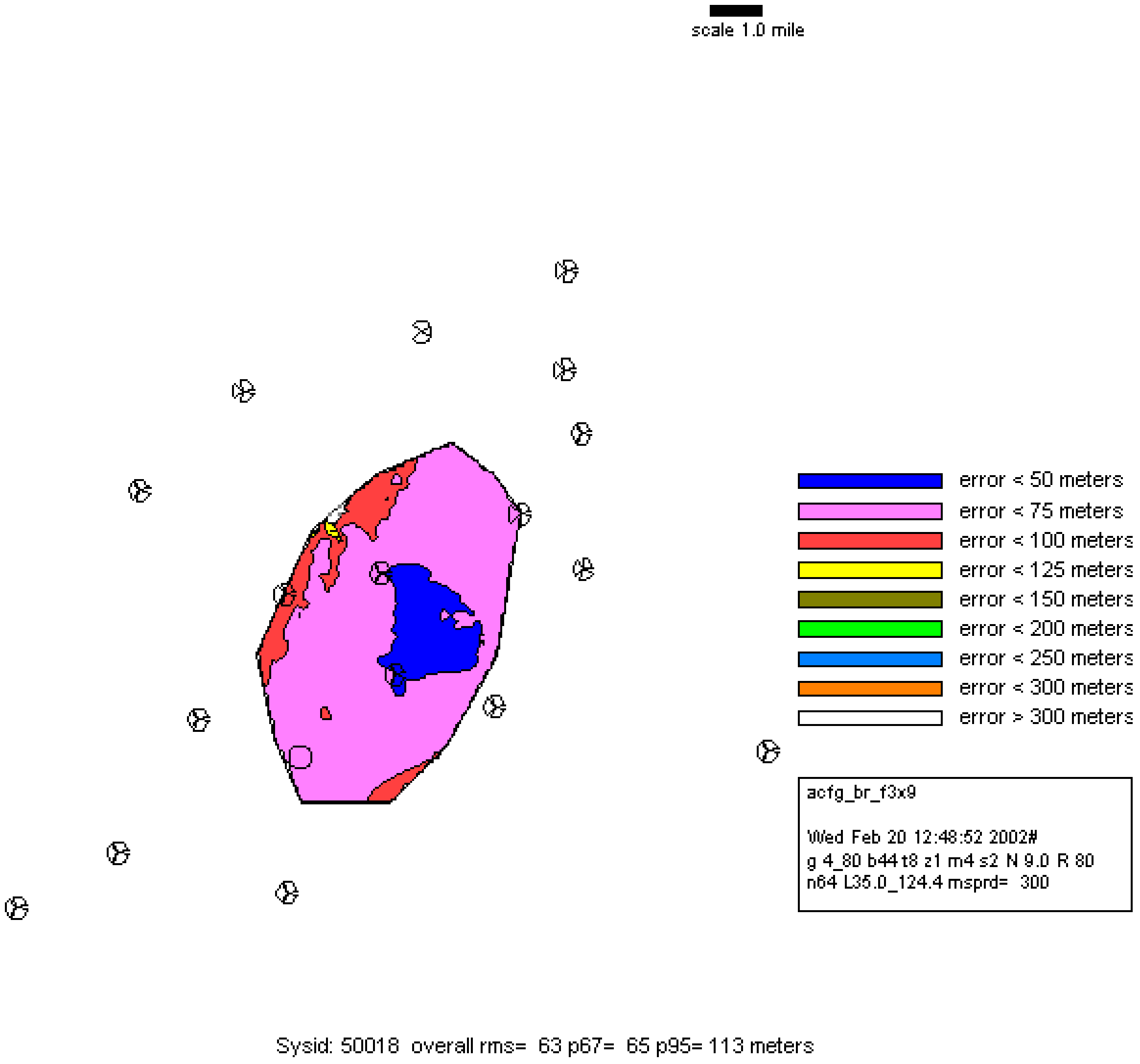


Figure 14: Wilmington 850 MHz GPRS 80 Burst Performance (50% LMU Density)

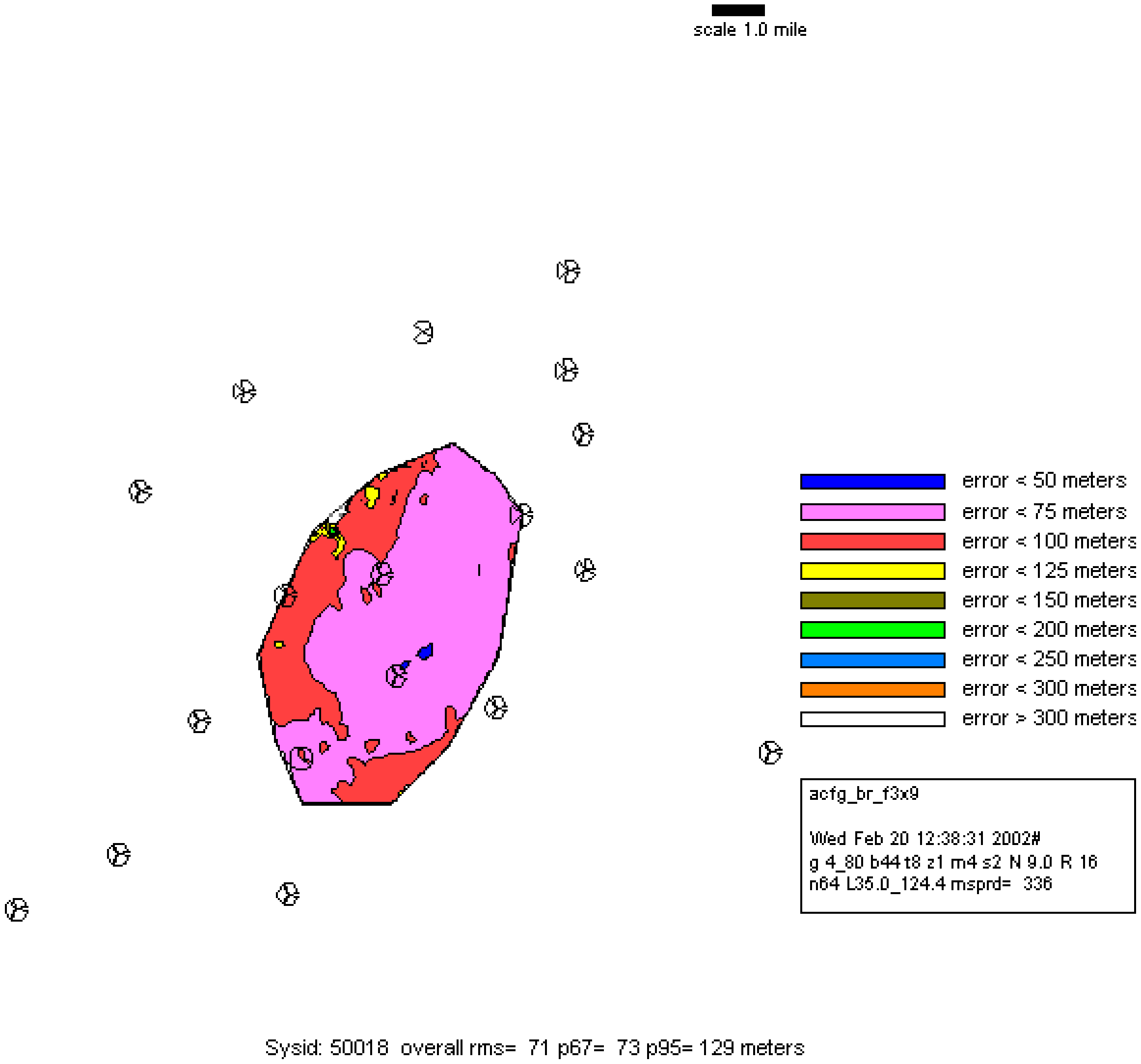


Figure 15: Wilmington 850 MHz GPRS 16 Burst Performance (50% LMU Density)

