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Terrestrial Evaluation of the Global Positioning System (GPS), Standard Positioning Service (SPS)

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Final Report

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16. Abstract

This report summarizes the results of static and navigation tests conducted in the Boston, Massachusetts area during the period of January through April 1985 and also in August 1985. The objective of these tests was to gather data to determine the viability of the GPS system, Standard Positioning Service (SPS), as a 'stand alone' terrestrial radionavigation reference. Companion LORAN-C data were obtained to provide an evaluation of comparative system performance.

The study concludes that GPS cannot serve as a 'stand alone' radionavigation system in urban environments characterized by multiple highrise buildings. In less 'hostile' environments, GPS was observed to be an effective radionavigation system with position accuracies exceeding those obtained with LORAN-C.

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PREFACE

The NAVSTAR Global Positioning System (GPS) is a satellite navigation system capable of providing highly accurate three-dimensional position and velocity information to users anywhere in the world. When fully operational in 1988, the anticipated accuracy using the Standard Positioning Service (SPS) portion of GPS is expected to be 100 meters 2 drms.

Considerable interest exists in the use of GPS as a primary system for future land navigation. The impetus for the replacement of existing navigation systems, e.g., LORAN, with GPS lies in its increased global coverage plus its inherently greater accuracy over current navigation systems. The Research and Special Programs Administration of the U.S. Department of Transportation, interested in exploring the use of GPS for terrestrial radionavigation, has funded the current program to evaluate GPS in typical land application environments. To provide an accurate comparison of GPS with the LORAN-C navigation system, parallel measurements were made using two state-of-the-art LORAN-C receivers. The test program was designed to include a sufficient number of navigation runs in different environments to allow an objective assessment of GPS for land usage.

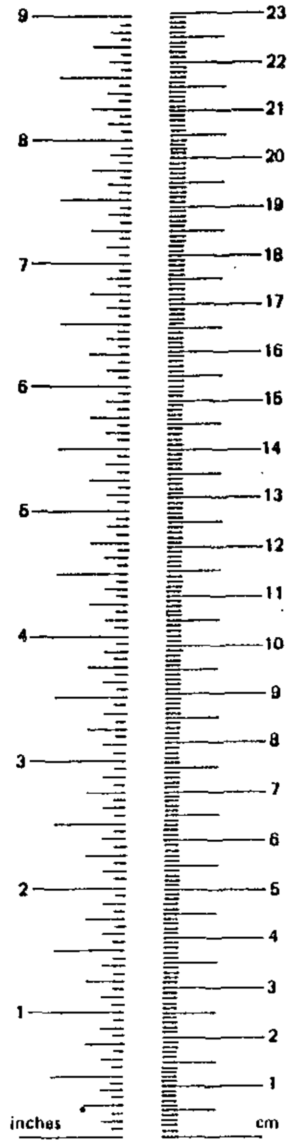
The Transportation Systems Center wishes to acknowledge the contribution and assistance of a number of individuals. Special thanks are due Mr. David J. Pietraszewski of the U.S. Coast Guard Research and Development Center, Groton, Connecticut for helpful discussions and contributions regarding GPS during the course of the program. Thanks are also due LCDR Robert L. Gazlay, Chief Radionavigation Information Branch, Office of Navigation, USCG, for supplying computer programs used for coordinate system transformations. Finally, Mr. Charles Dunne of the Transportation Systems Center (TSC), and Mr. Kam Chin and Miss Laura Gloshinski, Cooperative Education students at Northeastern University, are gratefully acknowledged for their assistance in conducting the tests and the final data processing.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

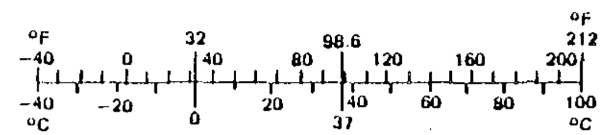
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	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

*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286, Units of Weight and Measures. Price $2.25 SD Catalog 1 10 286.



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	36	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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1.0 INTRODUCTION

This report summarizes the results of static and field tests of two NAVSTAR Global Positioning System (GPS) receivers, and two LORAN-C receivers. Initial static tests were conducted at the Transportation Systems Center (TSC), Cambridge, MA. There were followed by field tests in Boston and vicinity using a mobile test facility. The main objective of the test program was to gather data to establish the suitability of the GPS system, Standard Positioning Service (SPS), for use by the civilian sector as a terrestrial radionavigation reference system. It was also desired to acquire sufficient LORAN-C data to permit a comparative evaluation of GPS and LORAN-C systems performances. Funding for this work was provided by the Research and Special Programs Administration, US Department of Transportation.

The Block 1 NAVSTAR GPS tested in this report employed a satellite constellation comprised of six satellites (SV6, SV8, SV9, SV11, SV12, and SV13) in nominal 12 hour (43078.3 seconds nodal period) circular orbits. The Block 2 NAVSTAR system, designed to be operational in 1988, will employ 18 satellites in 55 degree inclined, circular orbits. Continuous three-dimensional global coverage will be obtained by placing three satellites, equally spaced, in each of six orbit planes 60 degrees apart in inertial space. Continuous coverage will be available for receivers using a 7.5 degree mask elevation angle. While block 1 satellites permit navigation to accuracies better than 20 meters, the SPS signals from the Block 2 satellites will be degraded to permit navigation accuracy of only 100 meters, 2 drms.

This test program represented an extension of previous GPS studies conducted at TSC in Spring 1983. In contrast to the previous program which yielded only qualitative conclusions on GPS land usage, this effort sought to establish definitive conclusions on GPS applicability for land navigation. Special emphasis was given to documenting the GPS performance in urban communities where hostile environments provide GPS with its most severe challenge. The latter tests allowed one to evaluate the performance GPS as a stand-alone radio navigation system* in highly developed urban regions. The test program included a wide variety of navigation runs to insure adequate data for GPS system evaluation.

*A stand-alone radio navigation system is defined as one requiring no additional external input data for effective system operation, other than the sensor antenna. For GPS receivers, external inputs could include velocity, direction, and altitude.

Test measurements fell into two main categories: (1) static or fixed-site measurements at TSC, as well as selected locations in the Boston area; and (2) GPS navigation tests at urban, suburban, and rural locations. In the static tests, measurement objectives were aimed at establishing limits on receiver resolution/accuracy and long-term stability. These tests included the study of GPS receiver response to continuously changing satellite configurations. Multipath effect and electrical noise interference were examined through a series of tests specially designed for this purpose. The principal emphasis in the mobile tests was the study of GPS limitations for land navigation. Test runs were conducted in sufficient detail to allow correlation between receiver performance and test environments. Tests were split into two periods, January through April 1985 and August 1985. This was caused by the fact that one GPS receiver was unavailable until Summer 1985.

The report is divided into four principal sections. The first section describes the GPS and LORAN-C receivers and associated equipment used for data processing and analysis. This is followed by a discussion of various factors which impact the accuracy of the test results including the dilution of precision (DOP), reference frame transformations, and observed software errors. The final sections present the results of static and mobile field tests, conclusions and recommendations. Data plots are included within the text of the report whenever it is germaine to the discussion.

2.0 EQUIPMENT DESCRIPTION

2.1 GPS EQUIPMENT

Two GPS receivers were evaluated. The first, the LTN-700, was manufactured by Litton Aero Products, Moorpark, CA. The second, the T-set, was manufactured by Magnavox Advanced Products and Systems Company. Both receivers utilized the SPS signal at L1 carrier frequency (1575.42 mHz).

2.1.1 LTN-700

The LTN-700 is a low cost receiver manufactured by Litton Aero Products, Moorpark, California, and specifically designed for commercial aviation applications. The receiver has alternate operating modes for marine and terrestrial application tests. It operates with single channel fast-sequencing (navigation mode) utilizing the Standard Position Service (Clear Access) code at L1 carrier frequency (1575.42 MHz). Digital signal processing is emphasized in the receiver, keeping analog RF signal processing to a minimum. Similarly, software digital signal processing is maximized, minimizing hardware digital signal processing. The LTN-700 set is comprised of a receiver-processer unit (RPU), a continuous control display unit (CDU), and an antenna with preamplifier for reception of bi-polarized satellite signals.

The LTN-700 achieves position fix only after completing a series of separate system operations. Following the turn on of the receiver and inputting of data required for receiver initialization (Initialization State), the LTN-700 enters the "Search the Sky Mode" to seek out visible satellites. If the GPS Almanac data is not present in the receiver memory bank or if the data is out-dated, the LTN-700 proceeds to acquire the Almanac data using the slow sequencing "Acquisition Mode". Once the Almanac data has been acquired, the LTN-700 enters the "Track/Navigation Mode" to provide a continuous update of user position with time. During this final operating stage, the LTN-700 uses fast sequencing to receive and store incoming data from successive satellites' signals. Acquisition was within 3 minutes when Alamanac data was current and approximately 24 minutes when Almanac data had to be reobtained.

2.1.2 T-Set

The T-set was designed for use by engineers in evaluation of marine and terrestrial aspects of the GPS system. As such, the form selected was a Digital

Products VT-100 series computer terminal, modified to function as a GPS receiver through addition of RF circuits and other GPS unique boards. The GPS operating program was loaded into the receiver each time the unit was energized, requiring a 24-minute start-up because no Almanac data was stored. In contrast to the LTN-700, the RF circuitry of the T-Set was designed to permit two channel operation. One channel was used for continuous, sequential track purposes (4 satellites) and the second was used for identification and acquisition of supplemental satellites. At the time of the evaluation, the T-set was using two channel software which output the navigation coordinates in WGS-72 based latitude/longitude. Earlier versions of software provided coordinate information with an Earth Centered-Earth Fixed reference system. WGS-72 coordinates facilitated our evaluation.

2.1.3 Receiver Specification Comparison

Typical of commercial receivers, performance specifications for the units are not identical. Tests with the units supported the fact that they were designed for different roles. Table 1 presents the basic specifications for each unit. These receivers were chosen to permit a performance comparison of sequential and multiplex tracking.

TABLE 1. GPS RECEIVER SPECIFICATIONS

RECEIVER	LITTON LTN-700	MAGNAVOX T-SET
Application	Aviation	Marine and Terrestrial
Form	Avionics Package	Digital Computer Terminal
Type	Single Channel SPS	Dual Channel SPS
	Multiplex (fast sequence)	Sequential
Velocity	600 m/s (meters/second)	400 m/s
Acceleration	40 m/s	6 m/s
Time To First Fix	<3 Minutes	3-24 Minutes
Accuracy	40 M CEP, 100 M 2drms	35 M, 2D 90% Probability
Geodetic Reference	WGS-72	Altitude Corrrected WGS-72
Satellite Mask Angle	7.5°	7.5°
RS-232 Data Output	9600 Baud	2400 Baud
Data Update Rate	Fixed Update	2 Second Minimum Interval

2.1.4 Display and Output Data

Displays from both receivers provided the operators with sufficient information to evaluate the status of receiver operation. Information included: position (latitude, longitude, altitude, velocity, acceleration and time); navigation status (satellites tracked, dilution of precision, signal quality information for each tracked satellite, elevation and azimuth) and engineering data (ephemeris status, operator designated information such as tracking constants, and Kalman filter residuals). The LTN-700 data was organized in 80 character pages while the T-Set had several 80 column lines organized by function. Neither set provided any alarm flag to indicate that insufficient data was available for navigation. It was not possible for the operator to see all variations with any selected display, so navigation performance had to be evaluated post-mission through data sorts.

