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FIELD TESTING OF A PULSE TRILATERATION AUTOMATIC VEHICLE MONITORING SYSTEM IN PHILADELPHIA
Volume I: Executive Summary

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FINAL REPORT

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16. Abstract

This report describes the Pulse Trilateration Automatic Vehicle Monitoring (AVM) system developed by Hazeltine Corporation, and presents results of the Phase I test program in Philadelphia. The Hazeltine system determines the position of mobile units by measuring the arrival times of the leading edges of vehicle pulse transmissions at a limited number of fixed receiver sites. Differences in time-of-arrival (TOA) of the transmissions are used by a central processor to compute the coordinates of the mobile units. Fixed signpost transmitters are used to improve time of passage accuracy at slow vehicle speed locations.

The Hazeltine system covers fixed route, random route, and special-case situations, in both low- and high-rise regions, and provides time-of-departure data for fixed route bus/transit applications. Data acquisition is automatic, with the basic data recorded on magnetic tape. Evaluation of the system's performance is provided by off-line simulation, which reflects the conditions and processing procedures proposed for the Phase II AVM tests in Los Angeles.

The report is divided into four volumes. This volume is an Executive Summary of the Philadelphia Phase I test results.

Volume 2, which represents the test results and data, describes the Hazeltine AVM system and the Philadelphia test configuration in detail, explains the data analysis and reduction techniques used, and proposes changes which would be made prior to Phase II. Volume 3 contains time point and location accuracy histograms for the tests discussed in Volume 2 (Section 4). Volume 4 accounts for aborted and excluded tests, and reproduces vehicle log sheets for all the tests.

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PREFACE

The work reported herein was performed for the Department of Transportation's Transportation Systems Center (DOT/TSC) in support of the Urban Mass Transportation Administration's (UMTA) research and development efforts in Automatic Vehicle Monitoring (AVM), aimed at the development and testing of advanced location technologies suitable for multi-user vehicle systems.

Government representatives responsible for the overall management of the program and for directing the contractual work include Mr. D. Symes of DOT/UMTA and Messrs. B.E. Blood and B.W. Kliem of DOT/TSC.

Hazeltine personnel contributing to the program included: Messrs. A.R. Abraham, J.B. Cohen, W.L. Corrigan, F.R. Dayton, G.N. Kerness, P. Nikolados, J.F. O'Connor, A.H. Riccio, W.C. Rogoza, L.E. Smith, and S.M. Weinstein.

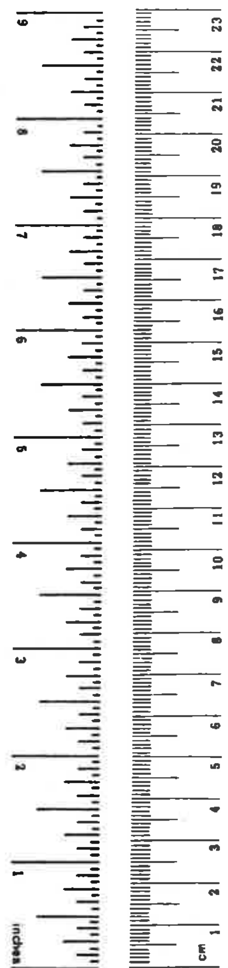
NOTE

During the winter of 1976-77, four different techniques for automatically locating land vehicles were tested in both the low- and high-rise regions in Philadelphia PA. The tests were carried out by four different companies under separate contracts to the U.S. Department of Transportation, Transportation Systems Center. The tests were designed to evaluate the techniques for their applicability as location subsystems for automatic vehicle monitoring systems. This document represents one of the contractor's final report. A summary report on all systems tested is available as Report No. UMTA-MA-06-0041-77-2.

METRIC CONVERSION FACTORS

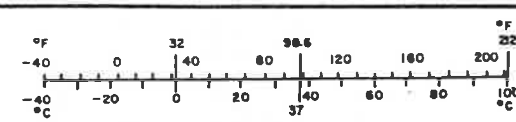
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

1.1 INTRODUCTION

This document reports on the testing of Hazeltine's Pulse Trilateration Automatic Vehicle Monitoring (AVM) technique in Philadelphia as part of the U. S. Department of Transportation's (DOT) multi-phase program to develop advanced AVM for multi-user applications. The Urban Mass Transportation Administration (UMTA) sponsored the program, which was administered by the DOT's Transportation Systems Center (TSC).

During Phase I, Hazeltine implemented the key elements of its trilateration location technique in Philadelphia, collected and analyzed performance data, and documented the results in this report.

Toward the end of the "official" (TSC Monitor present) tests - and based on preliminary analysis of early data - Hazeltine determined that its system was not demonstrating the vehicle-location accuracy capabilities of the trilateration system design as had been previously proven in tests in New York, N. Y., and Dallas, Texas. Further analysis showed that this problem was confined to the down-town Philadelphia "high-rise" area, and was attributable to receiver-site location.

To verify this conclusion in as short a time as possible, one receiving site was quickly relocated and supplementary tests were run. These "unofficial" tests showed a dramatic improvement in the location-accuracy performance of Hazeltine's AVM system in the down-town Philadelphia area, and verified our conclusion that receiver siting was the root-cause of out-of-specification performance during the official test phase. Consequently, Hazeltine's AVM system design for phase II in Los Angeles was reconfigured (and 6 receiving sites were added) to achieve complete confidence that performance requirements in Los Angeles will be met.

In summary, the Hazeltine system exhibited a location accuracy in Philadelphia of 270 feet at the 95th percentile in suburban areas, and 460 feet (95%) in a congested downtown high-rise district. The corresponding average errors (at the 50th percentile) were 97 feet and 140 feet respectively. The performance goal of 300 feet (95%) throughout the Los Angeles coverage area will be met using fixed-site receivers which are more optimally sited (as set forth in Volume 2, Section 5 of this report) than those used in the Philadelphia test program.

Time-of-passage accuracy (used to signal the departure of a bus from a designated point) of ±15 seconds (92%) was achieved <u>without</u> signposts in the suburban environment and ±15 seconds (93%) was achieved using a limited number (15) of signposts along the fixed routes.

The digital communications link which is an integral part of the Hazeltine AVM system was validated, exhibiting coverage levels of 98.5 % in the downtown areas and 99.8% in suburban areas, exceeding the requirement of 95%.

AVM is an important part of an overall command and control system for vehicle fleet management since it automatically provides the system operator and/or dispatcher with timely information on the location and status of all vehicles to be controlled. Some AVM systems (including Hazeltine's) also provide for two-way base-to-mobile digital communication. The location and communication information provided by AVM permits a significant improvement in the quality and level of service available from transit, police, commercial and other fleet operations.

1.2 THE HAZELTINE AVM SYSTEM

1.2.1 System Description

The Hazeltine AVM System uses a vehicle locating method that determines the position of the mobile unit by measuring the leading edge arrival times of pulse transmissions from the vehicle at fixed receiver sites deployed in the operating area. Differences in the time-of-arrival (TOA) of the pulse transmissions at each of the fixed receiver sites are used by a central processor located at a central fixed site to compute the coordinates of the mobile unit. The vehicle's location and other ancillary status-like data are displayed for use by vehicle fleet dispatchers and managers. The system also provides for the transmission of two-way base-to-mobile digital communications without using the mobile radio.