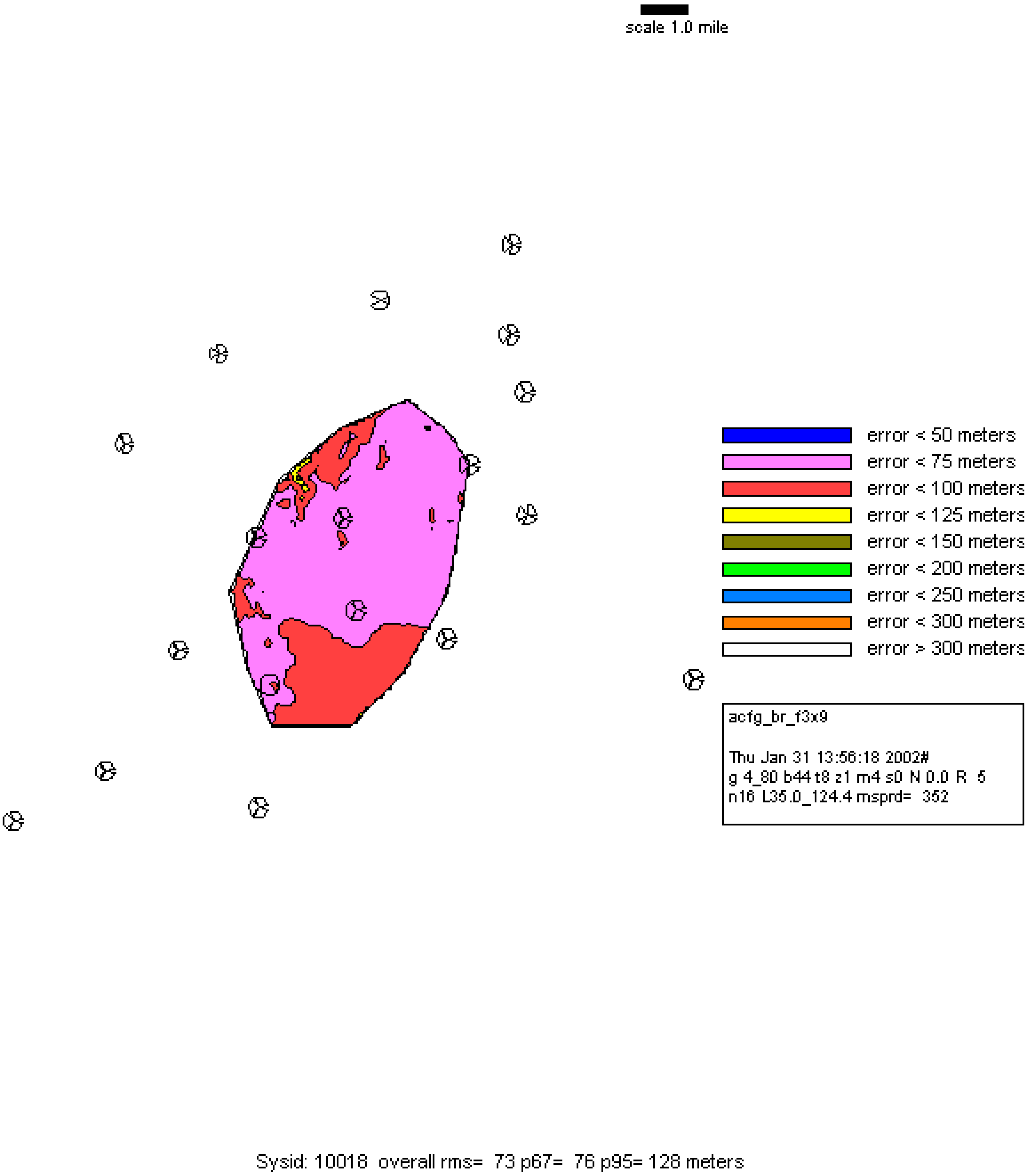


Figure 16: Wilmington 850 MHz E-OTD Performance

Houston Analysis

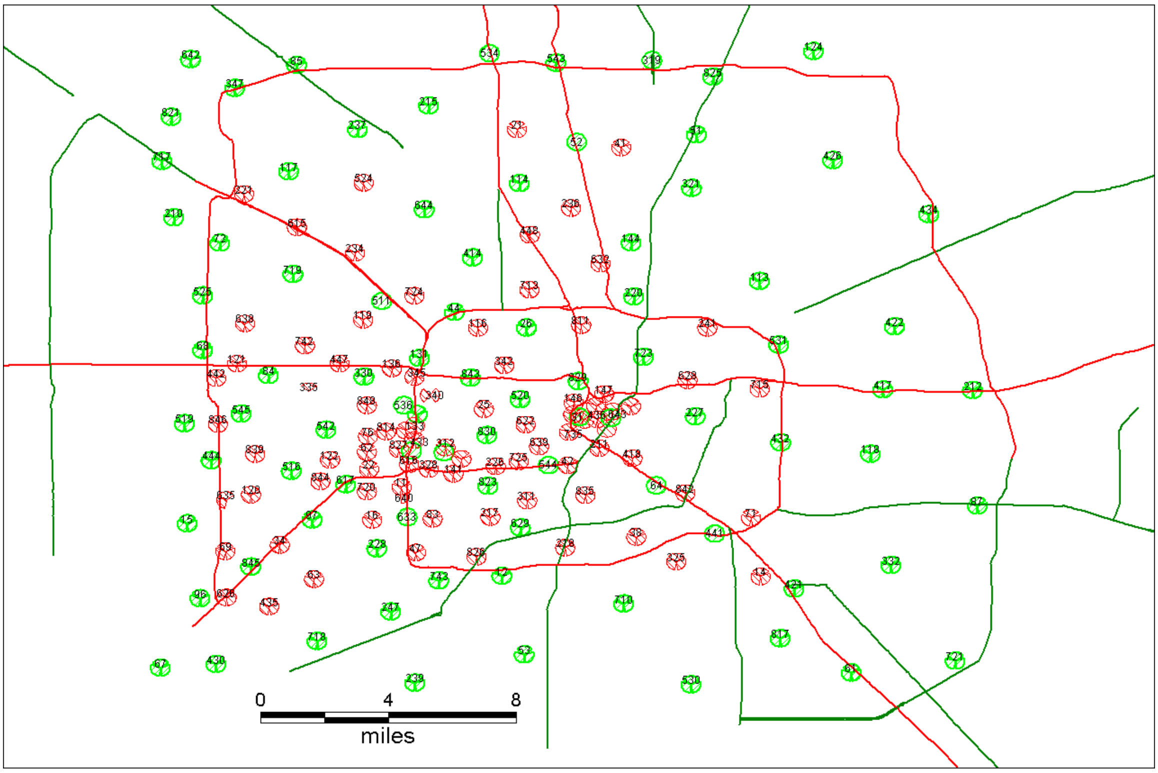
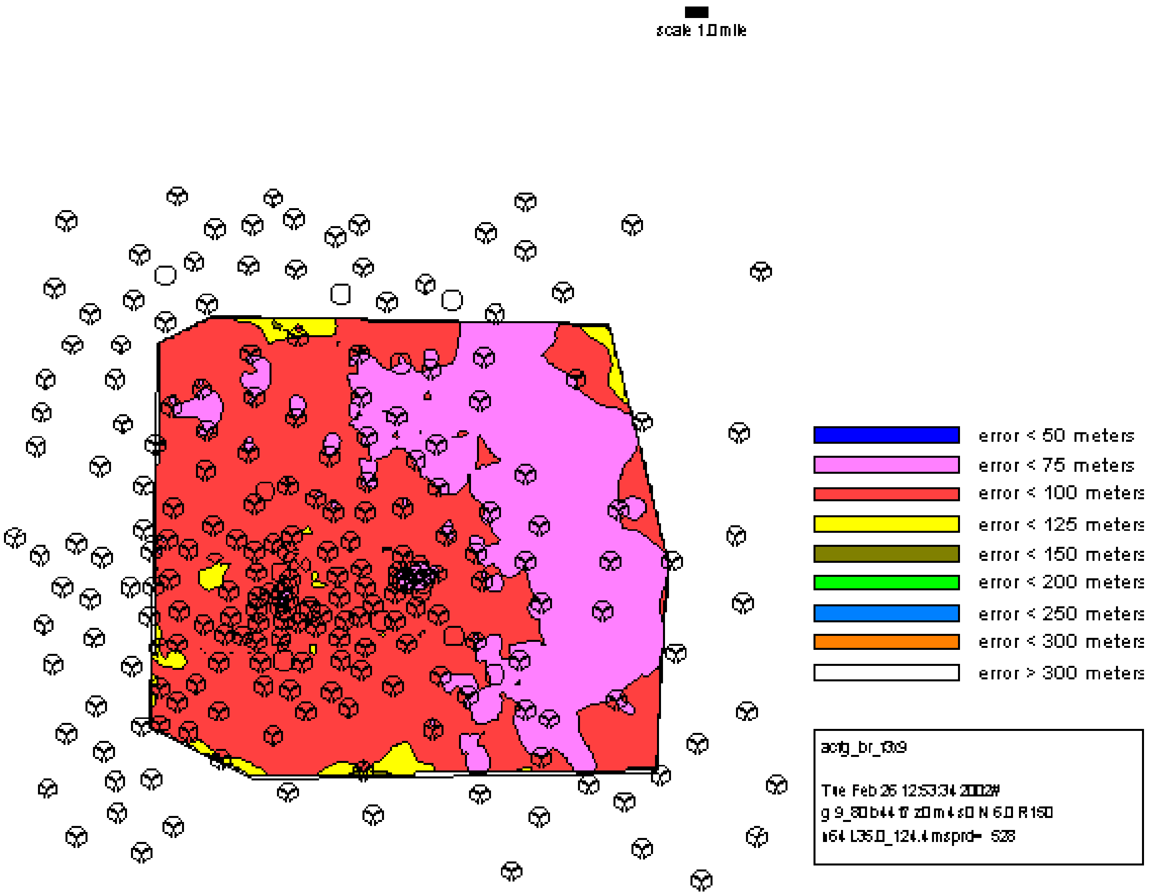


Figure 17: Houston 850 MHz AMPS/TDMA Network



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

Figure 18: Houston 850 MHz TDMA Performance

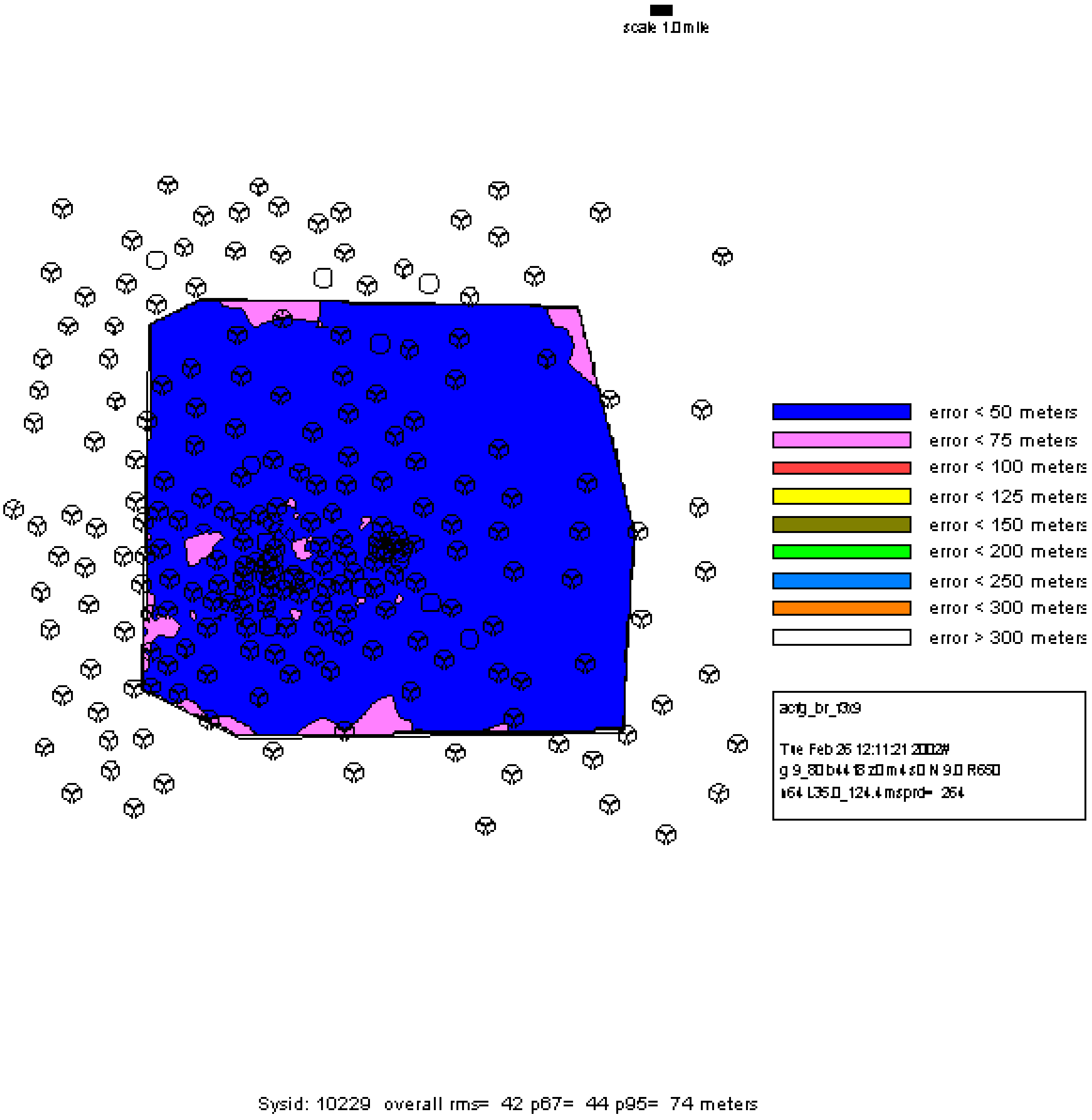


Figure 19: Houston 850 MHz GSM Performance (100% LMU Density)