All LTN-700 data were available at the RS-232 output. It was organized by "blocks" which corresponded to, but were not the same as the display information. Information was in a hexadecimal format, requiring supplemental unpacking programs. The data update rate was varied with the data block. For example, it was possible to get navigation solutions every second, while satellite azimuth data was only available every 10 seconds. All T-Set display data were not available on the data output. Two critical parameters, satellite elevation and azimuth were not output, making evaluation of receiver underway performance more difficult. The data rate from the T-Set was variable. Two second increments were the fastest rate. Neither unit was delivered with handshake protocol enabled. This required that the data recorder have a large buffer and reasonably fast transfer times to ensure that no data was lost.

2.2 LORAN-C EQUIPMENT

Two LORAN-C receivers were used in the evaluation, a Northstar 7000 and a Accufix 600. The Northstar 7000, manufactured by Digital Marine Electronics Corp., Acton, MA, was a marine LORAN-C receiver designed for simple yet reliable navigation operation. Its design emphasized simplicity and ease of operation. When interfaced with the EPSCO C2 Plotter, the Northstar 7000 provided real-time tracking capability. The Accufix 600 manufactured by Racal-Megapulse Inc., Bedford, MA, was a survey-grade receiver designed for engineering research work. It included advanced microprocessor circuitry with guaranteed accuracy and 10 nanosecond resolution. It offers a wide variety of output displays including latitude and longitude position with resolution/accuracy of 1/10th arc second. Both receivers provided RS-232 ports for communication of receiver output data.

2.2.1 Specification Comparison

Table 2 is a specification comparison for the receivers. Both required less adjustment than the GPS receivers, reflecting the fact that the LORAN-C system has been operational for over 20 years and receiver design is mature.

TABLE 2. LORAN-C RECEIVER SPECIFICATIONS

RECEIVER	MEGAPULSE ACCUFIX 600	Digital Marine Northstar 7000
Application	Survey	General Purpose
Stations	Master & 4 Secondaries	Master & 4 Secondaries
Time to First Fix	<5 Minutes	<3 Minutes
Velocity	60 Knots	150 Knots
Acceleration	Unspecified	Unspecified
Accuracy	TD-10 Nanoseconds	TD-10 Nanoseconds
	L/L-0.1 Arcsecond	L/L-0.01 Minute
ASF	Manual	Automatic
Geodetic Reference	WGS-72	WGS-72
RS-232 Data Output	300-1200 Baud	300-1200 Baud
Data Output Rate	5 Sets/Minute	1 Second Multiples

Again, the RS-232 ports were not provided with handshake protocol. The data messages were shorter and interface with microcomputers presented no problem. The minimum data update rate for the Accufix 600 was every 12 seconds, while that of the Northstar was every second. This included latitude/longitude, time differences, SNR of tracked signal, alarm flags for improper station operation, time, velocity and direction.

2.3 DATA PROCESSING EQUIPMENT

Three computers were used to gather and process GPS and LORAN-C test data. These included the HP-2647A graphics terminal, the HP-9845B desk-top computer, and the HP-86B personal computer. Figure 1 identifies the different computer components used in the GPS and LORAN-C data processing systems.

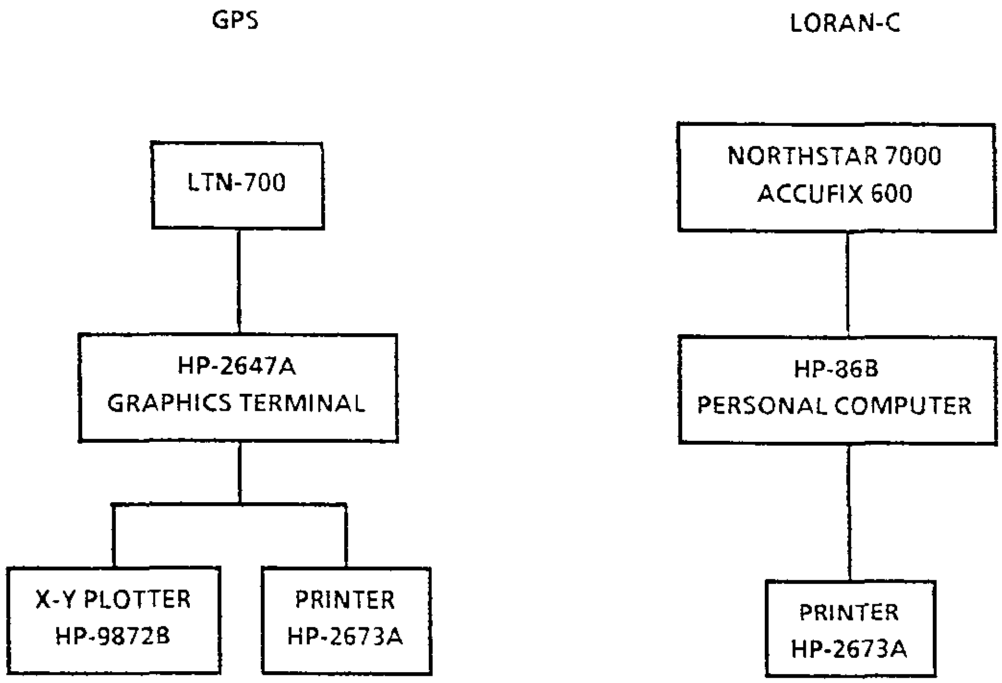


FIGURE 1. GPS AND LORAN-C DATA PROCESSING SYSTEMS

The HP-2647A was used to store GPS receiver output data on cassette tape and later to unpack the raw data using computer programs written in BASIC. An example of raw 'L' block data from the LTN-700 and its unpacked equivalent is shown in Table 3. Depending upon the type of data analysis desired, the processed data was either directed to an output printer (HP-2673A line printer) or to a HP-9872B X-Y plotter for generating GPS two-dimensional navigation plots.

The HP-9845B, being a higher level computer than the HP-2647A, was employed for the detailed GPS data analysis. This included statistical studies of position (2 drms) errors and the generation of two-dimensional scatter plots as well as plots of position (latitude, longitude, and altitude) with time.

TABLE 3. LTN-700 'L' BLOCK RAW DATA AND ITS UNPACKED EQUIVALENT DATA

Raw Data	Unpacked Data	Parameter
L	L	BLOCK NAME
3C	60	BLOCK SIZE
000030E8	12520	10 HZ COUNT
01080001	264	GPS WEEK
527640FE	124199	GPS WEEK
A8C33FE7	.739351	LATITUDE (in radians)
D9A7BFF3	-1.24064	LONGITUDE (in radians)
A448C073	-314.268	ALTITUDE (in meters)
F294BFF8	-1.55922	EAST VELOCITY (meters/sec.)
12644005	2.63398	NORTH VELOCITY (meters/sec.)
00000000	0	EAST ACCELERATION (meters/sec.)
00000000	0	NORTH VELOCITY (meters/sec.)
00000000	0	UP ACCELERATION (meters/sec.)

The HP-86B was dedicated to LORAN-C data storage and processing. Output data from the LORAN-C receivers were stored on disks and subsequently unpacked using HP BASIC programs. Data was then transferred to the HP-9845B for statistical analysis. The statistical analysis program used to analyze LORAN-C data was developed for the U.S. Coast Guard for the harbor monitoring program (ref. 1). Special programs were written for the HP-86B to produce plots on the HP-9872B plotter.

3.0 ACCURACY CONSIDERATIONS

Various factors affected the absolute accuracy of the GPS receiver during static measurements. These included the following potential error sources:

* Receiver accuracy as determined by hardware/software performance;
* Transformation of geographic reference ellipsoids required for comparison of known geodetic sites with measured GPS user position:
* Geometric Dilution of Precison (DOP) associated with the satellite constellation;
* Changes in navigation constellation; and
* Satellite (data) upload, i.e., receiver acquisition of latest ephemeris data.

3.1 GPS RECEIVER ACCURACY

The LTN-700 specifications listed 40 meters for circular error probability (CEP) and 100 meters 2 drms for the horizontal position error. The error specification for velocity was 1/10th meter/second (0.2 mph). These accuracy requirements set the performance standards for the receiver, independent of external system errors.

The LTN-700 receiver error in user position approached the limits set by the above specifications and in some cases exceeded it during the initial stages of the GPS test program. Random shifts in user position (data) were observed which were unrelated to external system parameters. These errors were subsequently corrected by Litton with the substitution of new processor software. During March 1985, an additional software error was discovered by Litton associated with the difference in reference time between signals leaving the satellites and arriving at the receiver. This error manifested itself as a displacement in longitude of 0.8 to 1.2 arc seconds from the true position. (The magnitude of measured GPS longitude was less than the true longitude). Section 5.3 presents further discussion on observed GPS error displacements.

3.2 REFERENCE ELLIPSOID TRANSFORMATION

Measurements of GPS user position at geodetic sites provided the best means for defining the inherent accuracy of the GPS receivers. Coordinates for these sites are generally expressed in the North American Datum 1927 (NAD-27) reference system or in the State Plane Coordinate system appropriate to the local regional area (Ref. 2). GPS receivers use the World Geodetic System 1972 (WGS-72) as the standard adopted by the Department of Defense (DOD) for worldwide mapping. Comparison of the geodetic site coordinates with the GPS user position required the transformation of the appropriate datum ellipsoid (NAD-27 and State Plane) into the WGS-72 ellipsoid system. Computer programs for performing the coordinate transformations were obtained from the Radionavigation Information Branch, Office of Navigation, USCG.

The transformation of coordinates from NAD-27 to WGS-72 is shown in Table 4 below for the case of geodetic site RAY 1957, located near the Raytheon plant in Bedford, MA. The latitude coordinate increased by 0.163 arc second while the longitude coordinate decreased by 1.122 arc seconds. Also shown for comparison are WGS-72 coordinates measured using high resolution differential GPS equipment (Ref. 3). The close agreement between measured site coordinates and WGS-72 transformed coordinates confirmed the validity of the coordinates transformation within a possible error of 0.06 arc second latitude and 0.12 arc second longitude.

TABLE 4. POSITION COMPARISON TABLE (RAY 1957)

NAD-27	WGS-72 (computed)	WGS-72 (GPS)*
N42° 28' 35.709"	N42° 28' 35.877"	N42° 28' 35.936"
W71° 17' 16.374"	W71° 17' 15.252"	W71°17' 15.133"

3.3 GEOMETRIC DILUTION OF PRECISON

The dilution of precision (DOP) factors describe ranging errors associated with the geometry of the satellite constellation relative to user position. The DOP factors include dilution of precision in two horizontal dimensions (HDOP), in the vertical dimension (VDOP), and combined dilution of precision in three dimensions (PDOP), i.e., PDOP = Square root ($HDOP^2$+$VDOP^2$). Estimated HDOP and VDOP values for four-satellite constellations were available on both GPS receivers visual displays.

*Measured by differential.

Figure 2 shows the variation of HDOP and PDOP of the six-satellite configuration over a typical 24 hour period in the Boston area (Ref. 4). The number in parenthesis gives the number of satellites associated with the DOP characteristics. The large DOPs between 18:00 and 19:24 sidereal time* result in correspondingly large GPS errors during this time as discussed in Section 4.2. For this example, optimum GPS accuracy is predicted for measurements made between 19:30 and 21:25 sidereal time, the period when DOP is smallest.