The principal system elements are (1) the Central Station Transmitter (located at a single fixed site), (2) a vehicle transponder located in each mobile unit, (3) Receiving Stations (fixed-site receivers) located throughout the operating area, and (4) the Central Station Processor and Display/Data Distribution Subsystem.

The Central Station initiates a roll-call sync signal (904.5 MHz)* which triggers pre-programmed electronic clocks in each vehicle transponder in the system. This sequence is shown diagramatically in figure 1. Vehicle transponders, as many as 5000 in the system, respond in sequence, each in its pre-programmed two-millisecond time slot (figure 2) which provides a unique identification of each vehicle through knowledge of the time-slot assignment at central.

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* The Federal Communications Commission has allocated two 8 MHz-wide frequency bands, 904-912 MHz and 918-926 MHz, for use by pulse trilateration AVM systems. The frequencies mentioned in this system description are for the 904-912 MHz band.

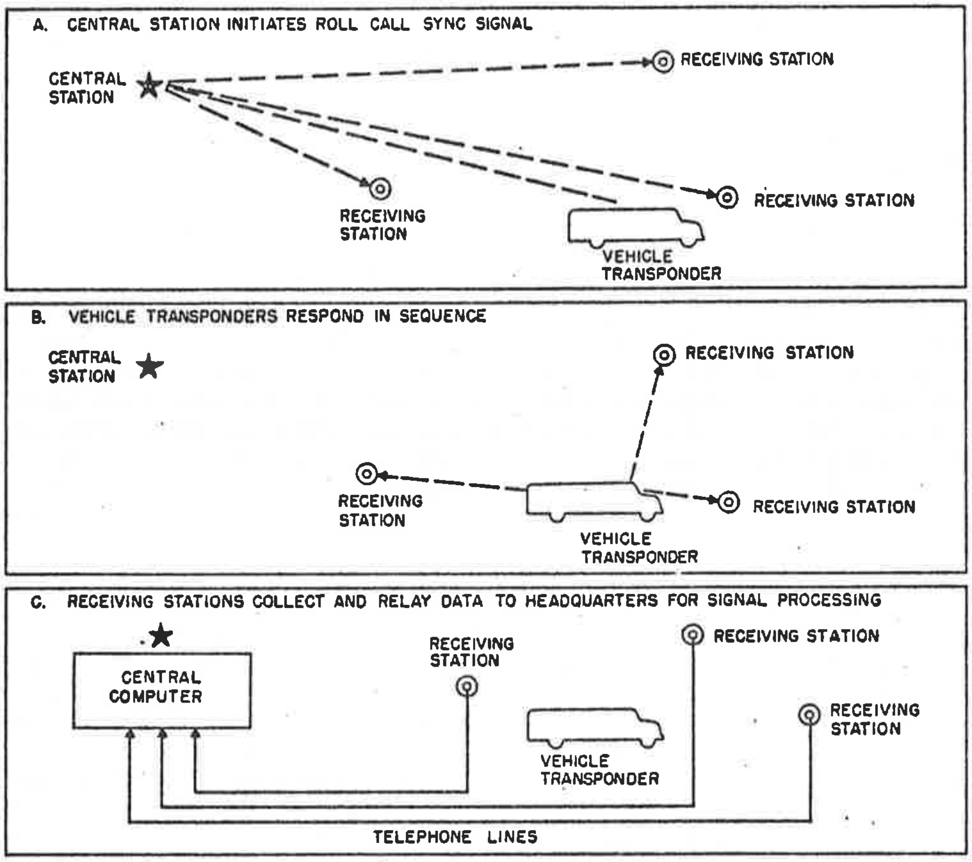


FIGURE 1. RADIOLOCATION SYSTEM - SEQUENCE OF TRANSMISSIONS

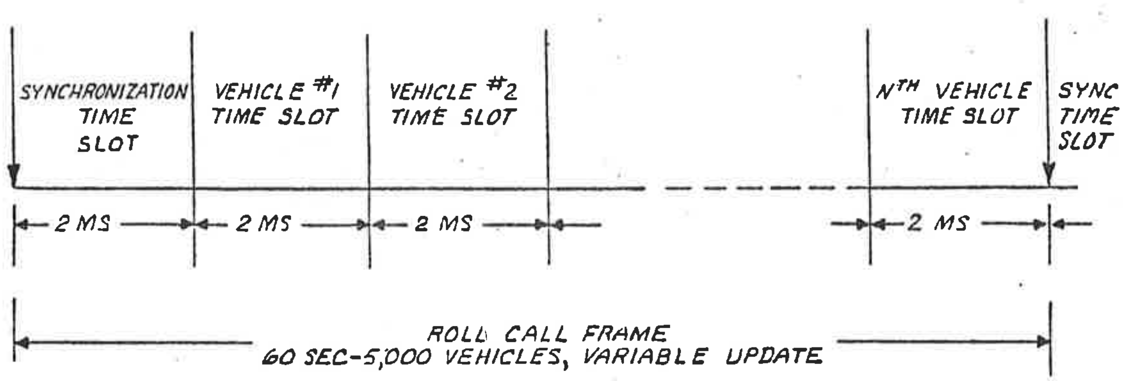


FIGURE 2. TIME-SLOT SEQUENCE

The vehicle emissions (pulsed signals on 908.0 MHz) are received by three or more fixed site receiving stations where the time of arrival (TOA) of the vehicle's pulsed emission is measured. The TOA information and other ancillary digital message data is relayed to the Central Station via telephone lines. At the Central Station the differences in TOA from three or more fixed receiver sites are processed (multilateration). The vehicle's position is computed as the intersection of two hyperbolic lines of position formed by the time differences. In addition to performing the position location computations, the Central Station Processor operates on the ancillary vehicle status message data and coordinates the activities of display processors which drive the dispatcher display. These dispatcher displays may be located at the Central Station or at remote locations in accordance with user/dispatcher requirements.

The principal function of all emissions in the system is to determine the location of the mobile vehicles. Pulsed emissions from the Central Station occur at (1) 904.5 MHz for vehicle transponder time-slot maintenance (to ensure that only one vehicle transmits at a given time) and supplemental base-to-mobile data transmission, and (2) at 908.0 MHz, sent to the fixed-site receivers for TOA calibration. The mobile vehicle transponder units emit signals on 908.0 MHz only. Included in this emission is the pulsed waveform used for both TOA measurement and for conveyance of ancillary mobile-to-base status messages.

In certain applications, it may be necessary to augment the basic system with a small number of fixed signpost transmitters which signal the vehicle's proximity to the signpost for subsequent reporting by the vehicle to central over the basic trilateration mobile-to-base link. It is important to recognize that these signposts are necessary only for the measurement of precise departure times from points along a given route when the vehicle is traveling at slow speeds, and not required for position location in the Hazeltine system. In fact, in the majority of areas covered by a typical AVM system, vehicle speeds are high enough and system location accuracy good enough that departure times can be measured adequately without signposts in those areas.

1.2.2 System Features

The Hazeltine AVM system provides location, identification, and two-way digital communications for vehicle fleets traveling fixed or random routes in suburban or central-city areas using a pulse tri-lateration technique.

a. The System is Readily Expandable

Coverage growth is achieved by adding fixed site receivers in a cellular fashion.

The very high capacity and variable update rate permit the maximization of cost sharing among the multi-users.

An integrated two-way digital communications capability can be extended to full extended length digital text communication.