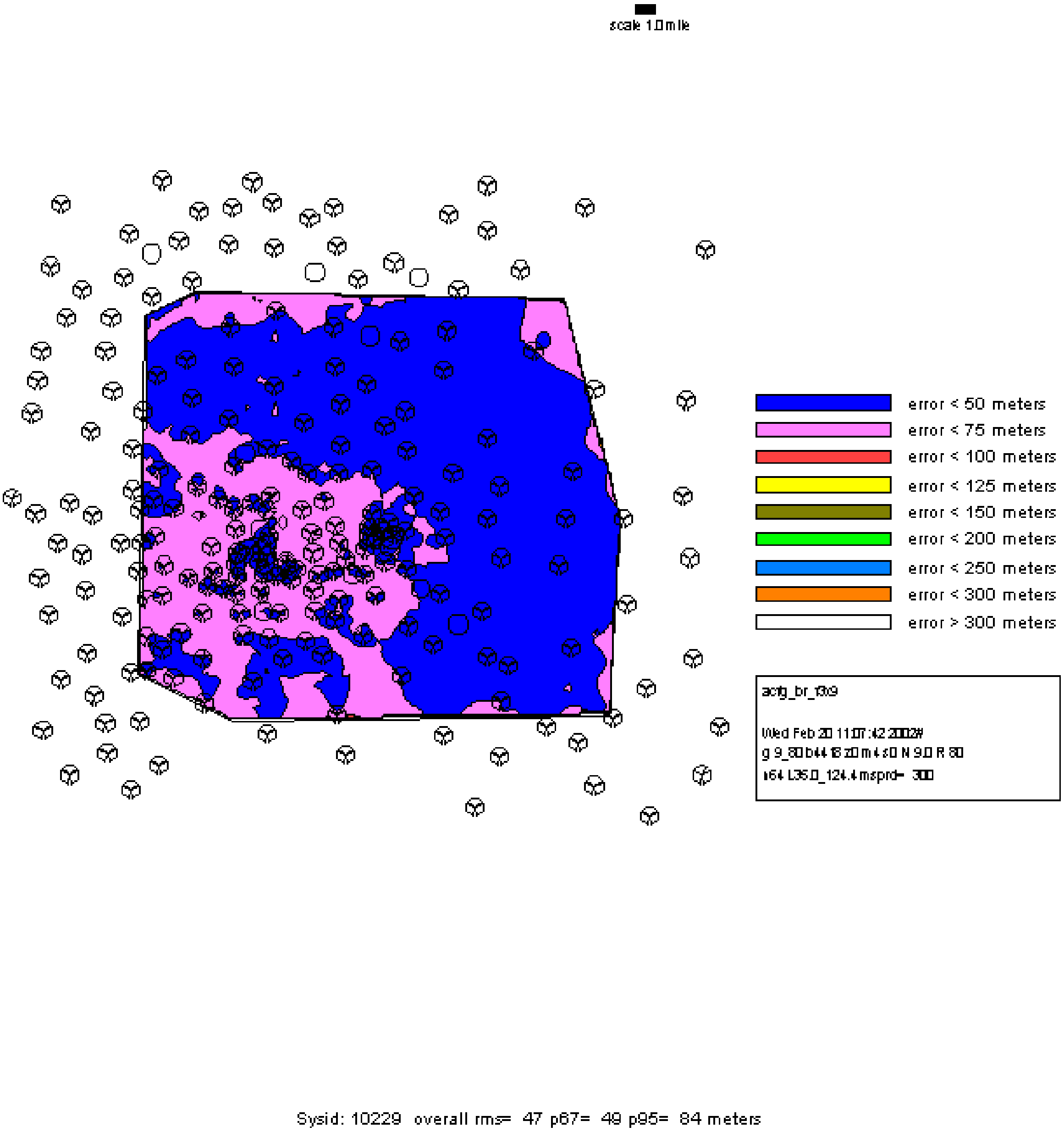


Figure 20: Houston 850 MHz GPRS 80 Burst Performance (100% LMU Density)

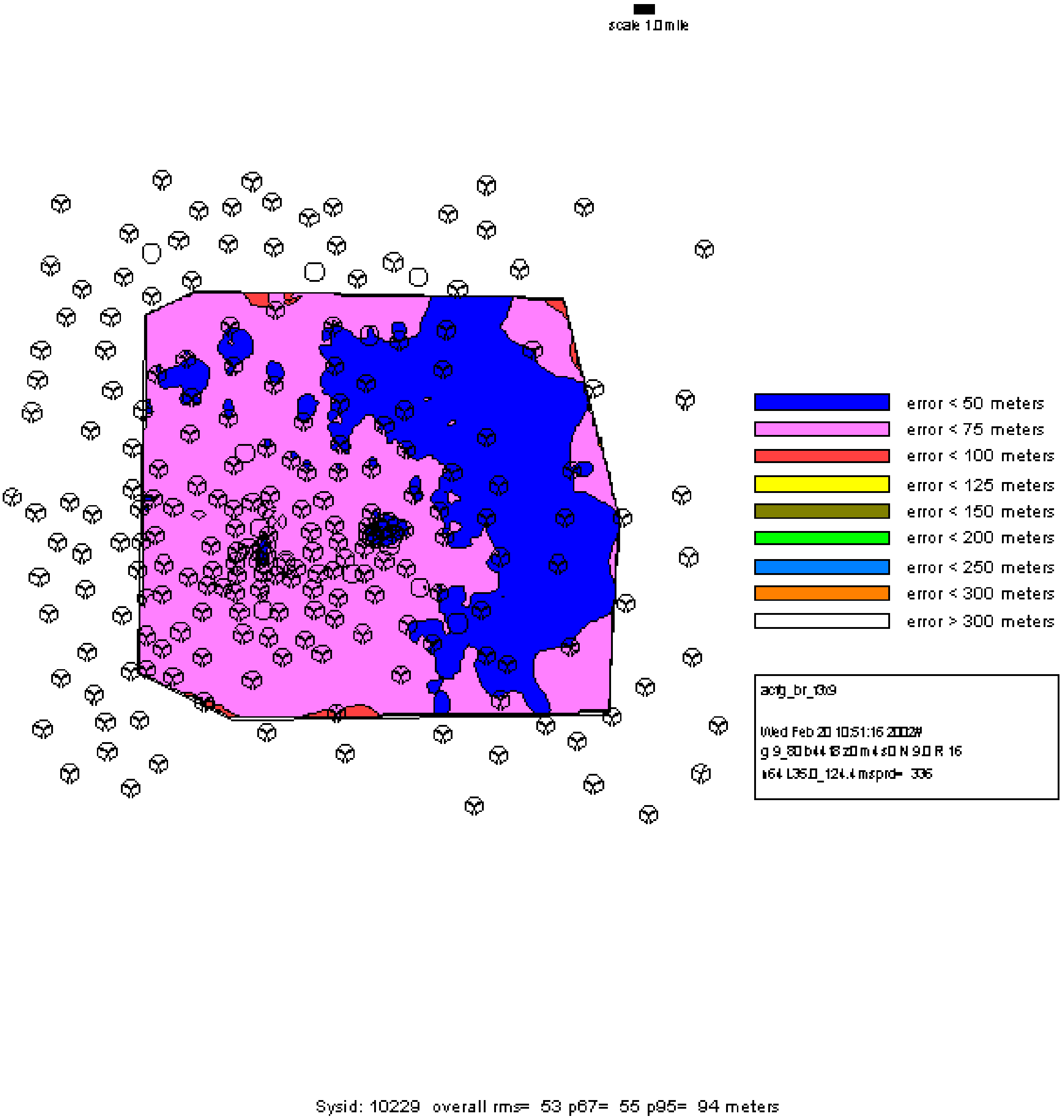


Figure 21: Houston 850 MHz GPRS 16 Burst Performance (100% LMU Density)

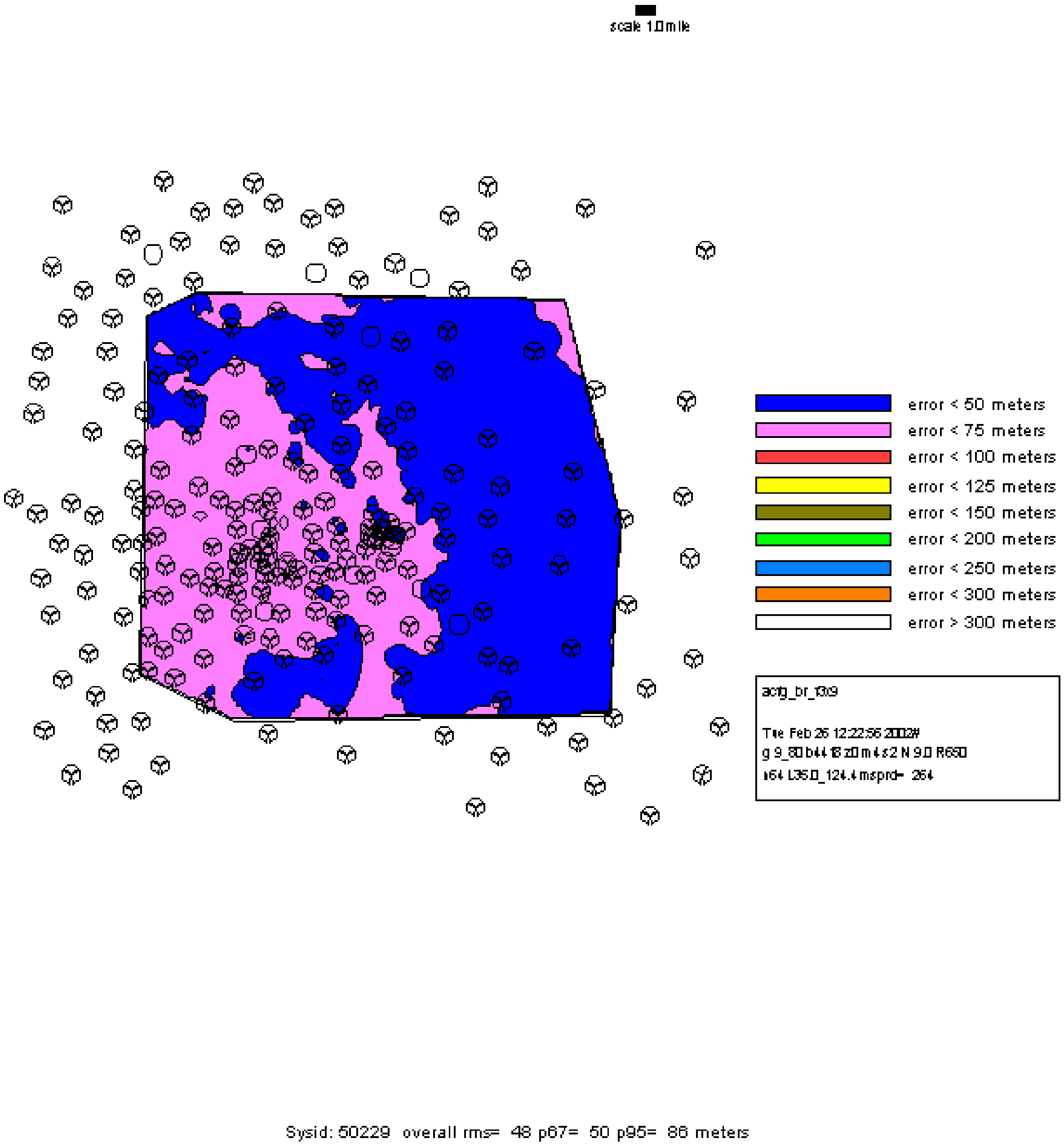


Figure 22: Houston 850 MHz GSM Performance (50% LMU Density)