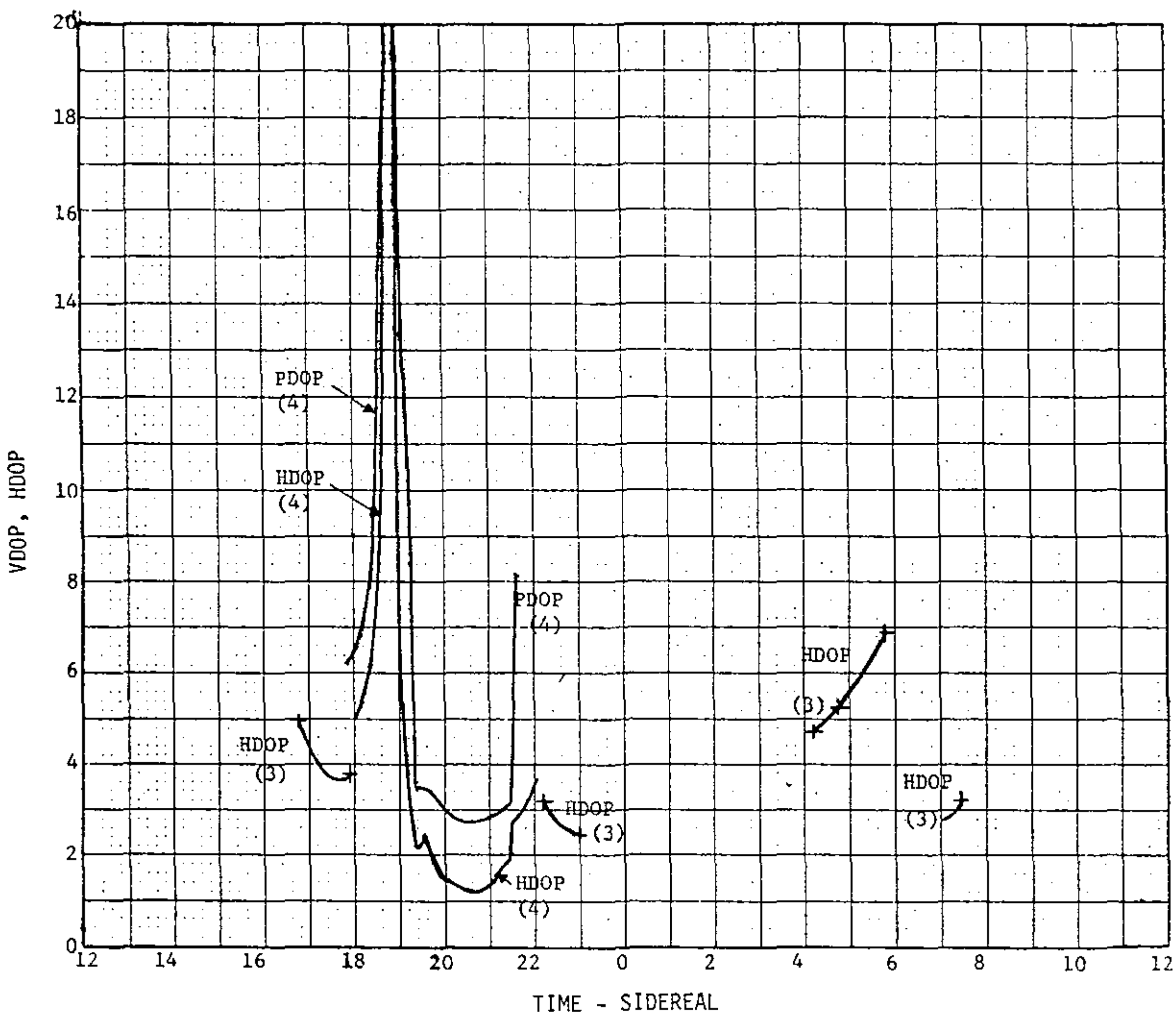


FIGURE 2. HDOP, PDOP VARIATION WITH TIME

* Sidereal time computed using the relation, Sidereal Time(Hr)=6.640392257+ 0.065098242(Julian Day)+1.00273791(GMT(Hr))

3.4 RECEIVER RESPONSE TO CHANGING SATELLITE CONSTELLATION

Both GPS receivers automatically selected the best four-satellite constellation based on geometric considerations. In most instances, the selection amounted to choosing the configuration with the lowest HDOP. Table 5 lists the constellations chosen by the LTN-700 during a test run with the primary satellite pass. During one 10-minute test period (20:54-21:04 sidereal time), the LTN-700 switched to three different satellite constellations. Only during the initial and final stages of the primary pass did the GPS receivers remain with a fixed satellite configuration for a period of time greater than 50 minutes.

TABLE 5. LTN-700 'SELECTED' SATELLITE CONFIGURATIONS

SAT Config.(SV#)	Time(hr:min,sidereal)
6 8 9 11	18:08-19:54
6 8 9 12	19:55-20:36
6 9 11 12	20:37-20:53
6 8 11 13	20:54-20:56
6 11 12 13	20:57-20:59
6 9 11 13	21:00-21:04
8 9 11 13	21:05-21:12
9 11 12 13	21:13-22:03

Frequent switching to alternate satellite constellations led to operational problems which were particularly troublesome during the the urban GPS navigation tests. In addition to short term interruptions in recorded data, selection of alternate satellite constellations often led to poorer receiver performance and occasionally to total loss of receiver (position) 'fix'. This problem was directly related to the restricted satellite visibility of the alternate constellation in urban areas with high-rise buildings.

4.0 STATIC TESTS

Static tests were conducted at fixed sites to study the following receiver characteristics:

* receiver accuracy as determined from ground truth measurements at geodetic sites

* receiver resolution, i.e., 2 drms error

* receiver response to changing satellite configurations

GPS receiver data was recorded on cassette tape to study the user-position variation with time. For the LTN-700, the standard procedure was to record 'L' block data continuously for 10 seconds at 2-minute intervals. For studies of receiver resolution requiring larger quantities of data, the 'L' block data was recorded continuously for longer periods of time, typically 120 seconds. For the T-Set, data was recorded at a rate which suited the test in progress.

4.1 GPS STATIC RESULTS

For the static test measurements conducted at the Transportation Systems Center (TSC), GPS antennas were positioned on the roof where there was an unobstructed view of overhead satellites.

GPS static tests generally lasted from 4 to 5 hours and provided data for scatter plots and position variation with time. Initial GPS data, obtained during the first several weeks of the test program, was invalid due to defective software in the LTN-700. This was evidenced by altitude variations in excess of 500 feet, and horizontal position variation greater than 100 meters 2 drms.* With the substitution of modified software, output position data met the receiver specification. The static measurements described in this report were obtained during test runs using the modified software including the ionosphere correction model incorporated into the LTN-700. No problem was encountered with the T-Set.

Typical GPS data showing latitude, longitude, and altitude variation with time are presented in Figure 3. With the exception of observations made when there were high DOPs, the receiver position stability was quite good. The LTN-700 outputs showed

* drms = distance root mean squared, a two-dimensional error term with a probability of 95.4 to 98.2 percent.

LTN-700 T-SET

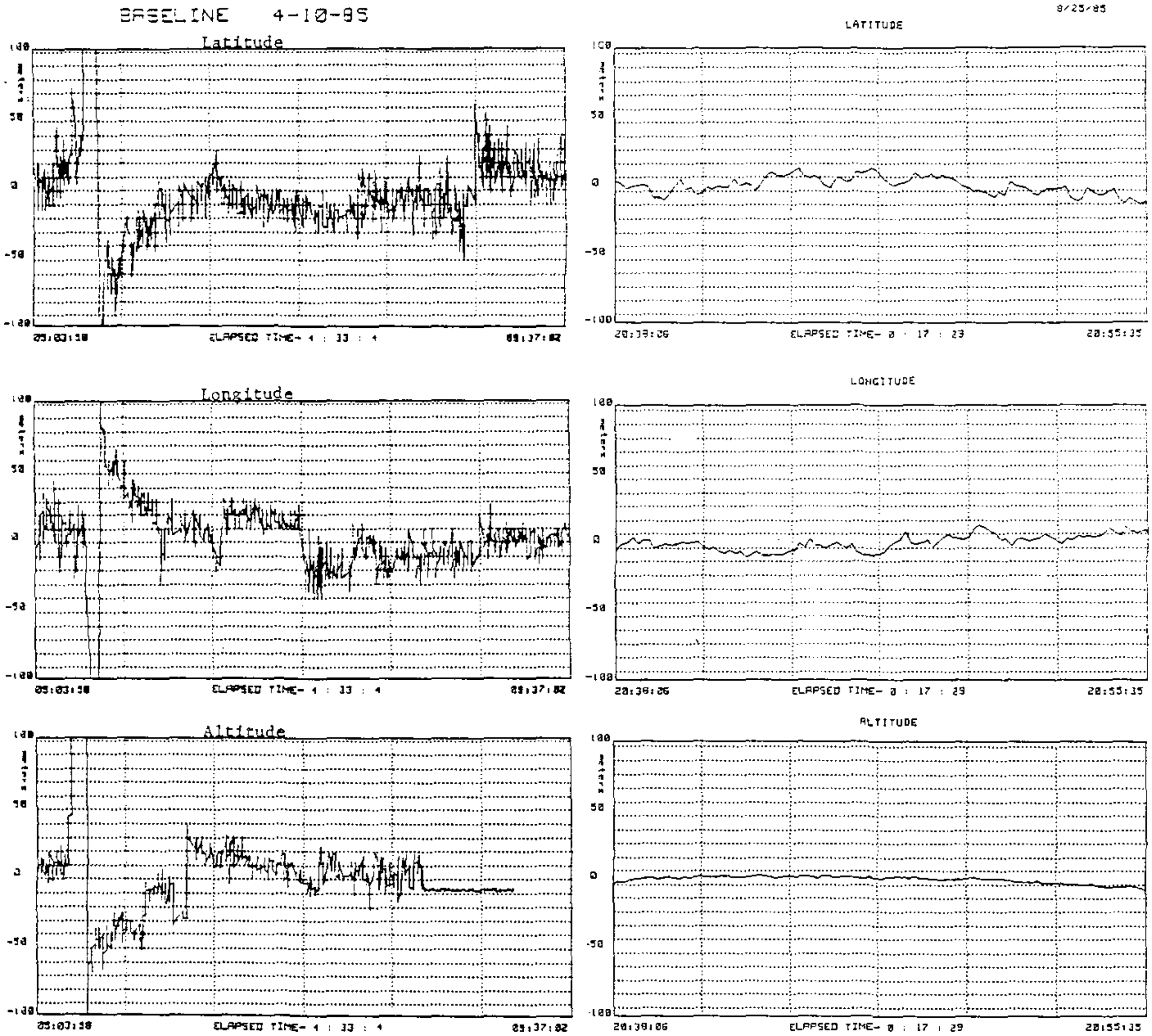


FIGURE 3. GPS STATIC POSITION VERSUS TIME

greater peak-to-peak variation than the T-Set. However, the T-Set had several tracking modes which apparently changed the positioning averaging constants.