The modular additions permit a financially phased implementation.

b. The System Uses Simple, Dependable Equipment

A small number of inexpensive fixed site receivers.

Vehicle equipment based on well developed proven beacon technology.

Straight-forward computer software.

c. The System is Operationally Self-Contained

No external signals are required for the location function.

Complete independence of the in-vehicle radio and land-mobile frequencies.

d. Spectrum Efficiency

Operates on one of two 8 MHz channels authorized specifically by the FCC for radio-location.

Available bandwidth provides large user capacity for both location and two-way digital data communication.

e. Minimal Risk

Extensive system development efforts are completed.

System performance has been validated (Dallas, N.Y.C., and Philadelphia).

In summary, the Hazeltine AVM system provides high capacity, area-wide location along with communication service to support the efficient management of multi-user vehicle fleets.

1.2.3. Dallas Police Configuration

Hazeltine is currently developing an AVM System to interface with an existing Computer Aided Dispatch System (CADS) for the City of Dallas. When implemented, the AVM System will improve the effectiveness of the Dallas Police Force by increasing officer safety, permitting more efficient assignment of patrol elements to calls, and by providing the dispatcher with more timely and accurate information regarding the status and location of patrol elements. The system will enable the police dispatcher to know the location of, and digitally communicate with, patrol vehicles in the 78-square mile Southwest Police District of Dallas (ie, one of five districts).

The current Dallas AVM development program consists of two phases. Phase I (completed in November 1976) consisted of (1) testing the Hazeltine location technique in Dallas and (2) performing the detailed system design for a Phase II system. Phase II of the AVM program comprises the hardware and software for vehicle location, the digital communication of status messages, and the integration of this information with that provided by the existing Computer Aided Dispatch System. The system being supplied will handle future growth to full city implementation which encompasses AVM for up to 700 vehicles traversing the 300 square miles of the City of Dallas.

1.3 PHILADELPHIA TEST PROGRAM

1.3.1 Objectives

The Government's stated objectives for the Phase I Philadelphia Test Program are to assess a variety of location subsystem techniques in order to select a contractor for the Phase II Los Angeles Implementation. Philadelphia was selected for Phase I, partly because it presented some of the most severe conditions which could be encountered by AVM systems deployed on a broad-scale throughout the country. Specifically, the urban noise environment, narrow streets, and tall structures in close proximity, all contribute to the severe nature of the Philadelphia environment.

Some specific performance goals to be used for system evaluation are:

Location Accuracy. 300 feet at the 95th percentile (no more than 5% of the points are to exhibit an error in excess of 300 feet)

Time-of-Passage Accuracy. 15 seconds at the 95th percentile (no more than 5% of the points are to exhibit an error in excess of 15 seconds)

Capacity and Update Rate. Ability to provide position location updates on at least 250 vehicles no less frequently than every 25 seconds.

Communications. Two-way base/mobile digital communications with 95 to 98% coverage without using currently authorized frequency channels.

1.3.2 Test Configuration and Instrumentation

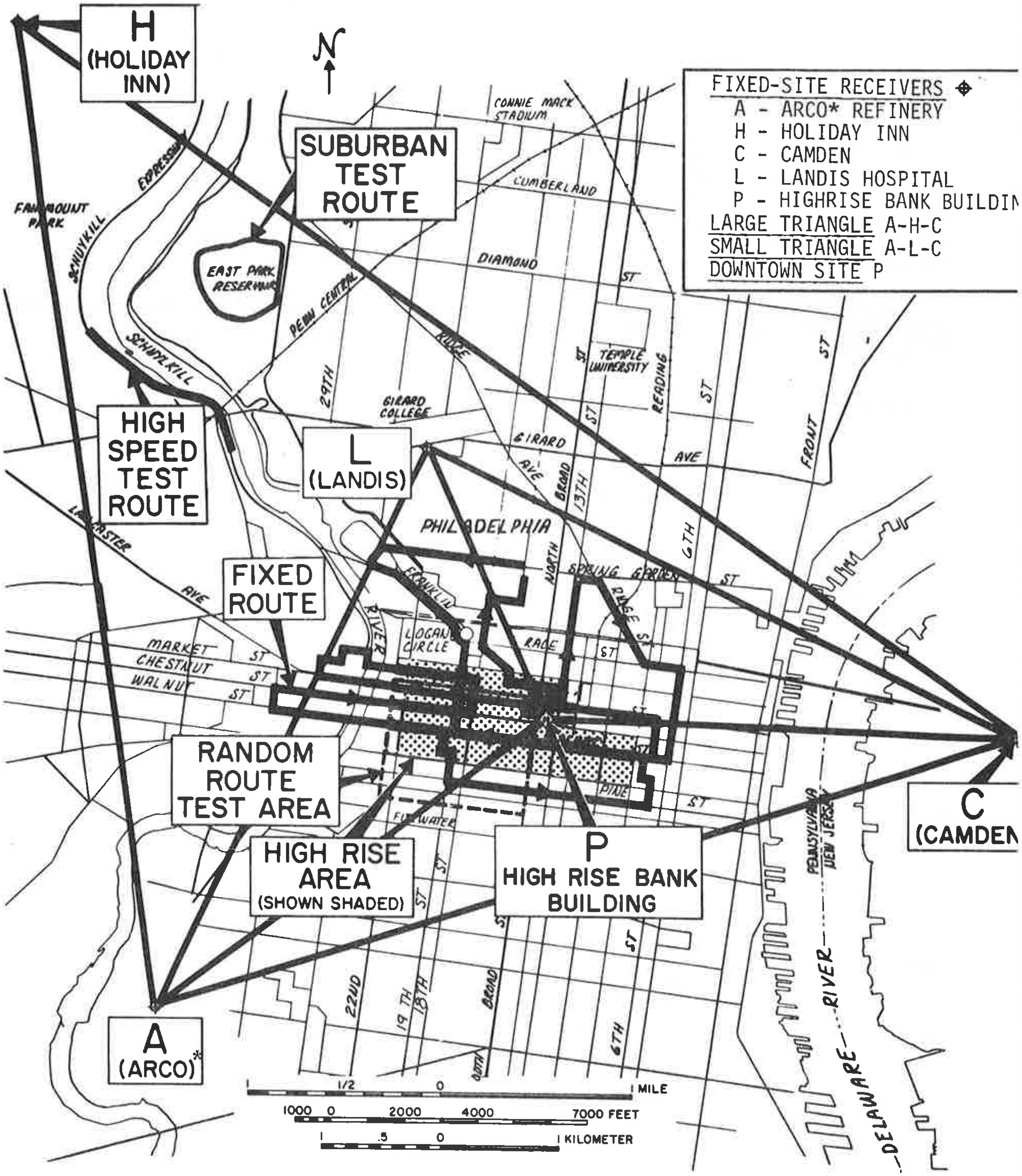
Figure C-1 is an overview of the Philadelphia test area. Five receiving sites are used in the test program to assess the performance and coverage available from different size triangles used in the trilateration computation. Table 1 summarizes the particulars of the fixed site receiver installations.