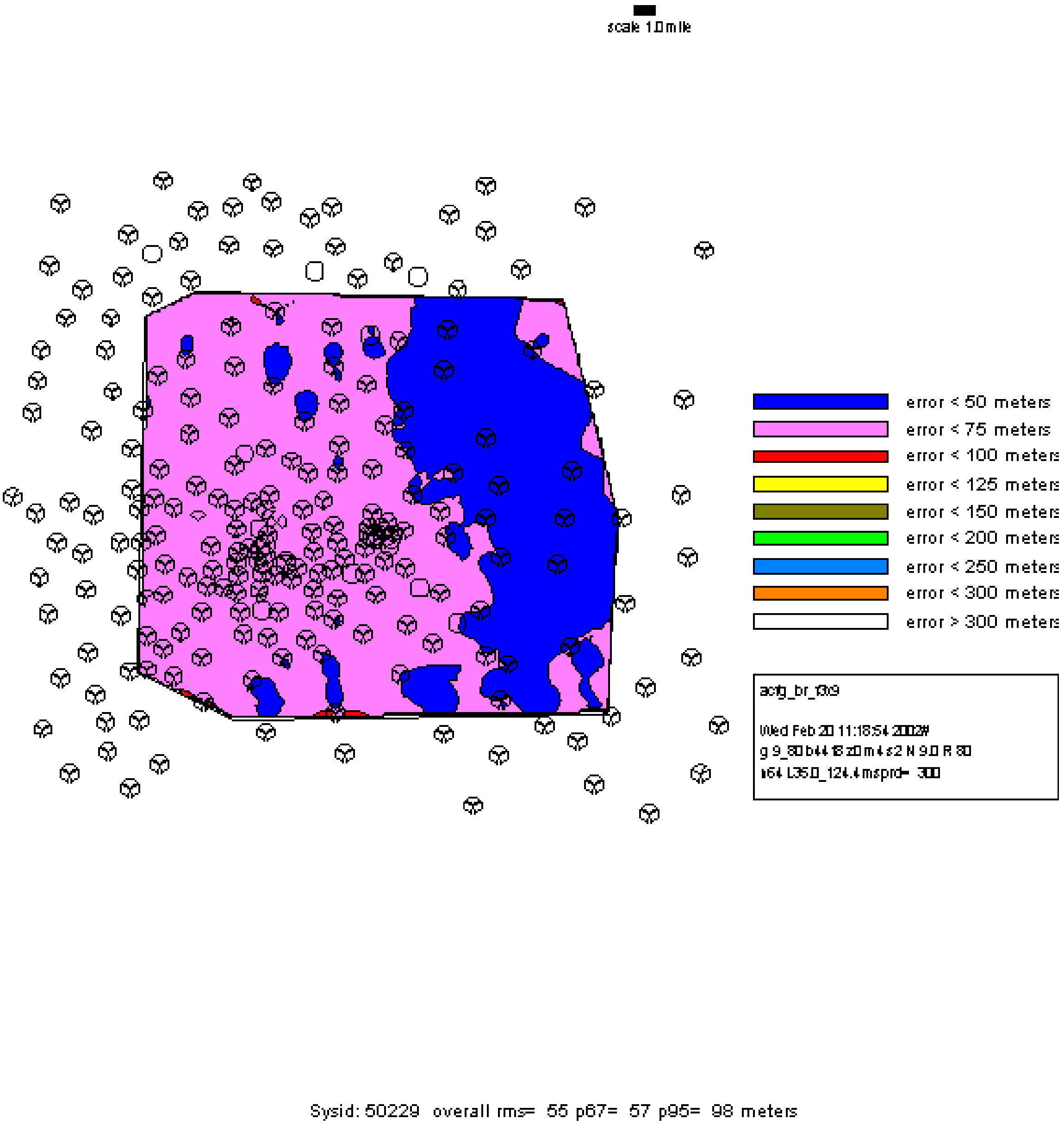


Figure 23: Houston 850 MHz GPRS 80 Burst Performance (50% LMU Density)

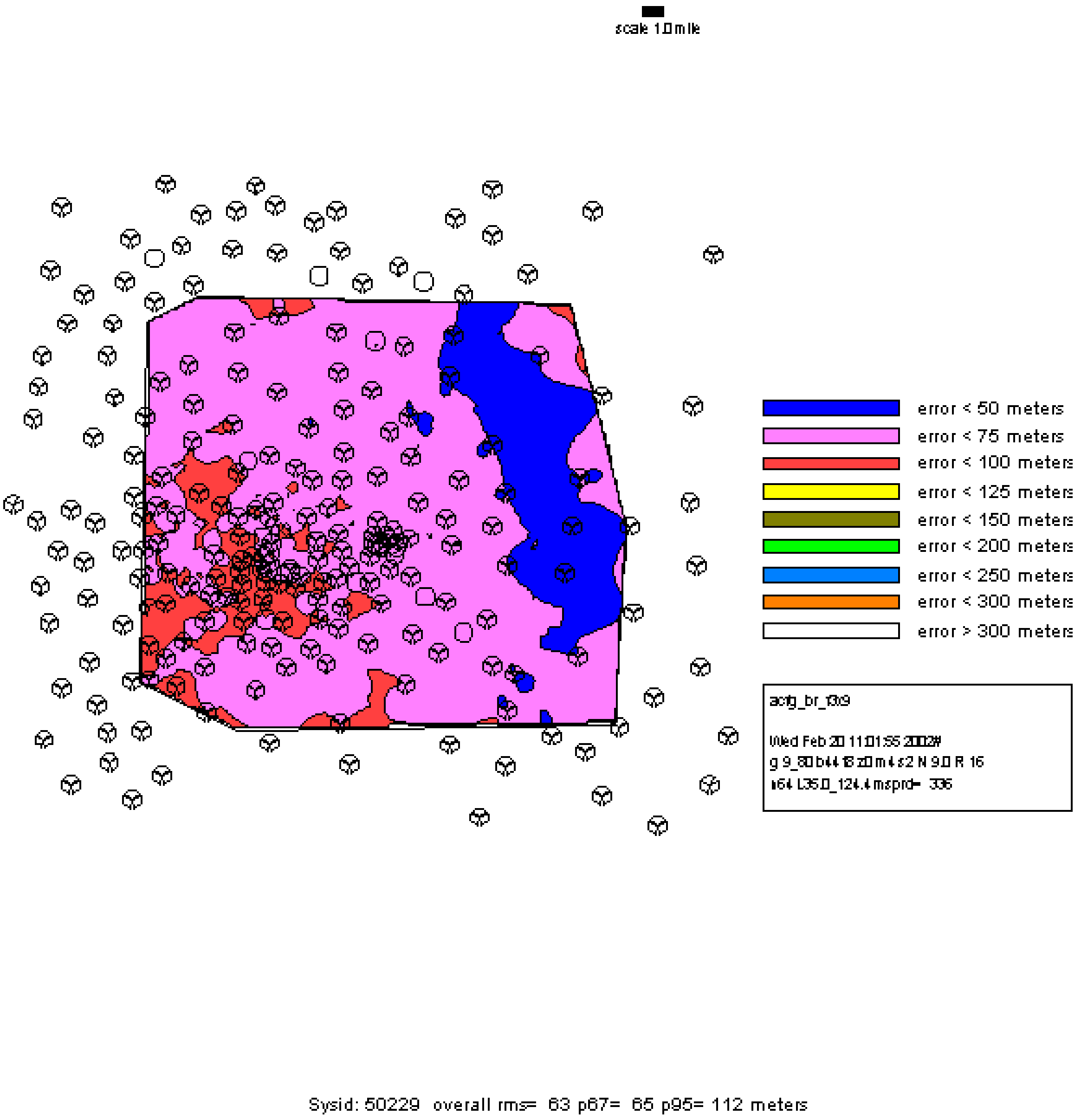


Figure 24: Houston 850 MHz GPRS 16 Burst Performance (50% LMU Density)