The variation in the mean deviation in latitude and longitude and 2 drms error (in meters) for the LTN-700 over a 4-hour period are shown in Figure 4. Values were found by statistically averaging recorded data in successive 15 minute time intervals. The data showed that optimum GPS performance occurred between 19:54 and 20:24 sidereal time, during which the 2 drms error was below 20 meters. This was better than the LTN-700 specifications which gave 100 meters as the rated 2 drms error (see Table 1).

Typical GPS scatter plot of data taken during the period of minimum 2 drms error are shown in Figure 5. For the LTN-700 the data set was comprised of approximately 40 position points taken over a 2-minute period. The 2 drms error for the LTN-700 was 17.9 meters. For the T-Set, the 2 drms error was 3.4 meters.

4.2 LORAN-C STATIC RESULTS

Figure 6 presents typical LORAN-C scatter plots of data obtained with the Northstar 7000 and Accufix 600 receivers. These represent all data points over a 5 hour period. It was noted that the LORAN-C 2 drms error described by the elliptical curve is approximately the same order of magnitude as the 2 drms error for the LTN-700 given by the circular curve in Figure 5.

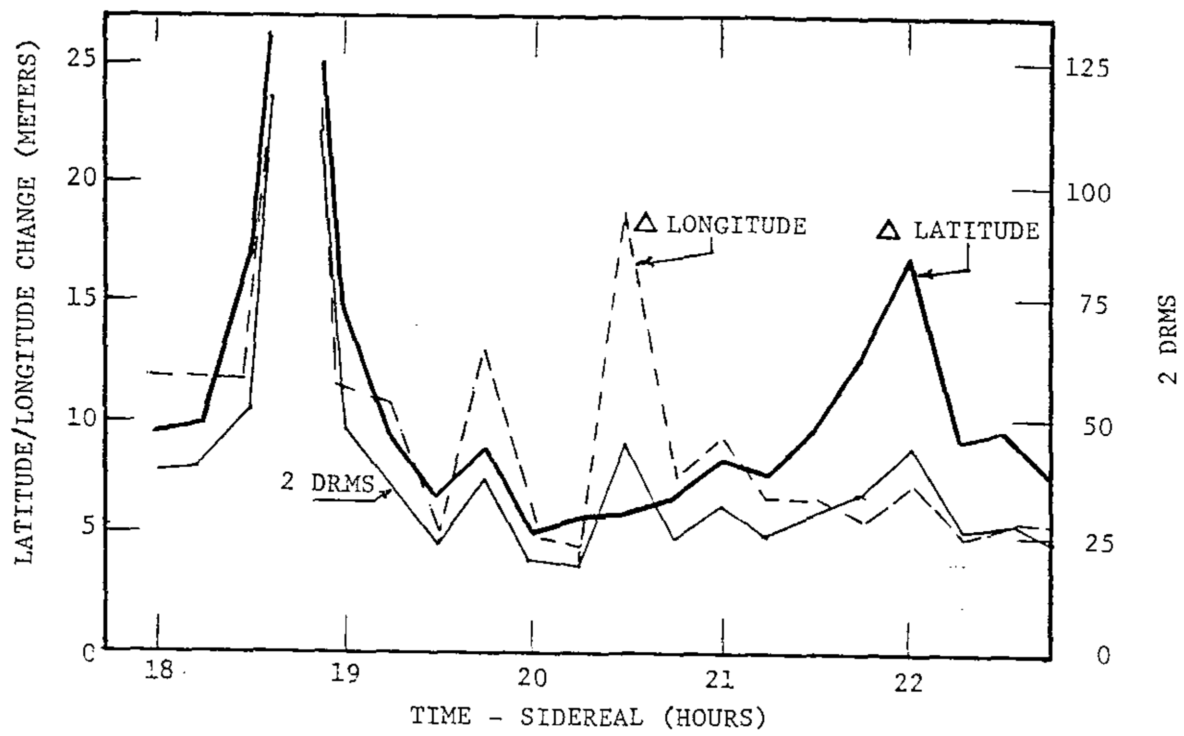
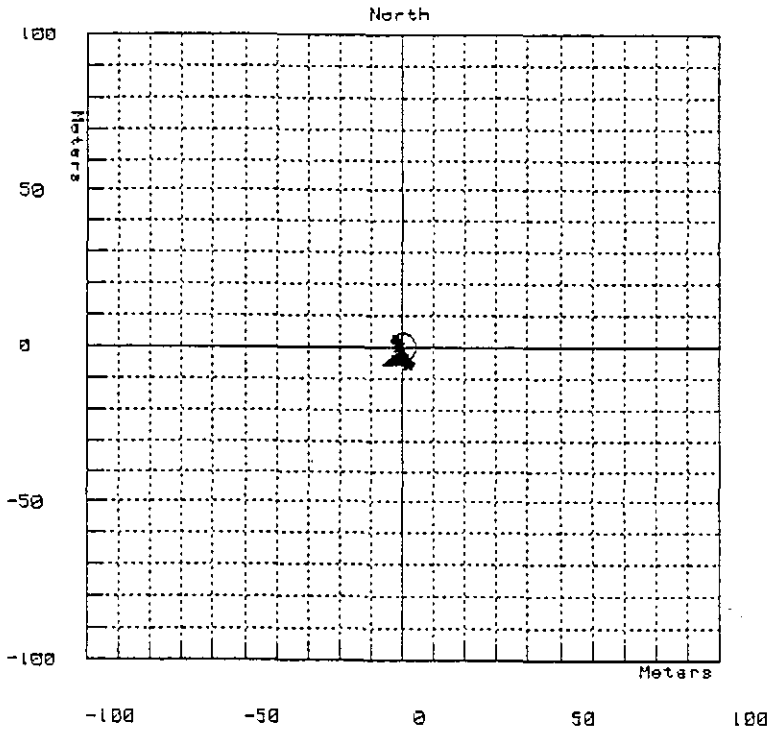


FIGURE 4. MEAN POSITION DEVIATION AND 2 DRMS ERROR VARIATION

T-Set



▲ Symbol Indicates Position of Survey Marker

LTN-700

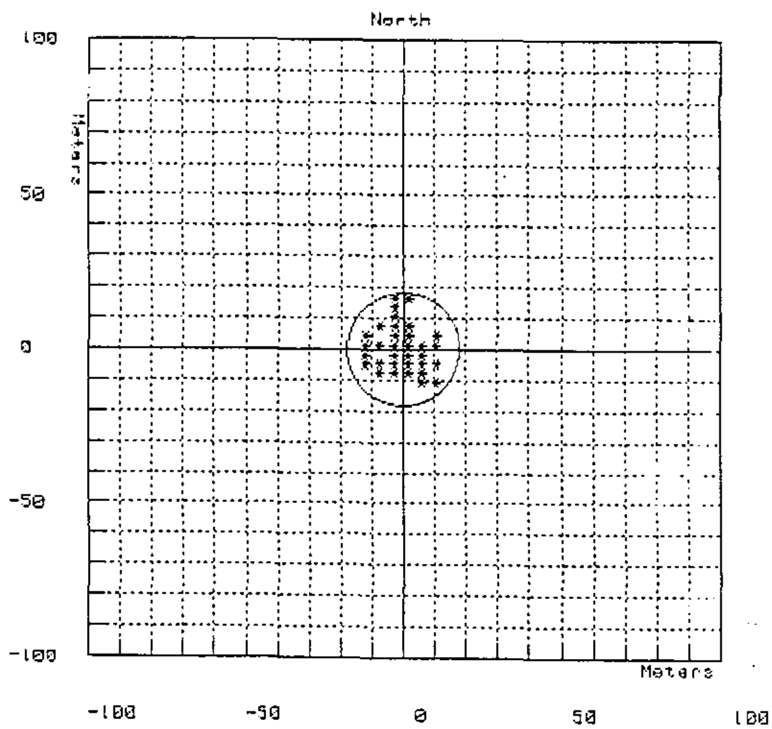
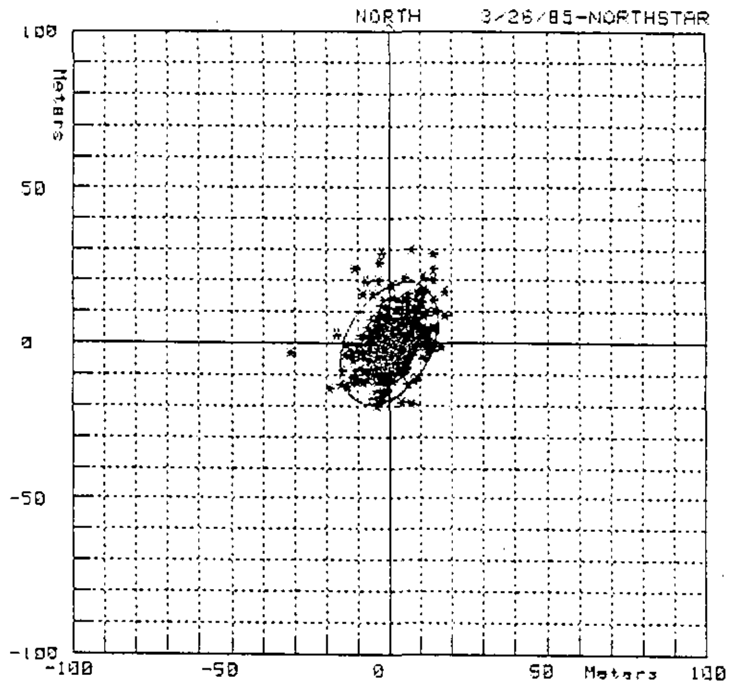


FIGURE 5. GPS SCATTER PLOTS AT MINIMUM 2 DRMS ERROR

Northstar 7000



Accufix 600

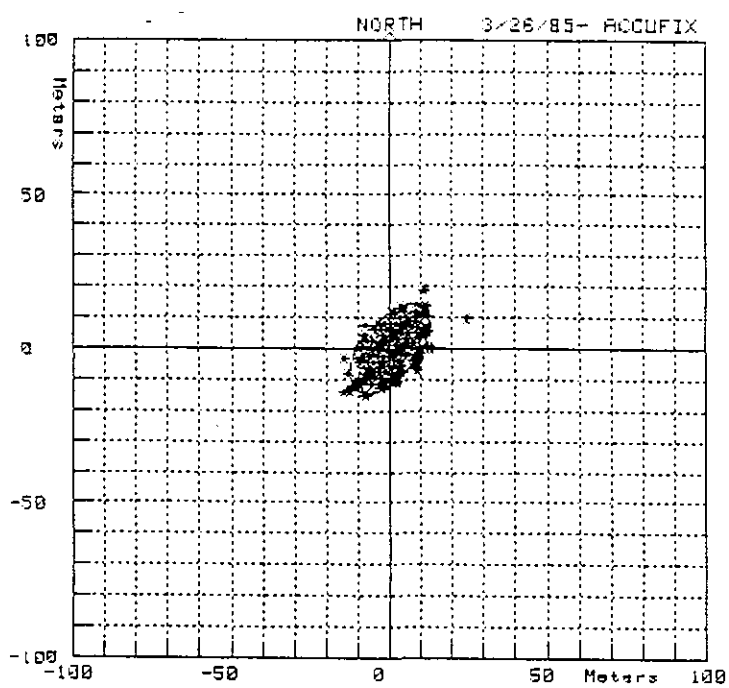


FIGURE 6. TYPICAL LORAN-C SCATTER PLOTS

5.0 MOBILE FIELD TESTS

GPS and LORAN-C mobile tests were conducted in urban, suburban, and rural environments. These tests had the following objectives:

* Determine absolute (position) accuracy of the GPS sets at selected geodetic sites;
* Gather GPS data to evaluate navigation capability of the receivers in urban, suburban, and rural environments;
* Document GPS satellite constellation visibilities for typical urban test runs;
* Study possible multipath and UHF noise interference effects on LTN-700 performance;
* Compare relative performance of GPS and LORAN-C for land navigation.