TABLE 1. FIXED-SITE RECEIVER INSTALLATIONS

Name	Location	Structure Ht (ft)	Ground El (ft)
Holiday Inn *(H)	City Avenue near Schuylkill River	240	230
ARCO**(A)	Atlantic Richfield Co. Flare Tower in S.W. Philadelphia near Passyunk Ave. and Schuylkill River	216	20
CAMDEN (C)	North Gate Apartments Camden, New Jersey	200	20
LANDIS (L)	Smoke stack of the Landis State Hospital on Girard Ave.	200	100
BANK (P)	Highrise bank building, Chestnut and Broad Streets	525	40

*Note: The central station synchronization/calibration transmitter was also located at the Holiday Inn site.

**Note: Atlantic Richfield Co.



*NOTE: ATLANTIC RICHFIELD CO.

FIGURE 3. TEST AREA OVERVIEW

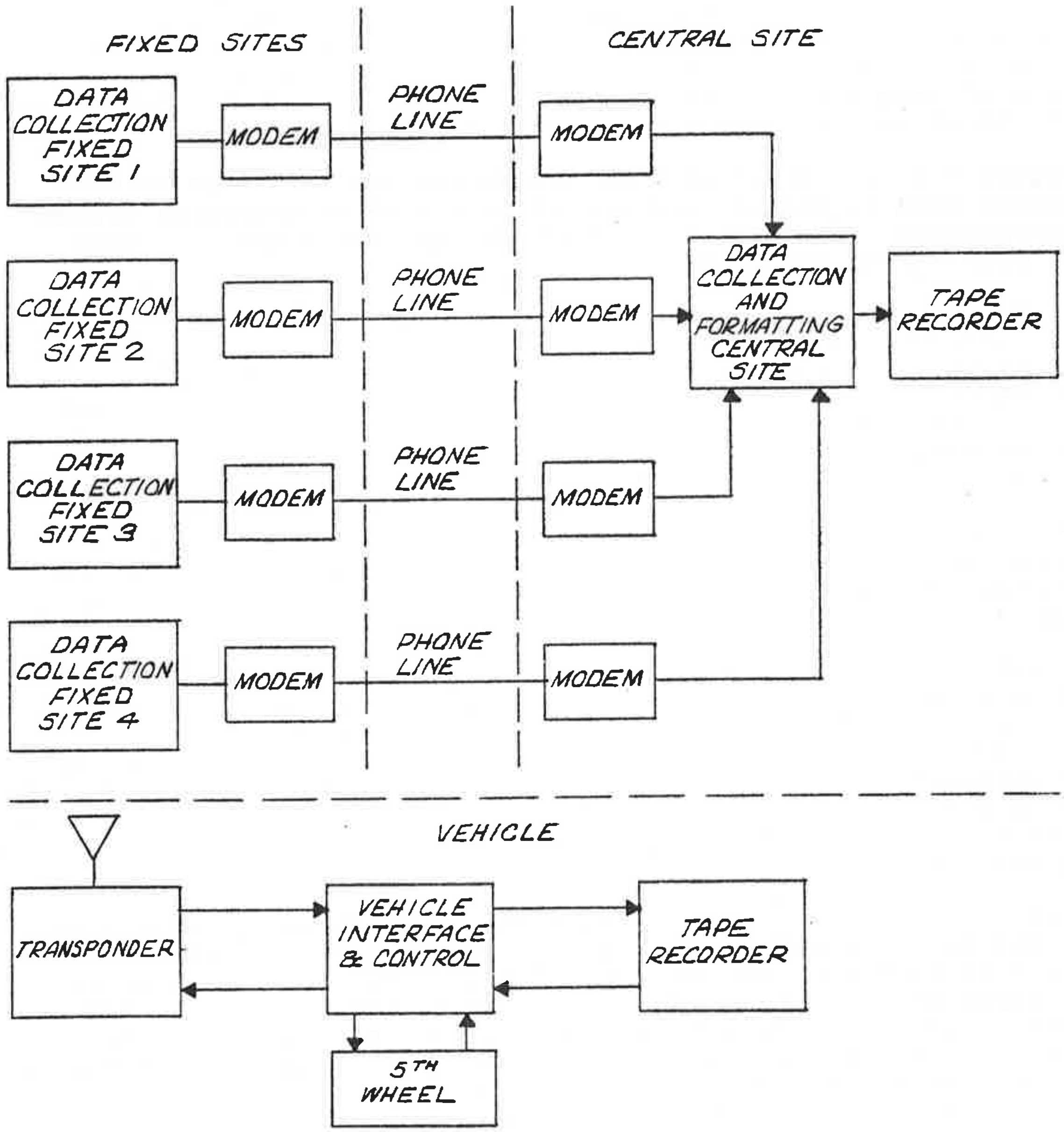


FIGURE 4. PHILADELPHIA DATA ACQUISITION SYSTEM, SIMPLIFIED BLOCK DIAGRAM

The triangle formed by Atlantic Richfield Co., Holiday Inn, and Camden is identified as the "large" triangle (AHC) and that formed by Atlantic Richfield Co., Landis, and Camden (ALC) is the "small" triangle. (The small triangle is denoted as such for comparison purposes only.) In fact, its leg lengths of 3-1/2 x 3-1/2 x 4-3/4 miles provide coverage of an area in excess of 5-3/4 square miles. The use of a highrise bank building permits three additional "downtown" triangles to be investigated, namely, APC, ALP, and PLC. These latter three triangles are denoted as the downtown site triangles. The large and small triangles have maximum leg lengths of 6-1/2 and 4-3/4 miles respectively. The maximum leg lengths of the "downtown" triangles vary from 3-1/2 to 4-3/4 miles.

Figure 4 is a simplified block diagram of the Data Acquisition System used to collect and record data used to determine system performance; figure 5 is a set of photographs of the equipment on site in Philadelphia.

The Central Site Equipment includes (1) the transmitter which broadcasts synchronization signals to the vehicle and calibration signals to the fixed site receivers, (2) an interface/control unit which processes the TOA data from up to four fixed site receivers and formats the data for tape recording, (3) a 9-track tape recorder to record TOA and other pertinent data. The fixed site receivers are connected to the central site by modem-driven telephone lines.

The vehicle equipment used for the tests includes the basic AVM transponder and roof mounted antenna, a fifth-wheel odometer for accurate location reference, a data interface/control unit, and a tape recorder.

In order to achieve the stringent time-of-passage requirement of ±15 seconds (95%) for slow moving vehicles traversing a fixed-route in the center city area, 15 signposts were installed. These units transmitted signals to the vehicle transponder indicating its proximity to the signpost. This information was appended to the standard AVM emission from the vehicle transponder used for TOA and transmitted back to the fixed site receivers and subsequently to the central site.

An off-line (non-real-time) post-test data processing program set is used to merge and synchronize the data recorded at the central site with that recorded in the vehicle. These programs replicate the location algorithm to be used in an operational system for extracting the position information from the TOA data, including special processes such as reasonableness/filtering tests on successive measurements, bias removal, and on-route correction for fixed route tests. The programs also automatically provide statistical information on location system performance.

Notwithstanding the use of off-line data processing, it is important to note that the Hazeltine test system configuration includes all critical system rf links in order to demonstrate the synchronization, position location, and two-way data communication capability of the system. In short, there are no "unaccounted for" system risk areas yet to be demonstrated.