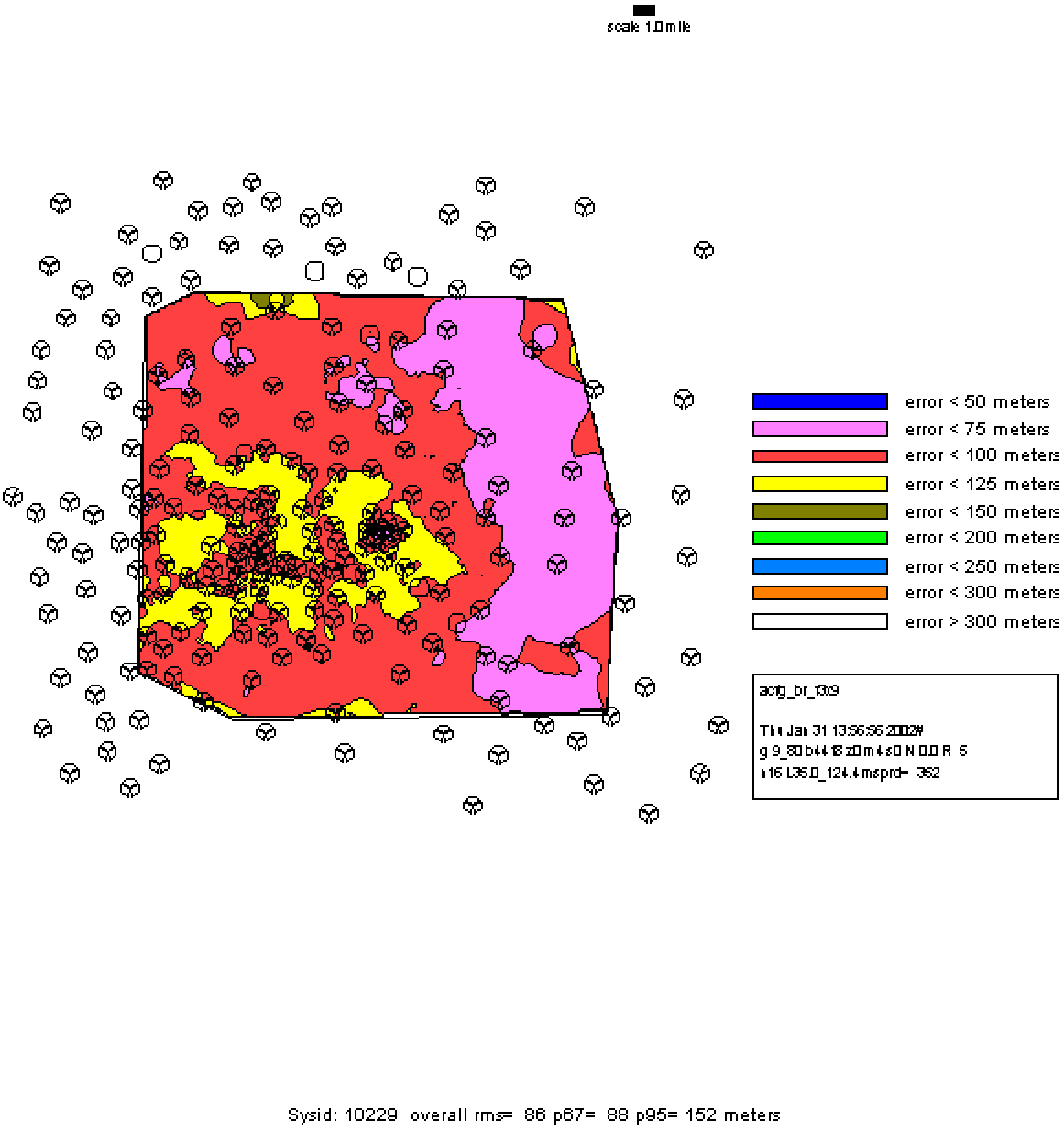


Figure 25: Houston 850 MHz E-OTD Performance

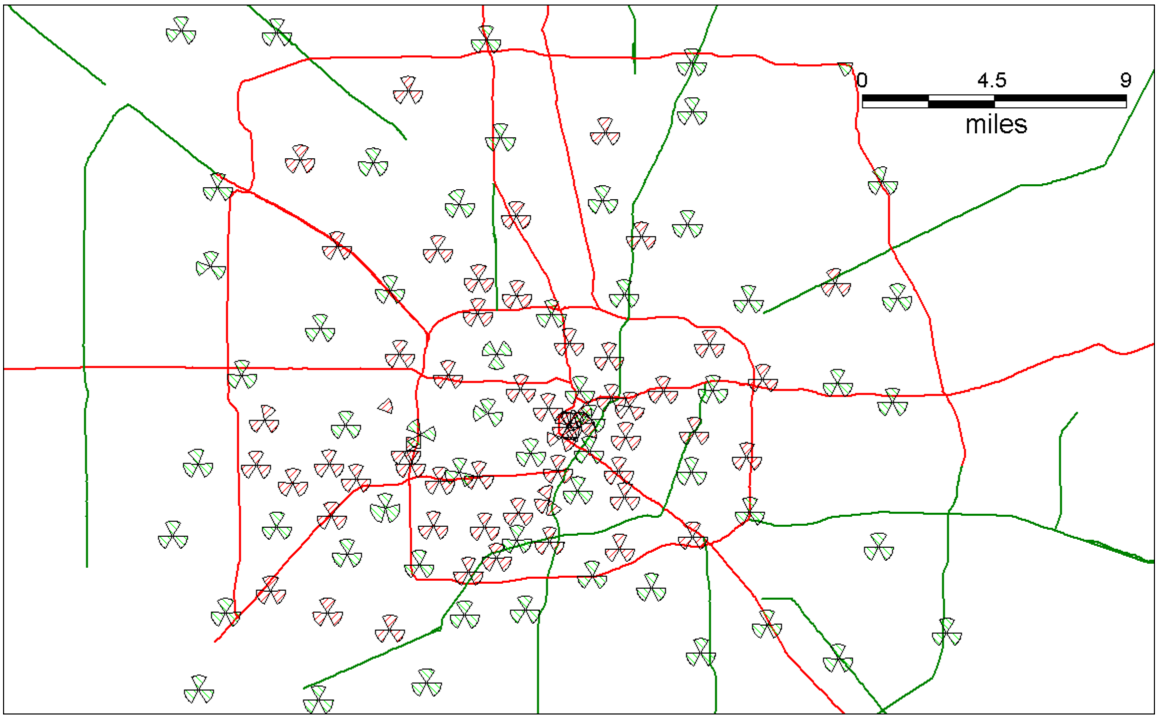


Figure 26: Houston 1900 MHz GSM Network

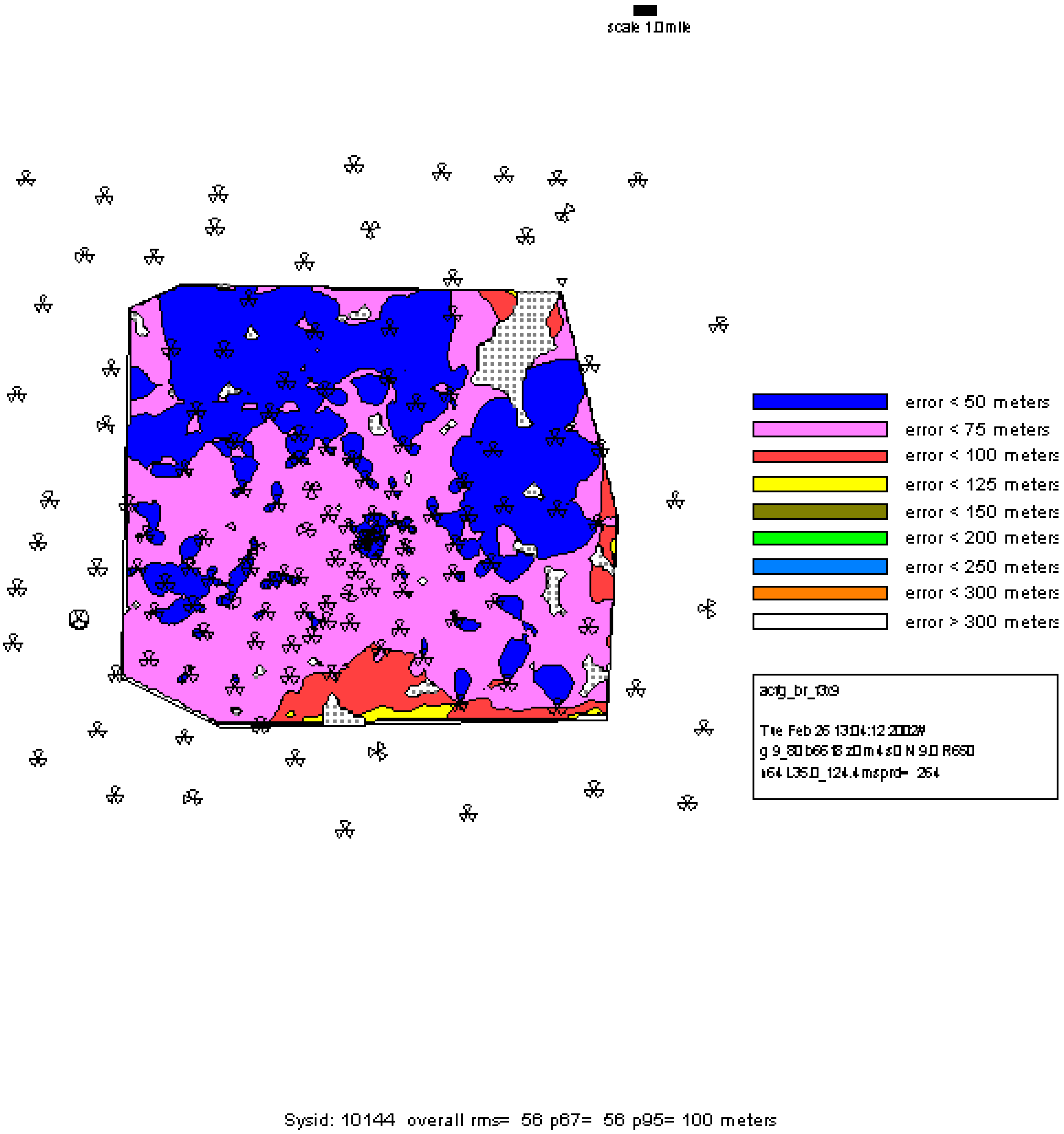


Figure 27: Houston 1900 MHz GSM Performance (100% LMU Density)