The equipment used in the mobile tests were mounted in a DOT mobile test facility (MTF). Figure 7 gives a view of the interior of the MTF showing the LTN-700

FIGURE 7. INTERIOR OF MOBILE TEST FACILITY (MTF)

and LORAN-C receivers and associated data gathering equipment. The LTN-700 L-band antenna was mounted on the MTF roof for maximum exposure. Separate 8-foot whip antennas for the LORAN-C receivers were attached to the rear of the MTF. Electrical power (120 VAC, 60 Hz) for the test measurements was supplied by a 4 kW Onan generator housed in a trailer attached to the rear of the MTF.

The mobile test program consisted of four major categories encompassing a wide variety of tests. The initial phase of the mobile tests centered on LTN-700 performance as measured by the acquisition of the minimum number of satellites required for position 'fix'. These tests involved a statistical determination of the number of satellite acquisitions by the receiver in different environments. Since receiver satellite acquisition is critical to effective GPS operation, the latter tests were given high priority. Ground truth measurements were conducted at selected geodetic sites in the greater Boston area to document the accuracy of the LTN-700 for position identification. Mobile runs were made in different surroundings to study the relative navigation capabilities of GPS and LORAN-C. Special emphasis was given to GPS performance in downtown Boston where tall buildings limit satellite visibilities. Finally, tests were conducted to investigate the effect of noise and multipath interference on GPS performance and measurement accuracy.

The LTN-700 was used for the bulk of the tests. Data analysis was complete when the T-set became available. Due to limited time, tests for the T-set were made at TSC, Arteries 10 and 12, and underway in Boston. The T-set also provided data for foliage tests.

5.1 DATA ACQUISITION AND MANAGEMENT

The receivers provided an enormous amount of data in a short period of time. A typical LTN-700 output during a navigation transmit would include time, position (latitude, longitude and altitude), four sets of satellite (SV) identification and status (SV number, signal to noise number (SNR), altitude, azimuth, health), horizontal dilution of precision (HDOP), velocity (horizontal and vertical) and course. Each traffic transit, typically 5 minutes long, would fill a standard HP storage cassette. LORAN-C receivers would provide time, position, time differences (TDs), SNRs for each station tracked, course and speed. Actual output data and format varied considerably between units, requiring individual sort and analysis programs. Tapes and discs were numbered sequentially, carefully dated and a log of all test runs was maintained. The data set for underway navigation contained more than 500,000 items, and over 10,000 positions were examined. Individual sort programs were used to examine parameters of interest; for example, position or identification and number of satellites tracked. All information was time tagged to facilitate cross comparisons. An outline of the mobile test program is as follows:

1) Receiver Satellite Acquisition Characteristics

2) Ground Truth Measurements at Geodetic markers

   ARTERY 10

   ARTERY 12

   ARTERY 13

   RAY 1957

   BEDFORD 1940

3) GPS Navigation Studies

   Boston (urban)

   Charlestown (urban)

   Bedford (suburban)

   Salem (small city)

   North Shore (rural)

4) Noise Interference, Multipath Studies

   Marsh at Lynn, MA

   In-house Tests at TSC

   Power Substation at West Medway, MA

   UHF TV Antennas at Rt. 128

5) Foliage Tests - Topsfield, MA

5.2 SATELLITE VISIBILITY CHARACTERISTICS

Current GPS system specifications set a minimum satellite elevation angle of 7.5 degrees as required for effective GPS operation. In terrestrial applications, receiver satellite acquisition was more often determined by the limiting satellite exposure imposed by the surrounding environment. GPS operation requires four satellites for a position 'fix' or, in the case of Altitude Hold (AH), a minimum of three satellites. To insure effective GPS operation, the elevation angles of at least three satellites should exceed the blocking angles of any intervening obstacles.

Figure 8 shows the satellite elevation angles for all six satellites on April 1, 1985 as seen by the receiver at Cambridge, MA. The operating times during a 24-hour period when three- and four-satellite configurations were visible is indicated above the figure. Four-satellite acquisition was possible for only 4 hours with the current constellation, while three-satellite acquisition was possible for 8 hours. These maximum acquisition times are reduced by uneven terrain in rural areas and elevated structures characteristic of urban areas. Typically, urban buildings can extend signal blocking angles of 40 degrees which, according to Figure 8 would limit GPS operation to only 90 minutes per day. This demonstrates how receiver environments can reduce GPS operational time considerably below that anticipated for satellite constellations with the minumum 7.5 degrees elevation angle.

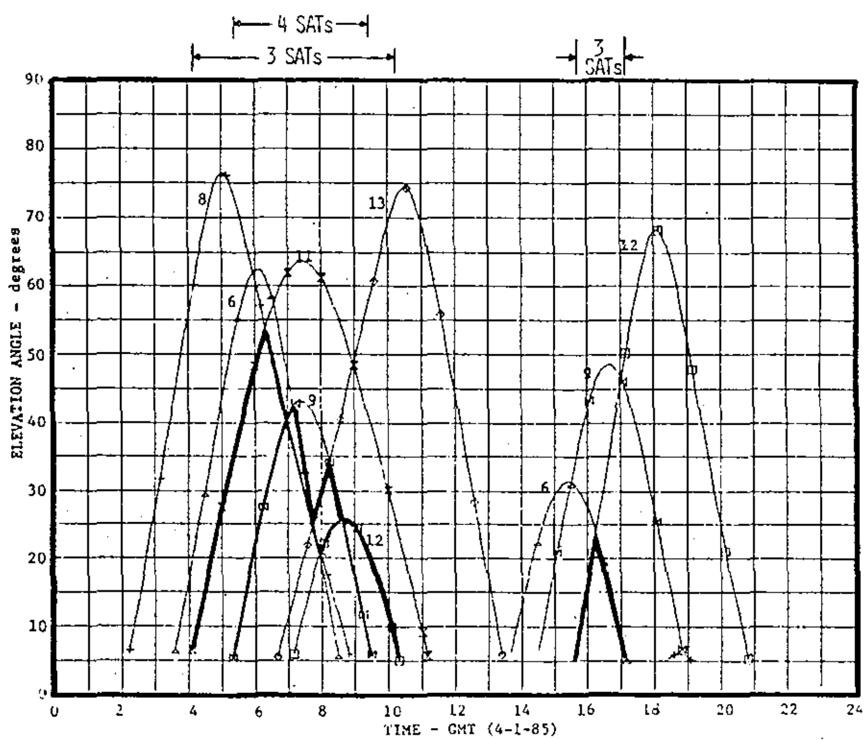


FIGURE 8. SATELLITE ALTITUDE CHARACTERISTICS

5.3 SATELLITE VISIBILITY DURING TRAFFIC TRANSITS

The number of receiver satellites tracked at any instant provides a useful indicator of receiver performance in 'hostile' environments. In certain urban environments characterized by reduced satellite visability, the number of satellite 'fixes' can easily fall below the minimum of three required for GPS position determination. To quantify the limitations imposed on GPS by surrounding environments, the number of tracked satellites was recorded for the LTN-700 along with the GPS position data. This could not be done for the T-Set due to limitations in data output. This information was then used to determine the statistical average of satellite availability over the given test route.

Table 6 shows the percent of GPS data obtained with a four-satellite fix and the corresponding data acquired with a minimum of a three-satellite fix for 13 mobile test

TABLE 6. OBSERVED GPS SATELLITE AVAILABILITY

Trip Run	Time(Sid)	4 SATs(%)	3 SATs(%)	SATs Above 7.5°*
Bunker Hill 1	19:18	0.0	51.1	6 8 9 11
Bunker Hill 2	19:22	80.7	96.5	6 8 9 11
Bunker Hill 3	19:27	75.0	87.5	6 8 9 13
Bunker Hill 4	19:35	17.5	61.4	6 8 9 11
Comm Ave 1	20:00	0.0	76.5	6 8 9 11
Comm Ave 2	20:06	2.4	93.3	6 8 9 12
Comm Ave 3	20:15	24.3	72.1	6 8 9 11
Salem 1	20:20	14.8	48.1	6 8 11 13
Comm Ave 4	20:22	42.8	74.9	6 8 9 11
Bedford Comm 1	20:29	36.5	100.0	6 8 11 13
Comm Ave 5	21:00	41.1	82.2	9 11 12 13
Tremont St	21:24	29.0	55.7	9 11 12 13
Bedford Comm 2	21:47	100.0	100.0	9 11 12 13

* Satellite selection through control of processor.

runs using the LTN-700. Runs are listed in chronological order beginning at 19:18 sidereal time and ending at 21:47 sidereal time. For the Tremont Street run, which described a route through downtown Boston, the receiver acquired a four-satellite fix for only 29 percent of the time while for a three-satellite fix (minimum), the percent time was extended to 56 percent. Other urban test runs experienced generally higher percentages of fix time. Best results were obtained for the Bedford Common run where GPS operation with a four-satellite fix was realized over the complete run.

The satellite configurations corresponding to the mobile runs were included in Table 6. In terms of maximizing the number of fixes, satellite configurations SV6-8-9-11 and SV9-11-12-13 proved the best choices. This stems partly from the particular choice of test route in relation to the stellar locations of the satellites and partly to the fact that these configurations were 'available' for longer time periods than the other configurations. Other satellites were declared "unhealthy" for the LTN-700 since this improved availability figures.

5.4 GROUND TRUTH MEASUREMENTS

Three different areas in the greater Boston area were selected for GPS ground truth studies. These included three sites at or near Nashua Street, Boston (ARTERY 10, 12, 13) and two sites located at Bedford, MA, (RAY 1957, BEDFORD 1940) In each case, the receiver antenna was positioned as close to the geodetic sites as physically possible.

5.4.1 GPS Survey Results

Typical GPS scatter plots for four of the five geodetic sites are shown in Figure 9 and Figure 10. Performance at the fifth site was representative of those included in the report. The origin in each plot was found by separately averaging the measured latitude and longitude. The circles show the receiver 2 drms error computed using the relation:

2 drms = 2 (square root) of (VAR(x) + VAR(y))

where: VAR(x) and VAR(y) are the positional variances associated with longitude and latitude, respectively.