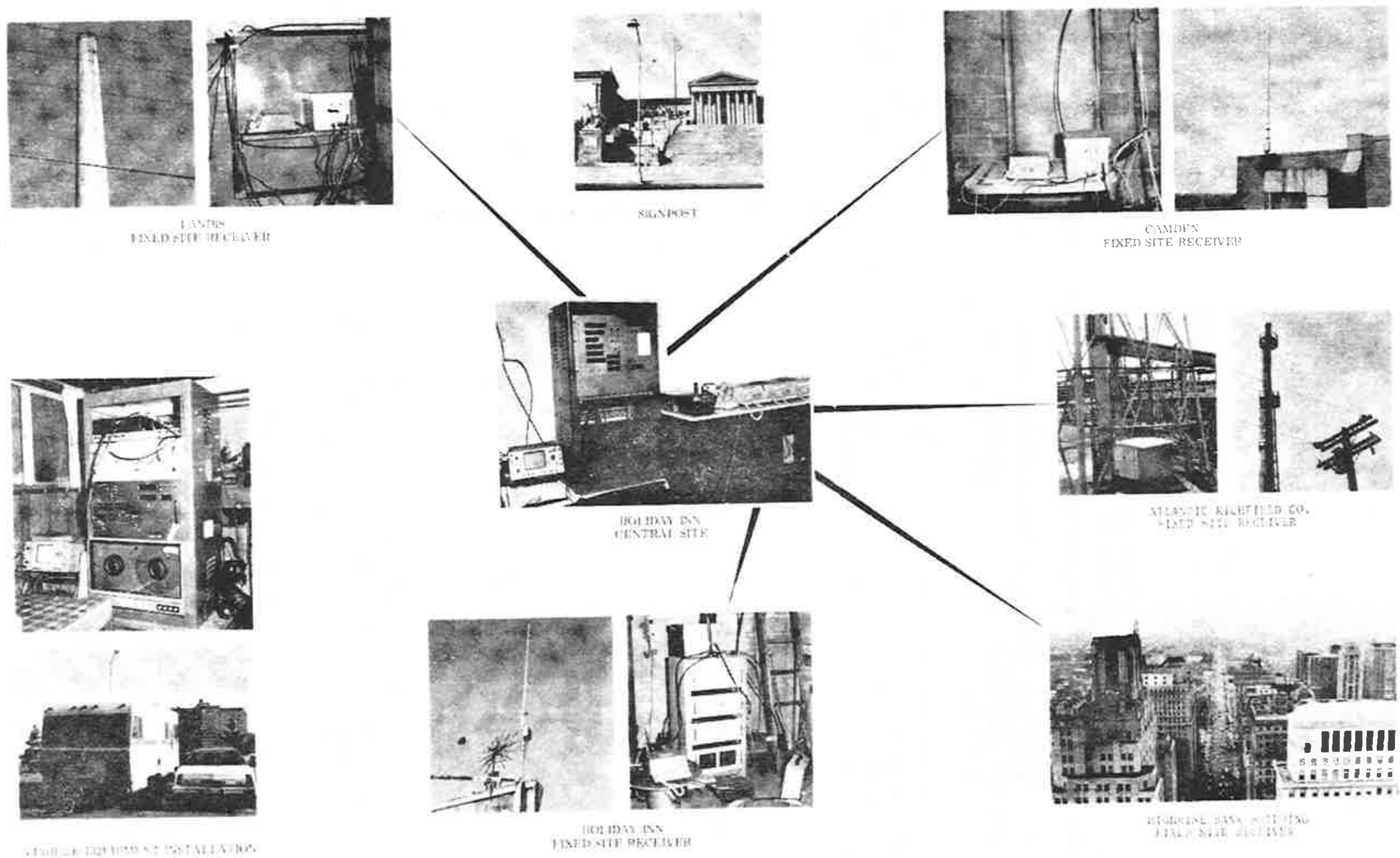


FIGURE 5. EQUIPMENT USED IN THE PHILADELPHIA TEST PROGRAM

1.3.3 Types of Tests

The tests performed in Philadelphia are grouped into three categories:

a. Fixed Route Tests - designed to demonstrate compliance with bus transit operations wherein a vehicle operates along specific routes at speeds and stop sequences simulating bus movements.

b. Random Route Tests - wherein a vehicle traverses an arbitrary (but pre-specified) path in the random route highrise area at speeds and stop-go sequences simulating automobile movement.

c. Special Tests - including those taken at high speeds, on routes with underpasses, near "noisy" power lines, measurement of ambient rf noise, time-of-passage performance without signposts, etc.

As shown in figure 3, the fixed route and random route test areas were selected by the Government to ensure that the system under test would encounter the severe operating environments of the dense high-rise center city area (shown shaded in the figure).

1.3.4 Test Conditions and Variables

The following parameters were fixed at indicated levels or available for selection during all or part of the test program:

fixed site receiver triangle configuration selected from appropriate combinations of the fixed sites

central station transmitter power 400 watts to 1000 watts peak (milliwatts average power)

vehicle transponder transmitter power 250 watts to 800 watts peak (milliwatts average power)

fixed site receiver threshold level 15 dB above noise

position update rate: vehicle emissions every 0.1 seconds available for processing with rates as slow as 1 every 10 seconds used to simulate operational, "system-level", performance

post position fixing algorithms: including bias correction, reasonableness/filtering, and on-route correction for fixed routes.

1.3.5 Test Chronology

The report documents the results of tests obtained in accordance with a previously submitted test plan and the results of certain supplementary tests which were not anticipated when the test plan was written

The supplemental data was collected (1) after an equipment modification was installed and (2) for certain tests, after an additional fixed-site receiver was installed (the one at the highrise bank building).

The principal equipment modification (known as the "zero-fill-fix") was implemented to prevent the deleterious impact of multipath on the vehicle-to-fixed site receiver preamble detection and time-of-arrival measurement at the fixed site receiver. This simple modification (which is a change in the transponder-to-fixed site receiver preamble pulse-code spacing) became necessary when the Philadelphia tests showed that multipath signals of significant amplitude could be found as late as 75 microseconds beyond the direct path signal. However, published data and prior observations indicated that significant multipath would be absent as early as 15 to 20 microseconds beyond the direct path signal.

The introduction of an additional fixed-site receiver at the highrise bank building was made when analysis of the data revealed that in certain instances the high-rise area was blocking the signal from the vehicle to one of three fixed site receivers to an excessive degree. Although a position fix was still established, it was made possible only by the reception of a reflected (multipath) signal from the vehicle which arrived at a time excessively delayed from the (unreceived) direct signal, thereby resulting in a significant location error. The initial spacing of receiver sites (for the Hazeltine Test Plan) was based on published path loss data for typical urban environments. The tests revealed however, that in the high-rise area, attenuation of the vehicle transponder signal was 10 to 15 dB more than the published average attenuation levels. Introduction of the PNB site significantly reduced the deleterious effects of excessive blockage (attenuation) of the direct signal and the associated reliance on substantially delayed multipath for accurate position location in or near the downtown high-rise area.