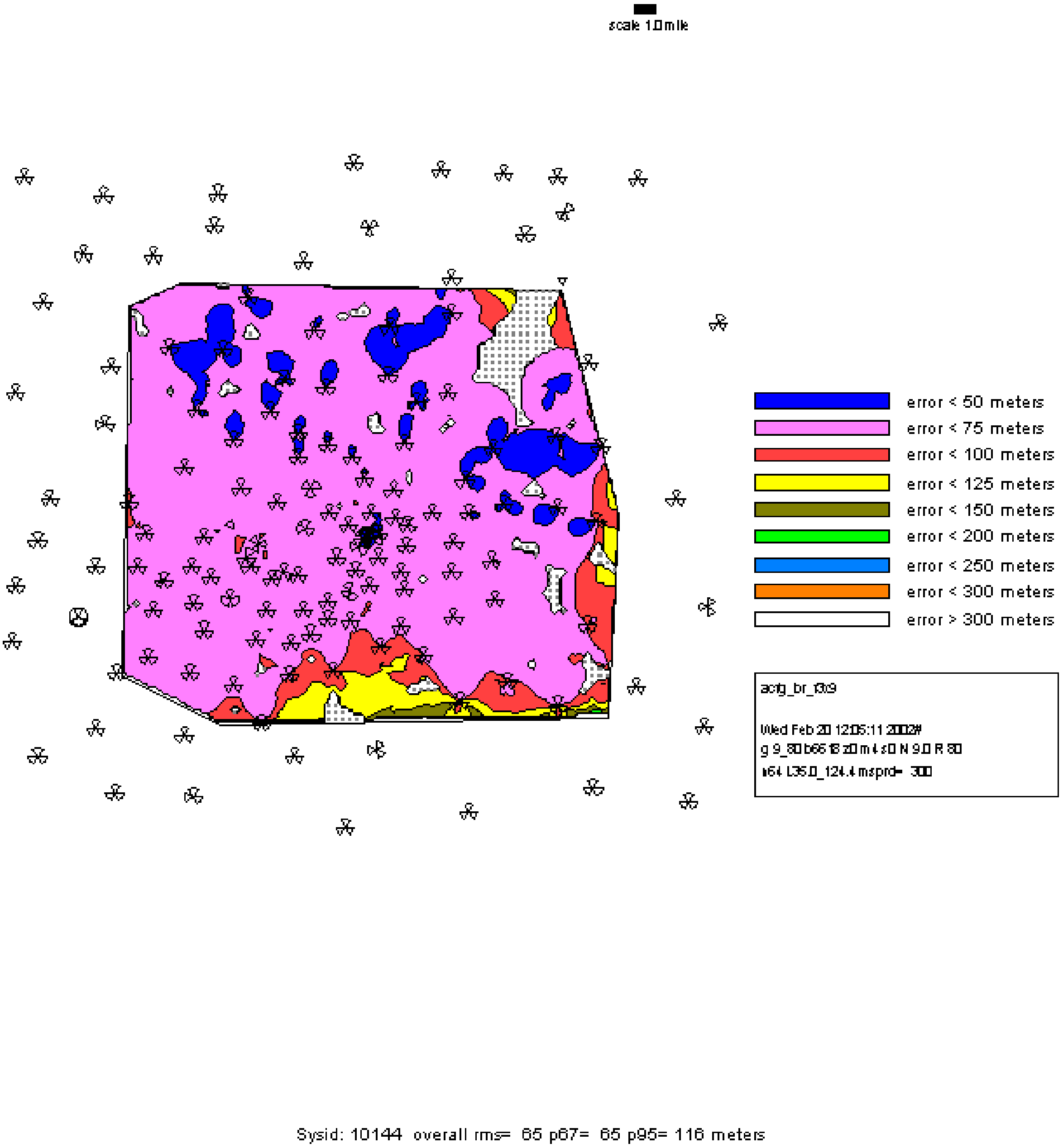
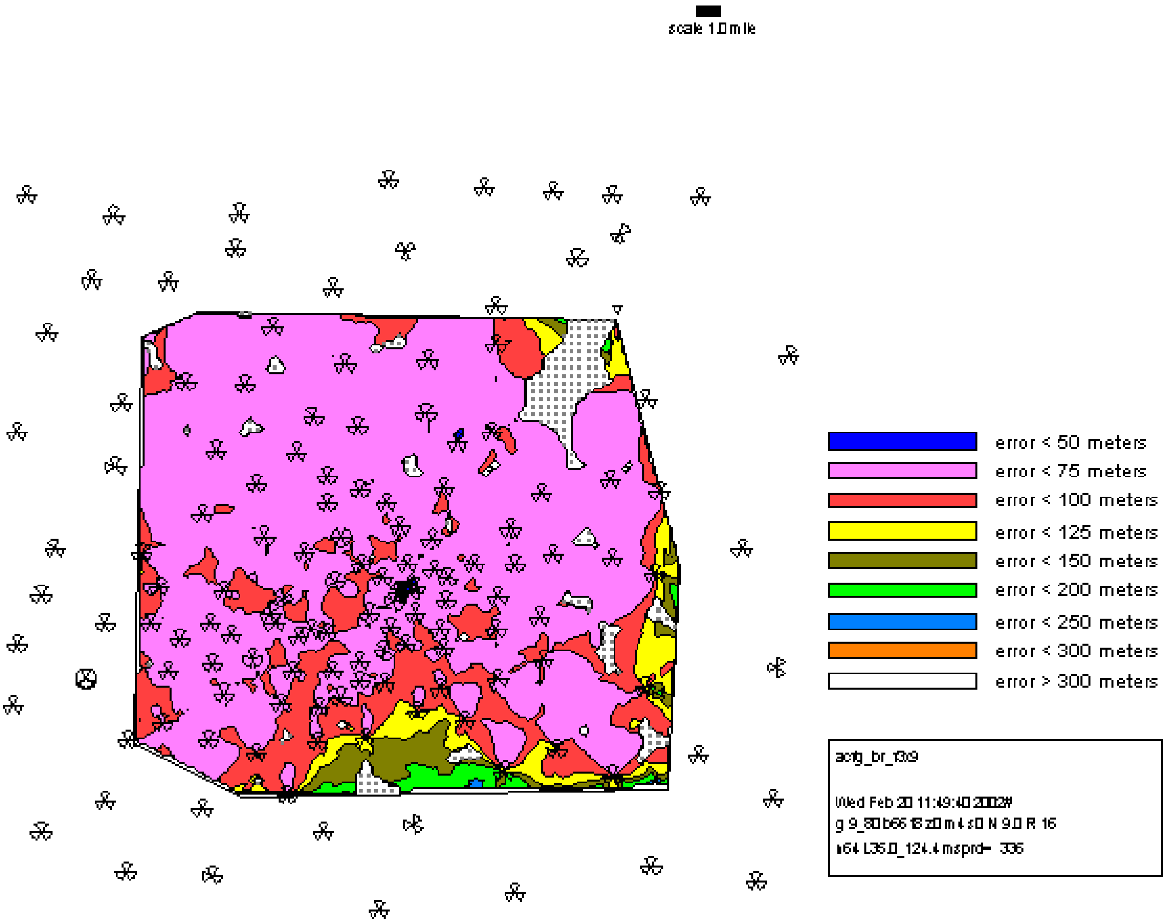
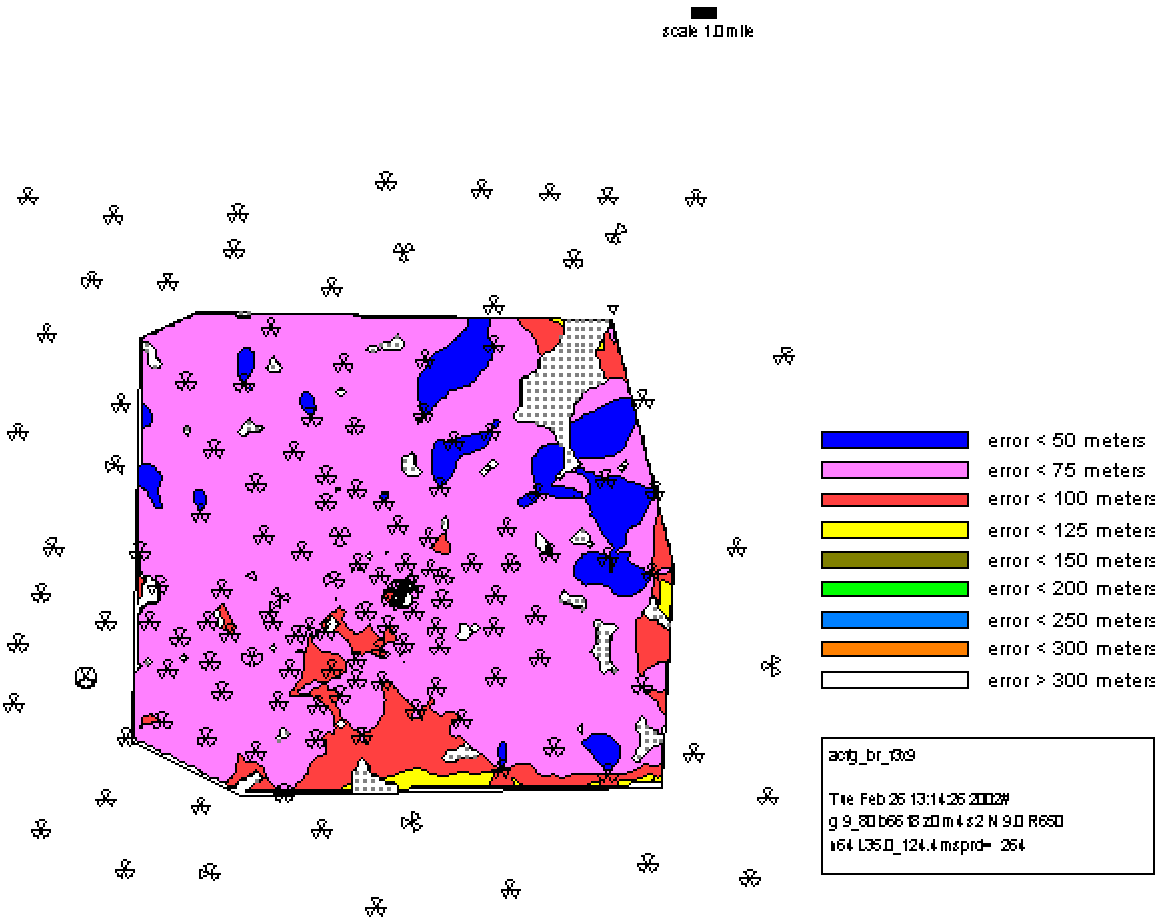


Figure 28: Houston 1900 MHz GPRS 80 Burst Performance (100% LMU Density)



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

Figure 29: Houston 1900 MHz GPRS 16 Burst Performance (100% LMU Density)



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

Figure 30: Houston 1900 MHz GSM Performance (50% LMU Density)

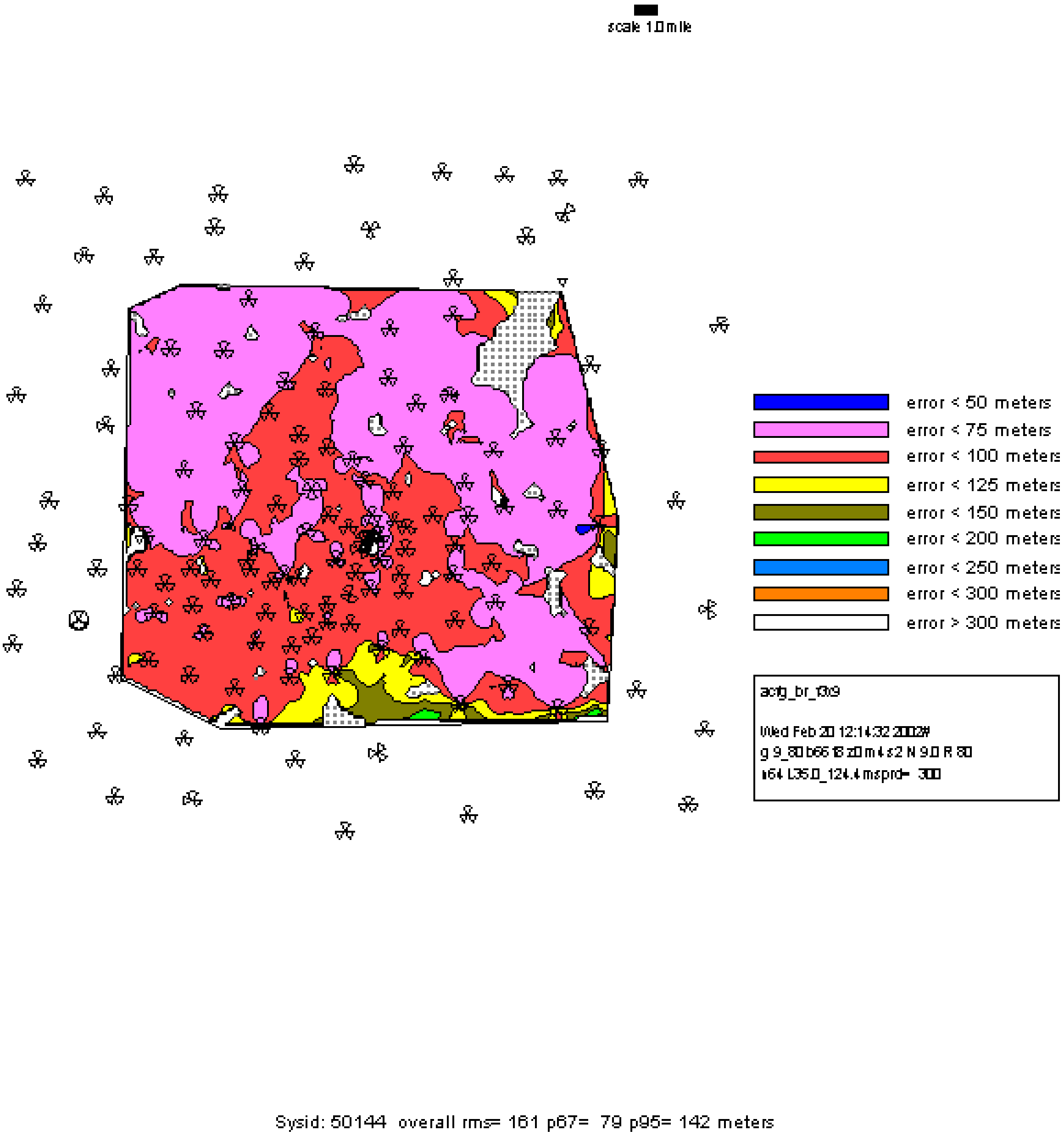


Figure 31: Houston 1900 MHz GPRS 80 Burst Performance (50% LMU Density)