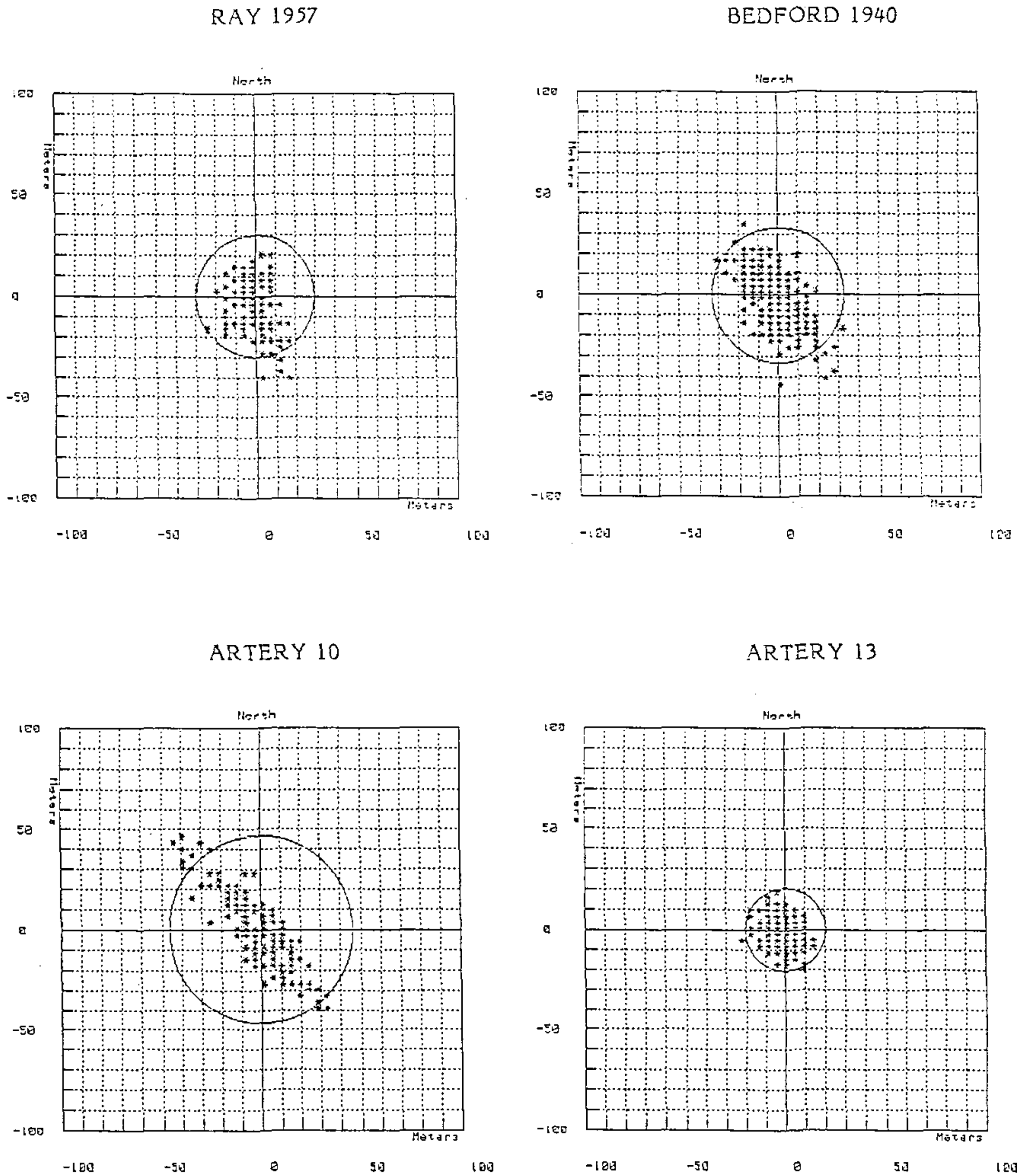


FIGURE 9. TYPICAL LTN-700 GROUND TRUTH SCATTER PLOTS

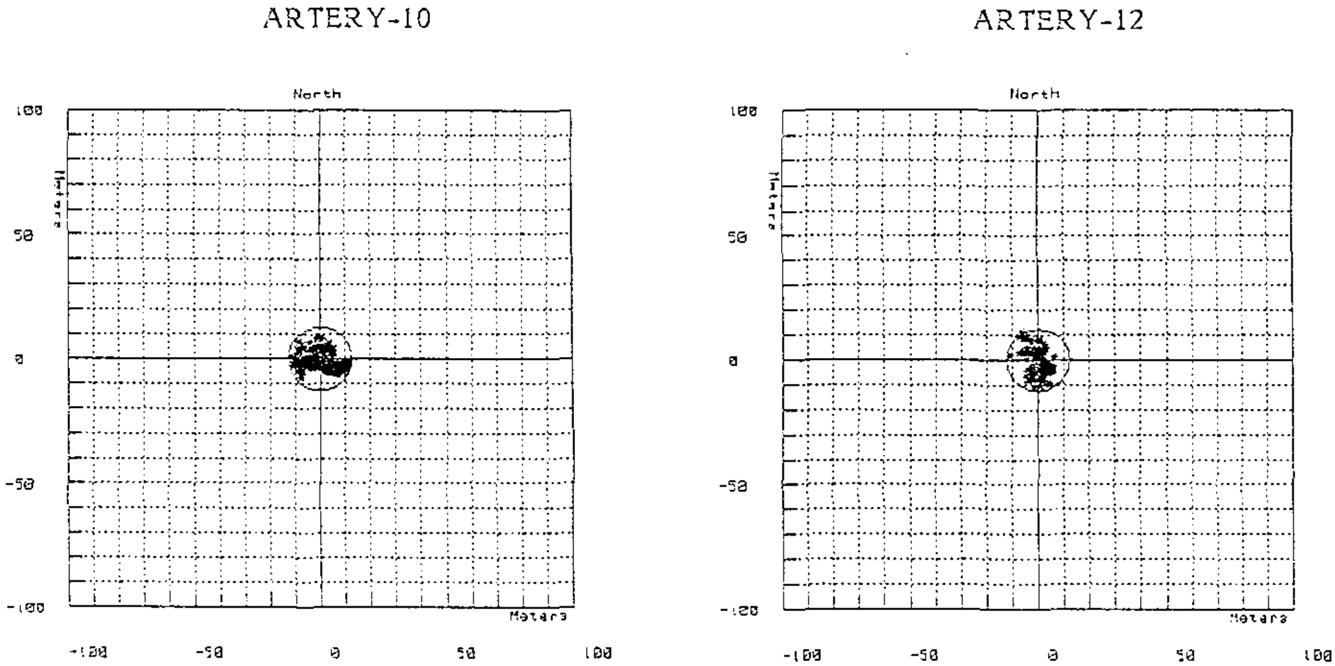


FIGURE 10. TYPICAL T-SET GROUND TRUTH SCATTER PLOTS

Table 7 presents the measured GPS position for the LTN-700 and the T-set as well as the corresponding survey coordinates (WGS-72) for the different sites. Data was adjusted for the difference in position between the receiver antenna and the actual site position. The measured 'user' position showed a consistent displacement in position from the true site coordinates which was most apparent in the GPS longitude.

TABLE 7. GPS GROUND TRUTH MEASUREMENTS

SITE	SURVEY COORDINATES		LTN-700 MEASUREMENT		T-SET MEASUREMENT	
	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
RAY 1957	N42°28'35.88"	W71°17'15.25"	N42°28'35.64"	W71°17'14.02"		
BEDFORD1940	N42°29'30.56"	W71°16'46.19"	N42°29'30.63"	W71°16'44.62"		
ARTERY 10	N42°21'59.24"	W71°03'51.10"	N42°21'58.96"	W71°03'49.86"	N42°21'59.27"	W71°03'51.35"
ARTERY 12	N42°22'01.66"	W71°03'58.27"	N42°22'00.90"	W71°03'56.56"	N42°22'01.71"	W71°03'58.76"
ARTERY 13	N42°22'00.59"	W71°04'08.15"	N42°22'00.15"	W71°04'06.79"		

The coordinate differences in Table 8 were used to estimate the limiting accuracy of the LTN-700 for position location. Table 9 lists the position displacement errors (arc sec) in latitude and longitude for each site. Average error (mean deviation) for the set of LTN-700 measurements was 0.48 arc second latitude and 1.49 arc seconds longitude. Part of the longitude displacement error was attributed to receiver software errors which have been shown by Litton to reduce the observed longitude by 1.05 arc seconds, i.e., GPS user position is 1.05 arc seconds east of true site position. Adjusting the data for this displacement error led to net error displacements of 0.48 arc second (14.3 meters) latitude and 0.44 arc second (10.1 meters) longitude. This equals an average maximum error of 17.9 meters for the LTN-700 receiver in locating absolute position. A similar computation for the T-set gave 8.56 meters.

TABLE 8. GPS POSITION ERROR DISPLACEMENTS

SITE	LTN-700		T-SET	
	Latitude Error	Longitude Error	Latitude Error	Longitude Error
RAY 1957	-0.18"	-1.23"		
BEDFORD 1940	-0.74"	-1.91"		
ARTERY 10	-0.28"	-1.24"	-0.03"	-0.25"
ARTERY 12	-0.76"	-1.71"	-0.05"	-0.49"
ARTERY 13	-0.44"	-1.36"		

TABLE 9. ASF VALUES AT SURVEY POINTS

	POSITION REFERENCE		ASF (usec)		
Site	Latitude	Longitude	W	X	Y
ARTERY #10	N 42° 21' 59.53"	W 71° 03' 49.92"	0.67	2.07	0.39
ARTERY #12	N 42° 22' 0.55"	W 71° 03' 56.06"	0.83	1.92	0.27
ARTERY #13	N 42° 22' 1.13"	W 71° 04' 7.30"	0.94	2.34	0.43
TSC	N 42° 21' 51.00"	W 71° 05' 9.00"	1.00	2.47	0.40
BEDFORD COMMON	N 42° 29' 29.87"	W 71° 16' 44.81"	0.85	1.47	0.50
RAYNAV 1957	N 42° 28' 36.13"	W 71° 17' 15.26"	0.02	1.83	0.15
LYNN MARSHES	N 42° 25' 51.23"	W 70° 59' 49.75"	1.11	2.94	1.45
AVERAGE			0.77	2.13	0.51

5.4.2 LORAN-C Survey Results

The gradients and crossing angles of LORAN-C signals in the Boston area are excellent. Position scatter, some observed over a 5 hour period, showed Time Differences (TD) variances of less than 50 ns. The two receivers normally agreed within 50 ns for all TDs. Scatter plots are shown for each receiver for four of the survey sites (Figures 11 and 12). The legend below each plot provides the 95 percent probability error ellipse, the variance (Sigma) for each TD, the cross-correlation of TDs (Rho), the maximum North/South variation (ATE), the maximum East/West variation (CTE), and the mean position (LAT/LON).

Data at Bedford Common and RAY 1957 were taken during rain squalls. Both LORAN-C receivers indicated reduced SNR conditions. Position scatter was larger than at other sites where the weather was clear.

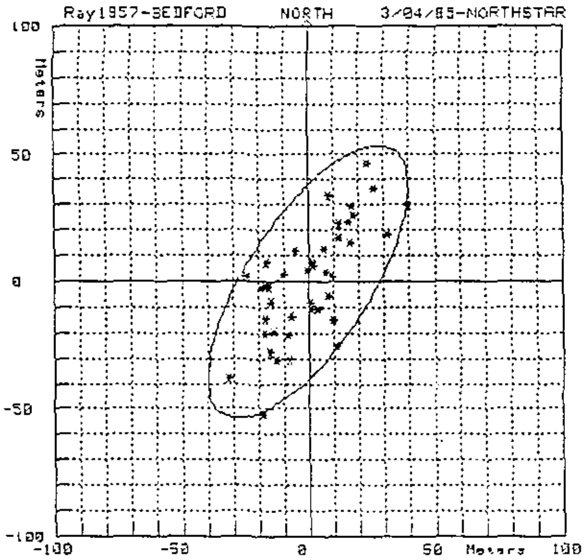
While the TDs agree, the latitude/longitude outputs from the receivers did not. This was due to the fact that the Northstar 7000 uses preprogrammed, automatic additional secondary phase factor (ASF) corrections while the Accufix 600 uses an operator initiated correction which is added to all fixes once entered. ASF* is the TD correction necessary to compensate for propagation variation caused by terrain. If ASF is constant in an area, position outputs will be accurate once the ASF is determined.