1.3.6 Highlights of the Test Results

The following is a summary of the test results highlights:

> The Hazeltine pulse trilateration system meets or exceeds the location accuracy goal of 300 feet (95%) with 6 mile typical receiver spacings in the suburban area. Specifically, tests run in the vicinity surrounding the reservoir (figure 3) with the "large" triangle (AHC) yielded location errors of 97 feet (50%), 131 feet (68%), 270 feet (95%), and 693 feet (99.5%) with a hit miss coverage (probability of obtaining a location fix on a vehicle) in excess of 98 percent. (Similar suburban performance was measured in the Dallas, Texas tests). A histogram of these Philadelphia suburban tests is shown in figure 6.
>
> The tests demonstrated that a time-of-passage accuracy of ±15 seconds, 92nd percentile is achieved in the suburban area without signposts. A histogram of this

Suburban Route Location Accuracy Histogram, Large Triangle (HAC), Subsystem Level, After Zero Fill, All 0.1-Second Data Samples for all runs, after bias correction (derived from first run), ID 204

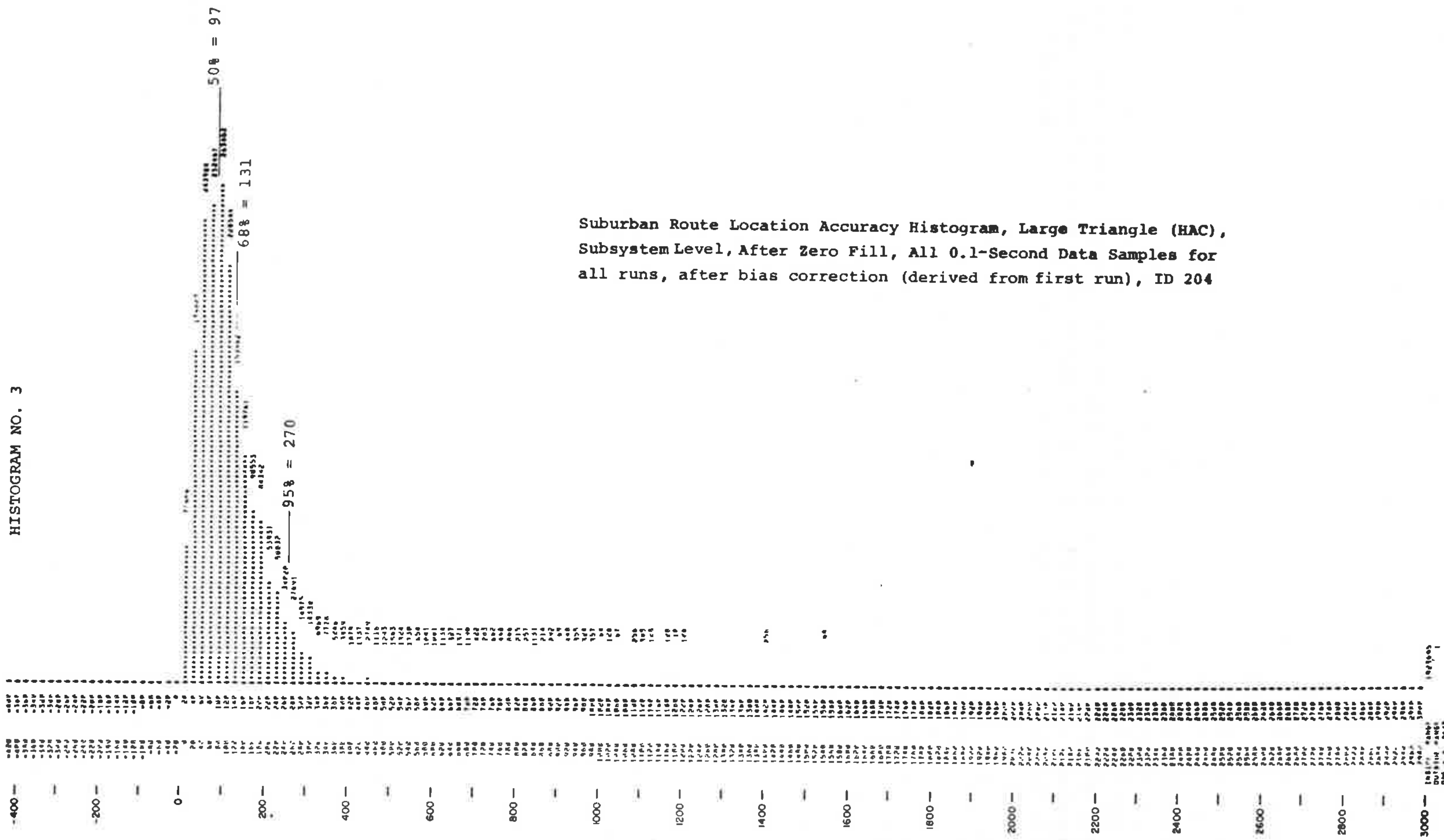


FIGURE 6. PHILADELPHIA SUBURBAN TESTS

data is shown in figure 7 indicating time of passage (accuracies of ±8.3 seconds (50%), ±10 seconds (68%), ±15 seconds (92%), ±21 seconds (95%) and ±27 seconds (99.5%). It is noteworthy that this performance was achieved without using on-route correction (a right-angle projection of the computed position fix onto the road) which can provide improved performance for fixed routes.

The tests demonstrated a 460 foot (95%) location accuracy in the central business downtown district when an additional fixed receiver was introduced. Specifically, a test of the northeast section of the fixed route was performed to determine the performance when the PNB site was used. Data was taken simultaneously with the original "small" triangle (ALC) and a new triangle (LPC) formed by the Landis, bank, and Camden sites. Figure 8 presents the histograms for this run using both triangles under the same processing conditions (zero-fill-fix, filtering, on-route correction). Note how the location errors decrease with the new triangle from 201 to 140 feet (50%),283 to 212 feet (68%), and 820 to 460 (95%).

Prior to the addition of the downtown receiver site, the official tests demonstrated a 95% location accuracy of 790 feet for the fixed route and 880 feet for the random route.

Time-of-passage accuracy of ±15 seconds (93%) was achieved in the high rise area using a limited number of signposts (15).

The performance of the communications link, which is an integral part of the Hazeltine AVM system, was validated. Specifically, the "hit-miss" statistics, which measure the combined performance of the base-to-vehicle synchronization link, the vehicle-to-fixed site receiver link and the fixed-site-receiver to central site telephone line links showed that coverage levels of 98.5% were achieved in the downtown areas (with the bank site in place) and 99.8% in the suburban area (using only the "large" triangle). This performance exceeds the requirement of 95% hit-miss coverage.

Tests performed with the large triangle (AHC) to ascertain location accuracy when the vehicle is under an underpass road reveals that, although the accuracy is degraded, the system continues to provide position fixes (about 94% hit-miss coverage) throughout the run.

As expected, location accuracy is essentially unaffected by high vehicle speeds (55 mph) with a pulse trilateration system.