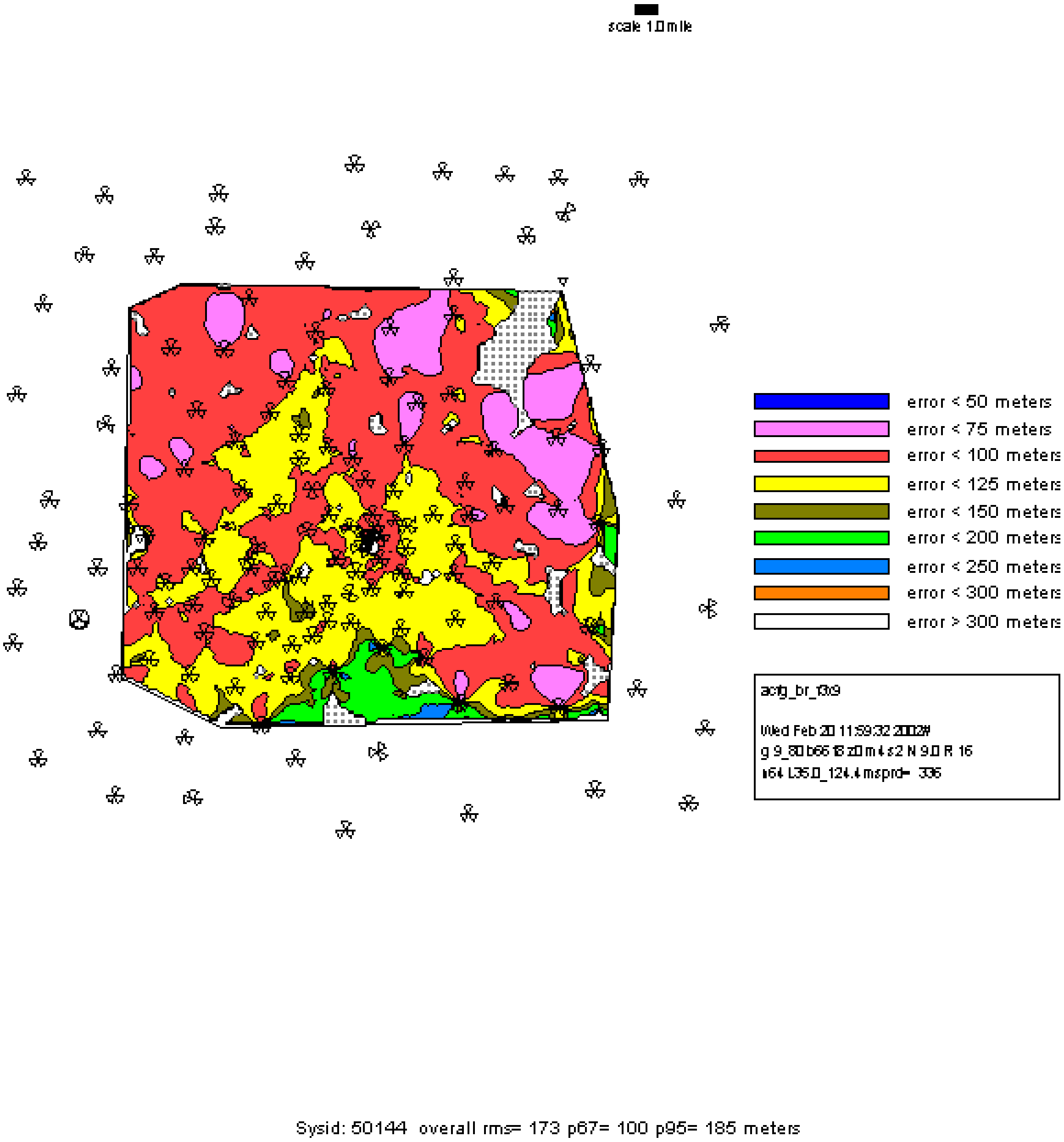


Figure 32: Houston 1900 MHz GPRS 16 Burst Performance (50% LMU Density)

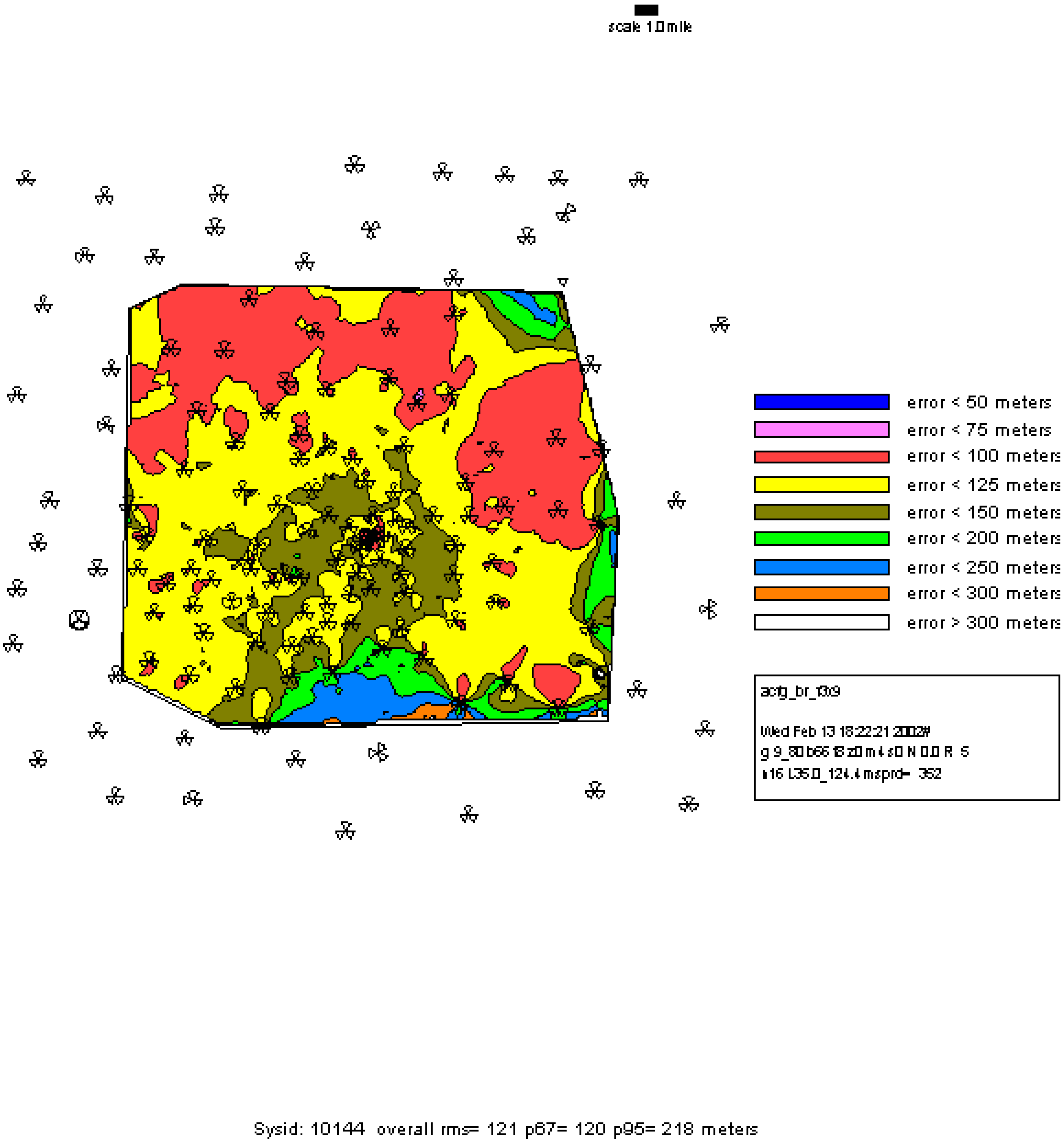


Figure 33: Houston 1900 MHz E-OTD Performance

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

Determining location by measurement of radio signals is a well-studied branch of physics and electrical engineering, with obvious applications in military and civilian realms. These location techniques have been applied to cellular radio systems to enable emergency and commercial location-based services for cellular system users. While the scale and complexity of cellular systems present unique technical challenges, the fundamental physics remains unchanged. The drivers of location accuracy are: signal integration time, signal bandwidth, signal-to-noise ratio of the received signal, receiver/transmitter geometry, ability to resolve multi-path, and the number of transmit/receive stations.

Three major classes of location technology have been proposed for standardization in GSM and UMTS networks: handset based measurements of satellite signals (A-GPS), handset measurement of base station signals (E-OTD/OTDOA), and base station-based measurements of handset transmitted signals (U-TDOA). Each technology has its inherent strengths and weakness from both a performance and complexity perspective.

	Base Station Measurements of MS (U-TDOA)	**MS Measurements of Base Stations (E-OTD)**	**MS Measurements of Satellites (A-GPS)**
Signal bandwidth	***200 KHz plus frequency hopping***	Limited to 200 KHz	Very Good ~1 MHz
Signal to Noise Ratio	Good	Good	Poor, Limited by satellite power constraints
Integration Time	Excellent, measurements of mobile stations made in parallel at 10 to 30 LMUs	Measurements of base stations (3 to 8) must be made sequentially	Typically limited to 1 second

The complex interaction between these three factors does not permit a simple qualitative analysis. However, we can use mathematical analysis to estimate the limits of performance of a location solution.

A.4.1 Location Accuracy

Location accuracy with any estimation method is a function of the accuracy of the TDOA measurements, the number of signal measurements, and the geometry of the transmitters or receivers.

The location error is approximated by:

$$\text{Location rms} = \text{TDOA}_{\text{rms}}\, N^{-1/2}\, \text{GDOP}_c$$

where N = number of sites (valid only for N>3)

$GDOP_c$ = the geometric dilution of precision (GDOP) relative to that at the center of a circular N-station configuration.

The accuracy of individual TDOA measurements is a function of the signal-to-noise ratio combined with integration time, signal bandwidth, the performance of super-resolution algorithms to resolve the multi-path, and the timing stability of the measuring devices.