Predicted TDs were calculated for each position using the standard USCG EEE-10A program which was provided by the Radio Navigation Division of USCG Headquarters (G-NRN-3). ASF numbers were calculated through differencing observed versus predicted TDs, then an average ASF value was produced for the area. ASF values for the static positions are shown in Table 9.

In Boston, the WX triad produces the best accuracy, with the WY triad producing slightly less accurate fixes. Resultant position variations are shown in Figure 13. The WX triad produced offsets of less than 150 meters, while the WY triad was within 300 meters. The vector diagrams suggest that the grid was warped at the RAYNAV and Lynn Marsh sites. The observed ASF variations were sufficiently large that correct identification of individual streets in urban situations was not possible.

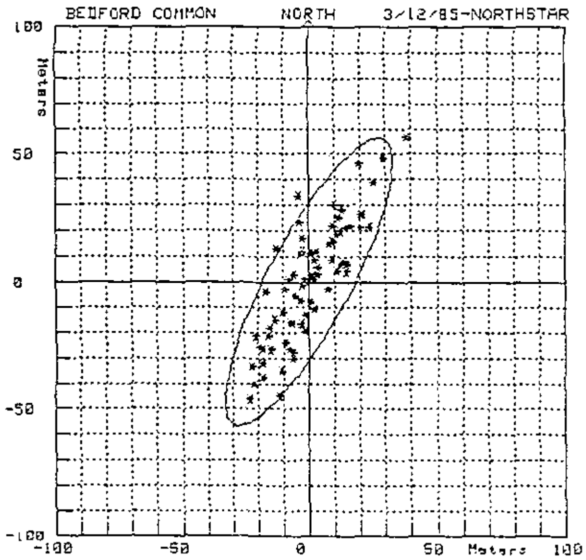
*ASF has been defined by the Coast Guard as the amount, in microseconds, by which the time difference (TD) of an actual Loran signal that has traveled over varied terrain differs from that of an ideal signal which has been predicted on the basis of travel over an all-seawater path. (Loran signals travel slower over ground).

RAY 1957



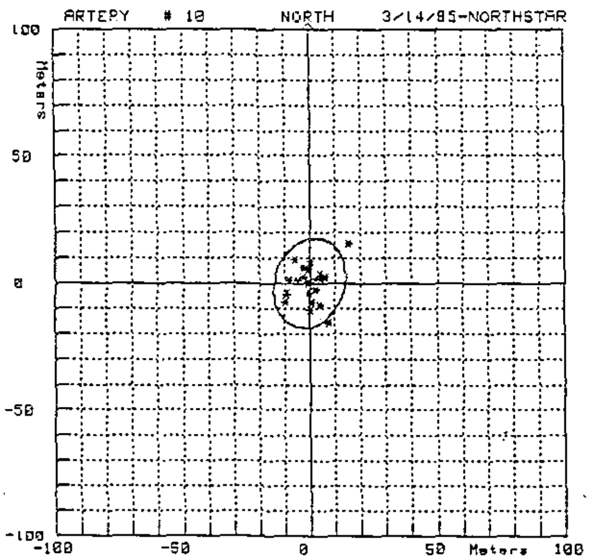
Probability of 95 %
Rho W X = .430
Max ATE = 54 Meters
Max CTE = 40 Meters
Sigma W = .127 usec
Sigma X = .062 usec
Mean LAT = 42 29 1
Mean LON = 71 17 32

BEDFORD 1940



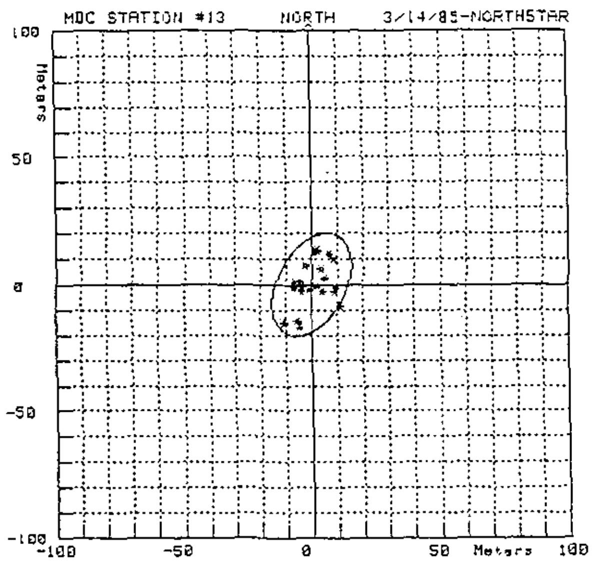
Probability of 95 %
Rho W X = .165
Max ATE = 56 Meters
Max CTE = 23 Meters
Sigma W = .122 usec
Sigma X = .040 usec
Mean LAT = 42 29 58
Mean LON = 71 17 17

ARTERY 10



Probability of 95 %
Rho W X = .332
Max ATE = 18 Meters
Max CTE = 14 Meters
Sigma W = .036 usec
Sigma X = .035 usec
Mean LAT = 42 22 3
Mean LON = 71 4 24

ARTERY 13



Probability of 95 %
Rho W X = .298
Max ATE = 20 Meters
Max CTE = 15 Meters
Sigma W = .043 usec
Sigma X = .033 usec
Mean LAT = 42 22 6
Mean LON = 71 4 10

FIGURE 11. TYPICAL NORTHSTAR 7000 GROUND TRUTH SCATTER PLOTS

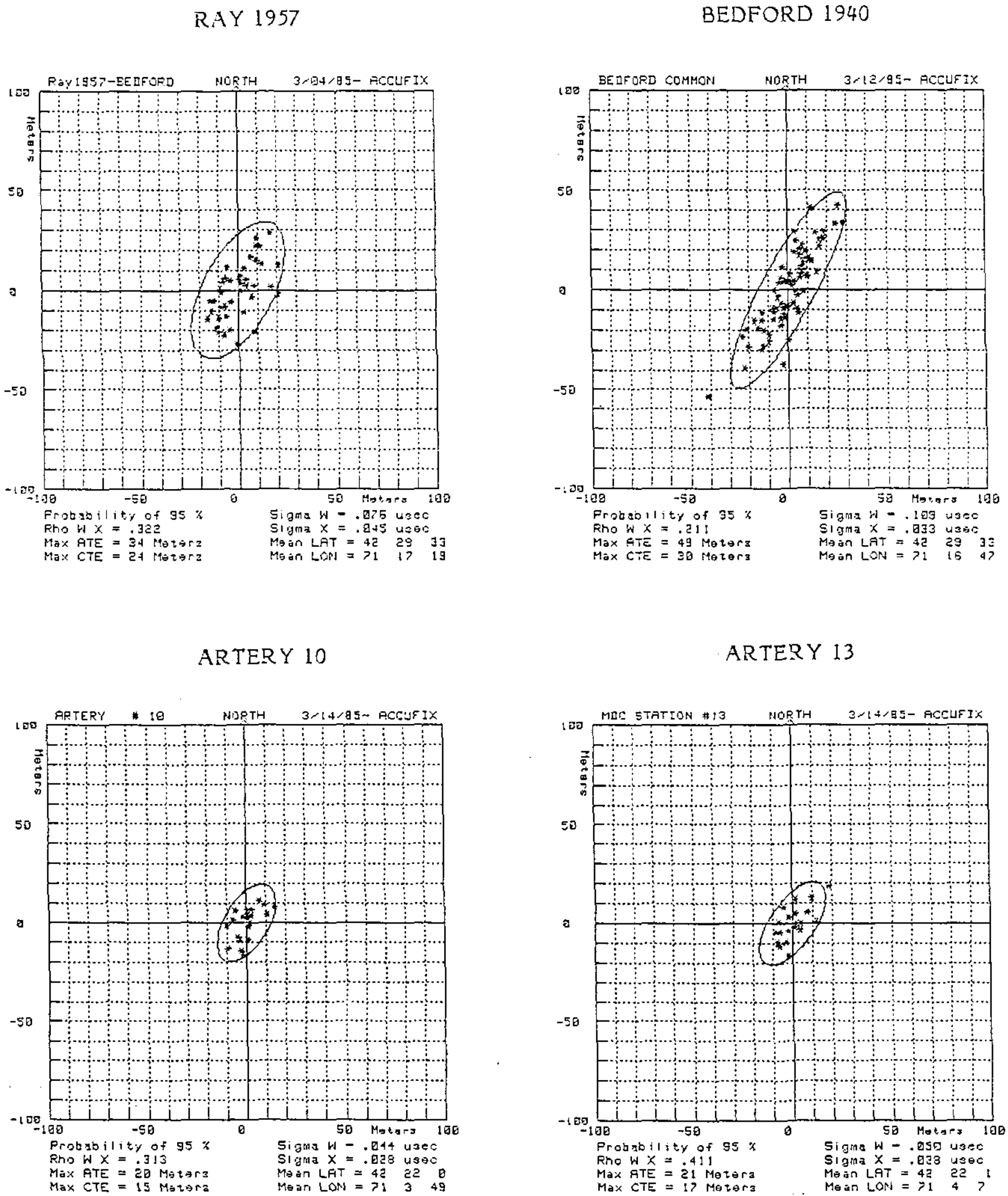
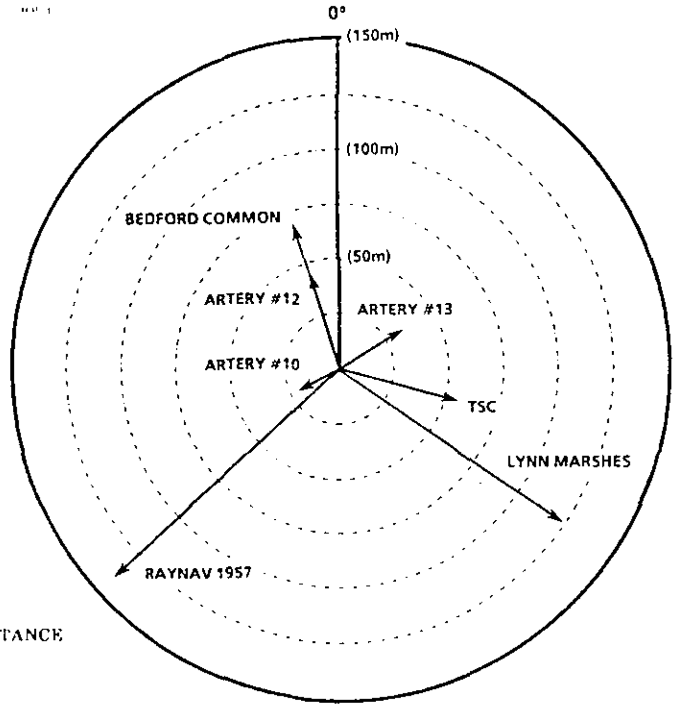