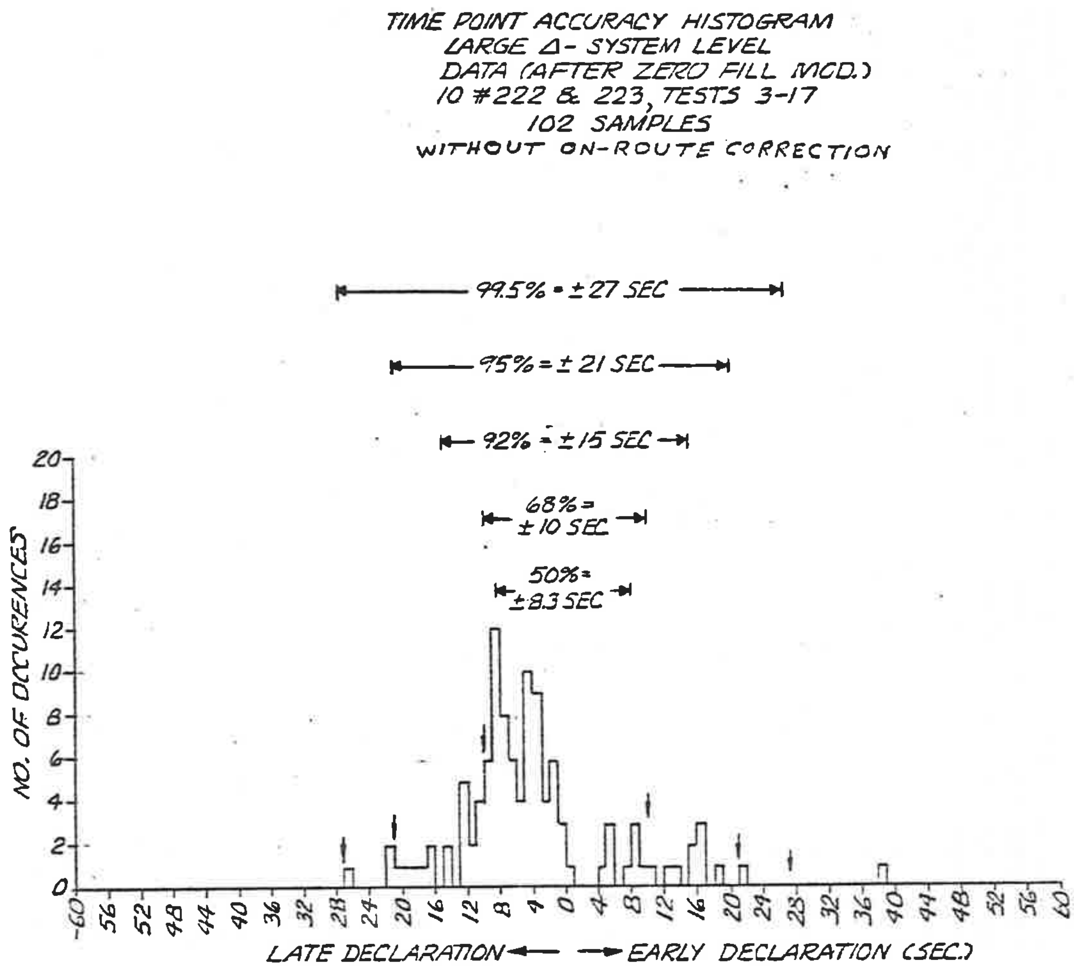
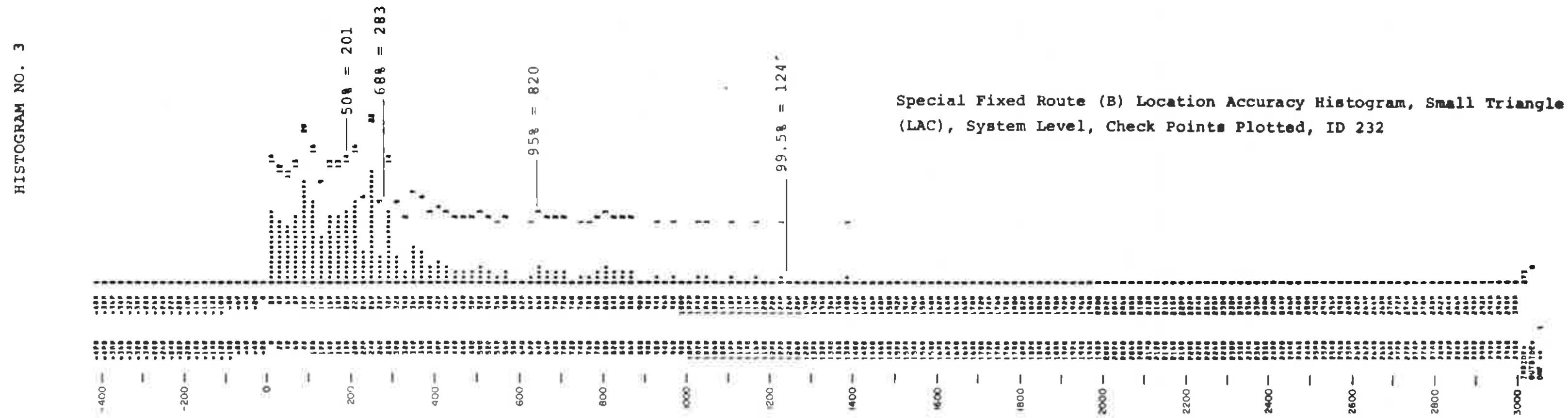


FIGURE 7. SUBURBAN ROUTE TIME OF PASSAGE ERROR HISTOGRAM



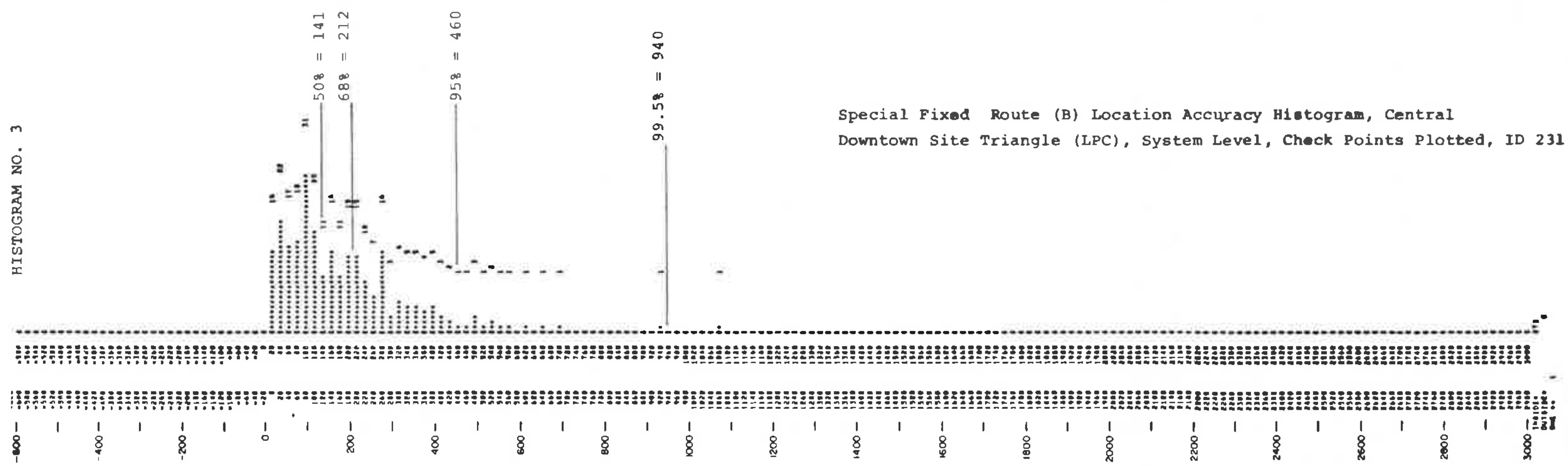


FIGURE 8. SPECIAL FIXED ROUTE TEST

1.3.7 Assessment of the Philadelphia Test Results

The testing in Philadelphia has accomplished all of the following:

a. Added significantly to the engineering data base on the characteristics and impact of the downtown urban high-rise environment of the pulse trilateration technique. Specifically the existence of multipath signals with significant amplitudes occurring as late as 75 microseconds after the direct signal, and the existence of attenuation caused by high-rise blockage some 10 to 15 dB in excess of previously published average attenuation levels.