A.4.2 SNR and Integration Time

The three major classes of location technology all use cross-correlation techniques to compute time delay measurements. A signal received at a receive station is cross-correlated against a reference signal. The sensitivity and accuracy of the correlation function is a directly related to the number of signal samples over which the correlation function integrates. The effective signal-to-noise ratio after taking into account the processing gain of the correlation function is referred to as the integrated SNR. The integrated SNR of the received signal ultimately determines if the signal can be detected by a receive station and the resulting accuracy of the time delay measurement

A.4.2.1 E-OTD

The signal-to-noise ratio of the signal received at the MS from the serving site is very high across the entire coverage area, usually high enough to provide service within buildings. The signal-to-noise ratio of the signal received at the MS from surrounding sites varies as a function of the distance from the surrounding sites and the propagation environment. The integration time is limited to only a few bursts because the MS can only listen to one signal at a time. This short integration time provides only 20 dB of processing gain, making it difficult for the MS to detect highly attenuated signals from distant or blocked sites.

A.4.2.2 A-GPS

GPS has very poor signal-to-noise ratio. A standard GPS receiver having an open view to the sky can typically detect the satellite signals and perform a location with an integration time of 10 milliseconds. A-GPS provides assistance data so that the MS is not required to demodulate satellite data, but only detect satellite signals. Using this technique, and increasing the integration time by 20 dB to 1 second, 20 dB of margin is provided to account for the smaller antenna, loss from placing the antenna near the body, and other losses due to blockage. The 20 dB of increased margin is not sufficient for in-building scenarios or dense urban environments. The increased margin is likely sufficient for most outdoor suburban and rural scenarios.

A.4.2.3 U-TDOA

The signal-to-noise ratio of the signal received at the serving cell site is very high across the entire coverage area, usually high enough to provide service within buildings. The signal-to-noise ratio of the signal received at surrounding cell sites varies as a function of the distance from the surrounding sites and the propagation environment. Because many LMUs simultaneously collect and process signals, a U-TDOA system can perform integration over hundreds of bursts, providing 40 dB of processing gain. Signals that have been attenuated 40 dB more than the signals at the serving cell site can be detected in a U-TDOA system.

A.4.3 Signal Bandwidth

Signal bandwidth determines the amount of multi-path that will naturally be resolved when performing correlation. As the signal bandwidth increases the resolution of the correlation function increases. This allows the correlation function to differentiate more components of the received signal and filter out more of the delayed multi-path components that are a dominant source of measurement error.

A.4.3.1 E-OTD

E-OTD utilizes the forward (base station transmit) control channels that are not permitted to frequency hop. Therefore the signal bandwidth for E-OTD is 200 kHz. The resulting multi-path resolution capability is 1/200 kHz or 5 microseconds, the equivalent of 1.5 km. Therefore multi-path components with differing propagation lengths less than 1.5 km will not be resolved.

A.4.3.2 A-GPS

Due to the spread spectrum characteristics of the GPS signals, the calculation of the effective signal bandwidth is not straightforward. The effective signal bandwidth is estimated to be approximately equal to the chip rate of the civilian C/A signal, or 1.023 million chips/sec. This results in an estimated effective signal bandwidth of 1 MHz.

However, since most multi-path signals from the satellites are too weak to detect and resolve, the multi-path resolution characteristics of the C/A GPS signal are not relevant to location accuracy in cellular systems.

A.4.3.3 U-TDOA

While U-TDOA utilizes the same 200 kHz signal as E-OTD, U-TDOA makes use of the uplink (MS transmit) control and traffic channels. These channels are typically frequency hopped. The hopping increases the effective signal bandwidth producing a 10% to 50% improvement in multi-path mitigation over a non-hopped GSM signal.

A.4.4 Super-resolution

Super-resolution algorithms allow resolution of multi-path signals within the inverse bandwidth of the signal. Super-resolution algorithms are very processing-intensive and the performance depends upon the integrated SNR.

A.4.4.1 E-OTD

Super-resolution is possible on signals received from nearby base stations but the MS may be limited by processing capacity, making more sophisticated super-resolution algorithms complicated to implement.

A.4.4.2 A-GPS

Most multi-path signals from the satellites would be too weak to detect and resolve.

A.4.4.3 U-TDOA

Because many LMUs simultaneously participate in the location processing, very long integration times are achieved, providing a high integrated SNR. Also, a large amount of processing is available at each LMU, allowing the most sophisticated super-resolution algorithms to be applied to the TDOA measurements. Super-resolution techniques provide a 20-30% improvement in accuracy for GSM.

A.4.5 Timing Stability of the Receiver

Every nanosecond of timing error introduced into the measurement process contributes 0.3 meter of error into the resulting time delay measurement. Therefore, it is very important to minimize any timing error introduced by the receivers involved in the timing measurements.

A.4.5.1 E-OTD

The oscillator in a MS is required to have a stability of 0.1 PPM for GSM and GPRS. The MS achieves this using a combination of temperature compensation and base station transmit signal to discipline the oscillator. At 0.1 PPM, over a 10-second interval, when the MS is making timing measurements for a single location, the timing of the MS may drift up to 1 microsecond, which alone could cause a 300-m location error. To obtain high accuracy, the timing stability of the MS must be improved by a factor of 10 relative to the performance required for normal GSM and GPRS communication.

A.4.5.2 A-GPS

Because GPS receivers typically have multi-channel receivers and can measure the satellite signals simultaneously, the timing stability required to achieve good accuracy is readily achievable.

A.4.5.3 U-TDOA

The timing of the LMUs is disciplined by GPS and can maintain very good synchronization accuracy of 20 nanoseconds.

A.4.6 Number of Measurements

Location processing is a statistical process. Since the propagation and noise environment varies geographically and over time, the magnitude of time delay measurement error varies with receive/transmit station and time. As a result, location accuracy increases as the number of receive/transmit stations and the number of time delay measurements increases.

A.4.6.1 E-OTD

In an E-OTD system, the MS makes measurements of the base station signals one at a time. To provide a location in a reasonable period of time, the MS must look at a small set of base stations for a short duration and integrate over only known bit sequences for a limited period of time. The standards allow the MS to make measurements of a maximum of 16 signals, but because of the short integration time, the MS will likely detect signals from a smaller number of base stations. E-OTD trial results published by VoiceStream[1] indicate an average of 5.1 base station measurements per location.

A.4.6.2 A-GPS

In an outdoor, unblocked environment, a typical GPS receiver can detect signals from 8 satellites. Because of the low integrated SNR, A-GPS can have access to a much smaller number of sites in indoor and urban environments.

A.4.6.3 U-TDOA

Unlike the downlink channels in a cellular system where only a single base station transmit antenna and a single MS receive antenna are used, the uplink channels use diversity receive antennas. This, combined with the fact that a U-TDOA system has very long integration times, allows up to 50 antennas to participate in a single location.

A.4.7 Geometry

In all flavours of TDOA location systems, the geometric distribution of transmit/receive stations around the device being located has an effect on location accuracy. As the transmit/receive stations are distributed geometrically around the device the time delay measurement error contributions created by the propagation environment in any one particular direction from the device is minimized. Also, the overall uncertainty associated with the position estimate is minimized. This impact of geometry on location accuracy is quantified in the form of geometric dilution of precision (GDOP).

A.4.7.1 E-OTD

With dense cell site spacing, the GDOP of E-OTD should be very good. With sparse cell site spacing, the short integration time may not provide detection at a large enough set of sites, leading to significantly degraded GDOP and location accuracy.

A.4.7.2 A-GPS

If the MS has a clear view of the sky, the A-GPS system will have adequate GDOP to compute accurate locations. When some or most of the sky is blocked, such as in an urban environment or indoors, the GDOP of A-GPS can be very poor, even to the point that a location cannot be determined.

A.4.7.3 U-TDOA

Given any cell site distribution except a very rural highway environment (a.k.a. “string of pearls”), the long integration time available to U-TDOA LMUs will allow the MS signals to be detected at a large number of sites at great distances from the MS resulting in very good GDOP.

---

[1] VoiceStream FCC Filing of Houston E-OTD Trial Status, October 1, 2001

Table 5-3: Summary of Factors Impacting Location Accuracy (GSM/GPRS)

	Base Station Measurements of MS (U-TDOA)	MS Measurements of Base Stations (E-OTD)	MS Measurements of Satellites (A-GPS)
SNR and Integration Time	LMU detects signals 40 dB below serving site level	MS detects signals 20 dB below serving site level	20 dB additional processing gain provides margin above required SNR for unblocked operation
Signal bandwidth	200 KHz plus frequency hopping	200 KHz	~1 MHz
Multi-path Mitigation	Provides 30 % accuracy improvement	Lower integrated SNR and minimal processing power make super-resolution ineffective	Reflected spacecraft signals so weak they typically can not be detected
Timing Stability	20 nanoseconds	1 microsecond without special improvements to support E-OTD requirements.	N/A, measurements made simultaneously.
Number of Measurements	Typically 30-50 receive antennas	Typically 3 to 8 transmit antennas	8 satellites outdoor suburban and rural; Few satellites in urban and indoor environments - can preclude successful location
Receiver/Transmitter Geometry	Adequate in rural areas; Very good in suburban and urban areas	Adequate in rural areas; Very good in urban Areas	Very good in rural and suburban areas; Poor in urban and indoor areas.

A.5 Conclusion

From a location accuracy perspective the significant different between GSM and TDMA is signal bandwidth. The 5:1 difference in bandwidth makes GSM significantly more immune to multipath than TDMA. A comprehensive analysis showed a 2:1 ratio of TDMA to GSM errors for the typical multipath case, and nearly a 4:1 ratio for the severe case. Based on this analysis, it can be confidently concluded that the RMS U-TDOA errors for GSM will be approximately half of those for TDMA. As a result, the accuracy of U-TDOA for GSM should be at least twice that of TDMA. In addition, the proposed system 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 multipath. Also, they do note take into account more aggressive techniques for mitigating the effects of multipath in a GSM environment that are possible with the proposed technology. These techniques for super-resolving multipath and detecting leading edge components have potential to improve results even further. The authors are 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 multipath. 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 multipath or limited cell site coverage.

Annex B: Functional Description of Predictive Model

The predicted location accuracies in Annex A are computed using the 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 the predictive modelling 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 is computed using these rms accuracy estimates 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):
        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:
    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 $(\mathbf{A}^T\mathbf{wA})^{-1}$ where

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 **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 ith sector.

It can then be shown that:

$$\text{HDOP} = (C_{11} + C_{22})^{½}$$

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

$$\text{HDOP} = [(ac + bc - e^2 - f^2) / (abc + 2def - be^2 - af^2 - cd^2)]^{½}$$

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 partial derivatives

Define the location of the phone to be at (0,0) and the ith 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 ith sector at (x_i, y_i) is assumed to be only that for a straight-line distance, then:

$$\tau_i = (x_i^2 + y_i^2)^{½}$$

and thus the partial derivatives are dimensionless and equal to:

$$\frac{\partial \tau_i}{\partial x} = x_i / (x_i^2 + y_i^2)^{½}$$

$$\frac{\partial \tau_i}{\partial y} = y_i / (x_i^2 + y_i^2)^{½}$$

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”.

Annex C:
Change history

Change history							
Date	**TSG GERAN#**	**TSG Doc.**	**CR**	**Rev**	**Subject/Comment**	**Old**	**New**
2002-06	10	GP-021932			Approved at GERAN#10 Plenary		6.0.0