b. Proved that a simple equipment modification (the zero-fill-fix) permits the system design to accommodate the long-time-delayed multipath.

c. Underscored the need for judicious selection of the locations for the fixed-site receivers to ensure that the resultant triangles used for trilateration provide three "commensurate" paths from the vehicle to the receivers to preclude multipath distortion of the location measurement. (It is important to recognize that accurate position location is achievable in the presence of multipath when all three paths experience similar multipath delays. Direct line-of-sight from the vehicle to all three receivers, although desirable, may not always be available. Under these conditions, "commensurate" multipath delays permit the achievement of accurate position location.)

d. Verified the performance of the pulse trilateration AVM system in the Philadelphia suburbs and central business high-rise area which are likely to represent the most severe environments (multipath, noise, blockage, etc.) ever encountered by a system to be widely deployed in urban environments.

e. Provided a sound basis for establishing a workable system configuration for Los Angeles which provides the requisite level of performance for both location and time-of-passage.

1.4 THE LOS ANGELES CONFIGURATION

The results of the Philadelphia test program suggest the following points pertinent to the Los Angeles AVM configuration:

1.4.1 L.A. Receiver Deployment

Nineteen fixed site receivers are needed to provide the coverage required for L.A. Their deployment is shown in figure 9. Sites with triangular cell lengths in the order of 2 miles are necessary in the central business district in order to accommodate the anticipated effects of the high-rise environment. In the north and northeast sections of L.A., receiver sites are placed at the crest of surrounding hills to ensure adequate coverage of the vehicle routes.

FIGURE 9. AVM FIXED-SITE RECEIVER LOCATIONS FOR LOS ANGELES CONFIGURATIONS

1.4.2 L.A. Similarities to Dallas

Substantial portions of L.A. are similar to Dallas where the performance of the system has already been verified, providing better than 300 feet (95%) location accuracy. The 78 square mile area of the Dallas Police Southwest Postal District will be covered by 7 to 9 fixed site receivers. The receiver density of 19 receivers per 150 square miles for Los Angeles is consistent with a nominal average receiver density of one receiver per 8 to 10 square miles.

1.4.3 Extrapolation of Philadelphia Results

a. Location Accuracy

In Los Angeles, a large number of high-rise apartment and office buildings taller than 7 stories are located in a one (1) square mile area which lies within the area bounded by the Hollywood Freeway on the north, Harbor Freeway on the west, Santa Monica Freeway on the south, and Main Street on the east. This high-rise area which is similar to, but not as dense as the Philadelphia high-rise area, constitutes less than 1% of the total Los Angeles system coverage area. A cluster of four sites (#1, #15, #16, and #17) shown in figure 9 are planned specifically to provide coverage consistent with 300 feet (95%) location accuracy requirements. This extrapolation is based on the fact that the fixed site receiver spacing is diminished and the height of at least one antenna in the pertinent triangle is increased for Los Angeles compared to the Philadelphia configuration as shown in the following table:

TABLE 2. SITE-RECEIVER SPACING AND ANTENNA TRIANGLE COMPARISONS

Location	Triangle	Triangle Leg-Lengths (miles)	Height of Tallest Antenna in Triangle: Structure Height	Height of Tallest Antenna in Triangle: Ground Elevation	Measured Location Error
Phila.	ALC (small triangle)	3½, 3½, 4 3/4	216 ft	20 ft	820 ft (95%)
Phila.	PLC (Downtown)	1 3/4, 2½, 3½	525	40	460 ft (95%)
L.A.	#1, #15, #16	1, 1½, 2	750	250	*300 ft (95%)

*Extrapolated

The utilization of the L.A. triangle (#1, #15, #16) in the potentially worst case portion of the L.A. environment with a fixed site receiver leg spacing of 1, 1½, 2 miles and an antenna height of 1000 feet (750 feet structure height plus 250 feet ground elevation) should readily permit the realization of 300 feet (95%) location accuracy.

b. Time-of-Passage Accuracy

As indicated above, the Philadelphia tests demonstrated a time-of-passage accuracy without signposts of ±15 seconds (92%) and ±21 seconds (95%) which is slightly in excess of the goal of ±15 seconds (95%). This suburban time-of-passage accuracy will be improved in L.A. by revising the computer processing algorithm to make use of knowledge of the vehicle direction to exclude certain measurements. The algorithm used in the Philadelphia tests was based on the use of an "arrival" circle of 300 foot radius and a departure circle of 400 foot radius, centered at the time point. When measured location was within the 300 foot circle, time is recorded and when a subsequent location measurement indicates the vehicle is outside the 400 foot circle, the time is recorded again. Time-of-departure is computed as the average of the two recorded times. It is readily apparent that the time point accuracy can be improved by making use of knowledge of the bus direction when recording departure time. For example, when the vehicle is moving north, a measurement 450 feet to the south should not be accepted as a departure. This improvement together with others detailed in the report (Volume 2, Section 5) form the basis for our conclusion that time-of-departure accuracy of ±15 seconds (95%) will be met in the suburban areas without signposts.

c. Other Aspects

Although the Philadelphia testing can be logically extrapolated to the receiver configuration proposed for L.A., Hazeltine intends to verify the coverage adequacy by carrying out a detailed site survey and measurement activity prior to configuration-freeze, in order to remove any residual siting uncertainties.

The substantial capacity of the Hazeltine system permits update rates higher than every 10 seconds per vehicle. Although not specifically planned for L.A., the availability of this higher update rate feature coupled with powerful, but routine, data processing (including data reasonableness/filtering tests and on-route correction for fixed routes) provides even further assurance that adequate reserve is available such that performance goals will be achieved in L.A.

Although 30 signposts are proposed to meet time-of-passage requirements on the fixed routes, suburban time-of-passage measurement will be achieved without signposts as a by-product of the accurate location measurement.

The L.A. configuration is modularly expandable to provide additional coverage by the simple addition of fixed site receivers in an incremental (as-desired) cellular fashion.

1.5 CONCLUSIONS

The Philadelphia test program has added further to the growing data base which verifies the efficacy of pulse trilateration AVM for vehicle monitoring, command and control in transportation applications.

Siting of the fixed receivers can be a significant factor in system performance. Optimum locations cannot always be predicted but, rather, require a modest level of on-site empirical evaluation.

Although fixed site receiver spacings on the order of 1.5 to 2 miles may be required in certain high-rise areas, the major portions of the AVM area are covered by widely spaced receiver sites (typically 5 to 7 miles apart) thereby maintaining the cost/performance attributes of pulse trilateration AVM.

The successive improvements in system performance in Philadelphia are directly traceable to the introduction of the zero-fill-fix and the downtown fixed site receiver to combat the effects of excessive multipath delays and blockage. These improvements (which led to a two-to-one improvement in location accuracy), coupled with the 270 feet suburban accuracy achieved in Philadelphia (and in Dallas) form the basis for our confidence that the proposed L.A. configuration will provide 300 feet location accuracy at the 95th percentile.

The Philadelphia test experience is further verification that pulse trilateration AVM is technically and economically feasible for deployment in a broad range of vehicle fleet management systems.

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