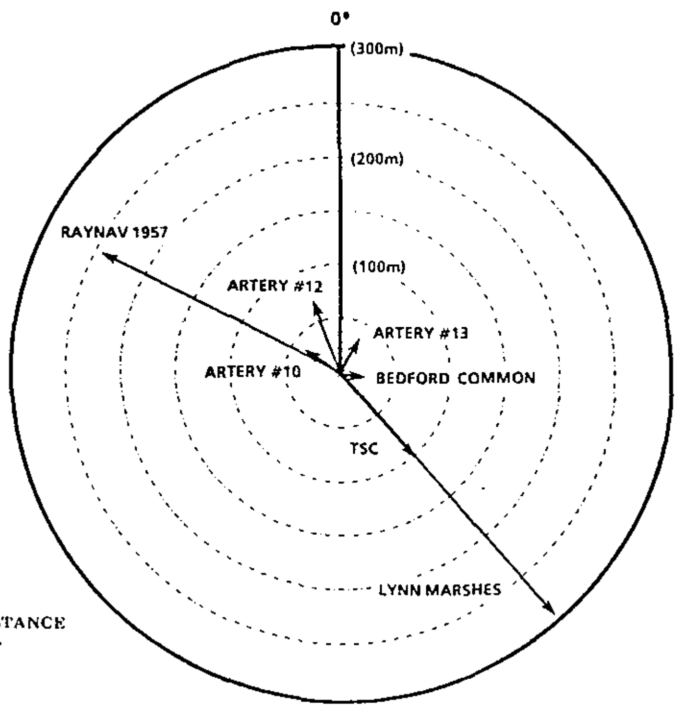
FIGURE 12. TYPICAL ACCUFIX GROUND TRUTH SCATTER PLOTS

RANGE/BEARING W-X



AVERAGE W-X DISTANCE OFFSET IS 72.02m.

RANGE/BEARING W-Y



AVERAGE W-Y DISTANCE OFFSET IS 115.68m.

FIGURE 13. LORAN-C POSITION VARIATIONS FOR SURVEY POINTS

5.5 NAVIGATION TESTS

Navigation tests were made in different communities to study how well the GPS receivers could track selected test routes. Position data were recorded and the resulting files were used to generate map plots.

The LTN-700 GPS navigation plots were displaced in position from the actual test route by amounts roughly equal to the error displacements shown in Table 8. LORAN-C plots were similarly displaced due to Additional Secondary Phase Factor. To facilitate evaluation, all navigation plots were shifted in position to give the best fit to the test route in question. The best fit approach also minimized the errors associated with map accuracies and ellipsoid transformation.

Table 10 lists the location and type of each navigation test run. The number of runs made at each location is given in parenthesis. GPS plots are presented for sample runs for each route category to illustrate the navigational performance of the LTN-700 in different surrounding environments.

TABLE 10. SUMMARY OF GPS NAVIGATION TESTS

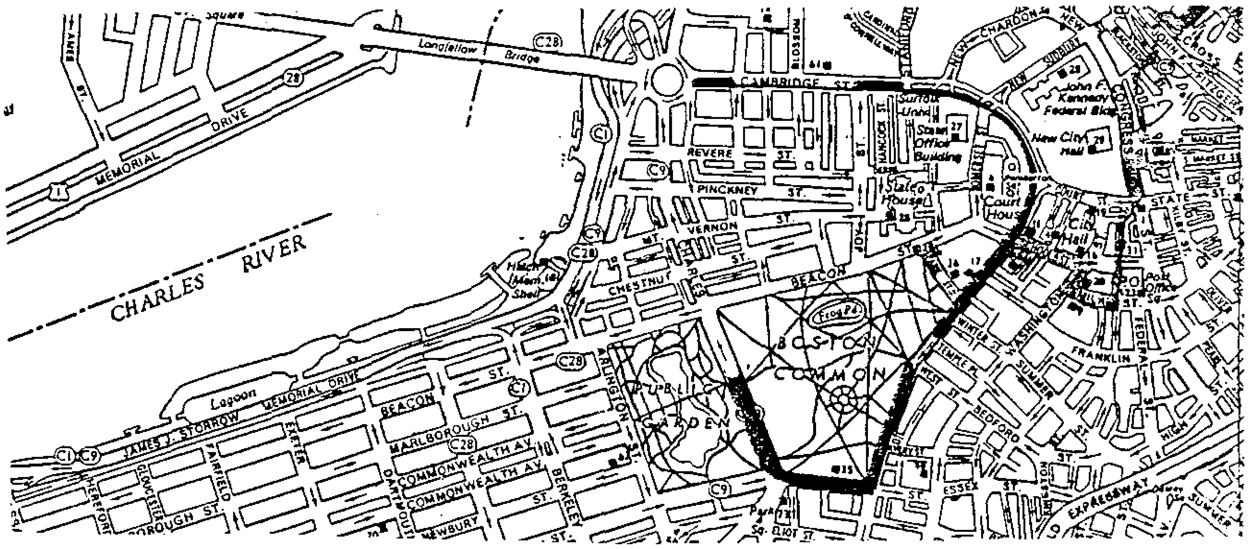
Location	LTN-700	T-Set
	Type (Number of runs)	
Tremont St., Boston	Urban (3)	Urban (2)
Public Garden, Boston	Urban (2)	
Commonwealth Ave, Boston	Urban (5)	Urban (5)
Bunker Hill, Charlestown	Urban (5)	
Bedford Common, Bedford	Rural (3)	
Salem City, Salem	Urban (2)	
Route 95 North, South	Rural (5)	
Topsfield, MA	Rural (5)	Rural (3)

5.5.1 Tremont St., Boston Run

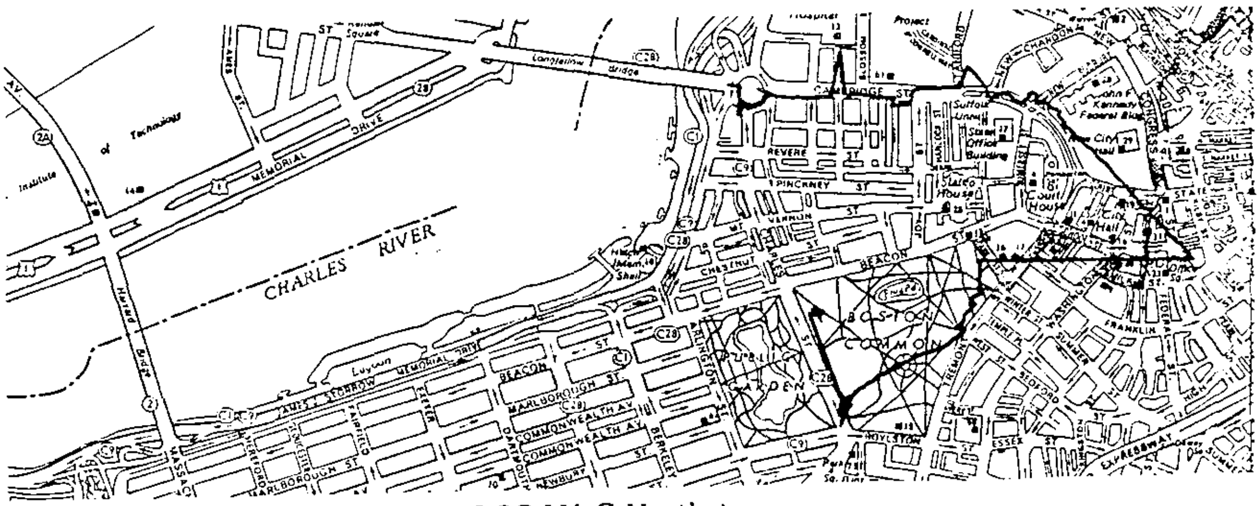
Figure 14 shows the route through a highly developed downtown area in Boston. The GPS and LORAN-C navigation plots exhibit similar behaviors with both types of receivers often showing course deviations at the same general locations.

In the vicinity of the Government Center, a close-packed complex of high rise buildings, satellite acquisition was reduced to a single satellite. The marked departure

Tremont St. Test Route



GPS



LORAN-C Northstar

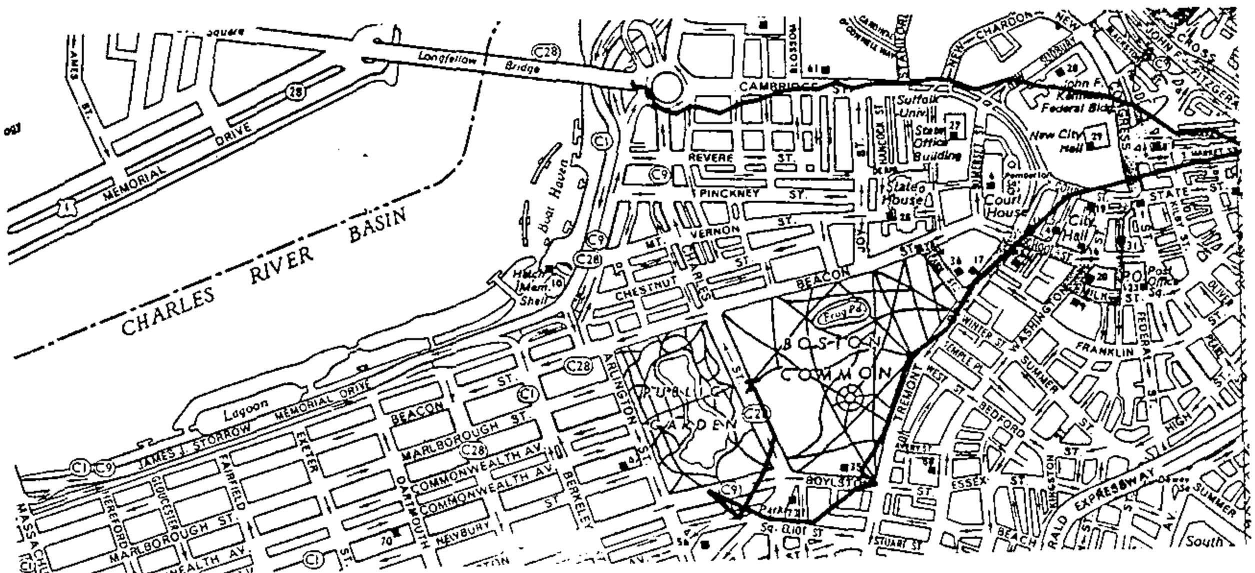


FIGURE 14. TREMONT ST., BOSTON NAVIGATION PLOTS

of the GPS receiver's position from the test route confirmed the receiver's inability to track with fewer than the minimum required number of satellites. Prior to reaching the route destination, a four-satellite 'fix' was obtained and the receiver was able to track the final segment of the run. While only one transit for each receiver is shown, the performance for each test run was repetitive. Both GPS receivers experienced problems in the same area and never fully recovered until the MTF turned into the Boston Common area where there was unobstructed visibility.

Both LORAN-C receivers tracked the course route except for two deviations. These deviations were associated with sharp fall-offs in SNR at Government Center and at the location of the intersection of Boylston and Tremont Streets. This performance was repeatable and was duplicated on each transit.

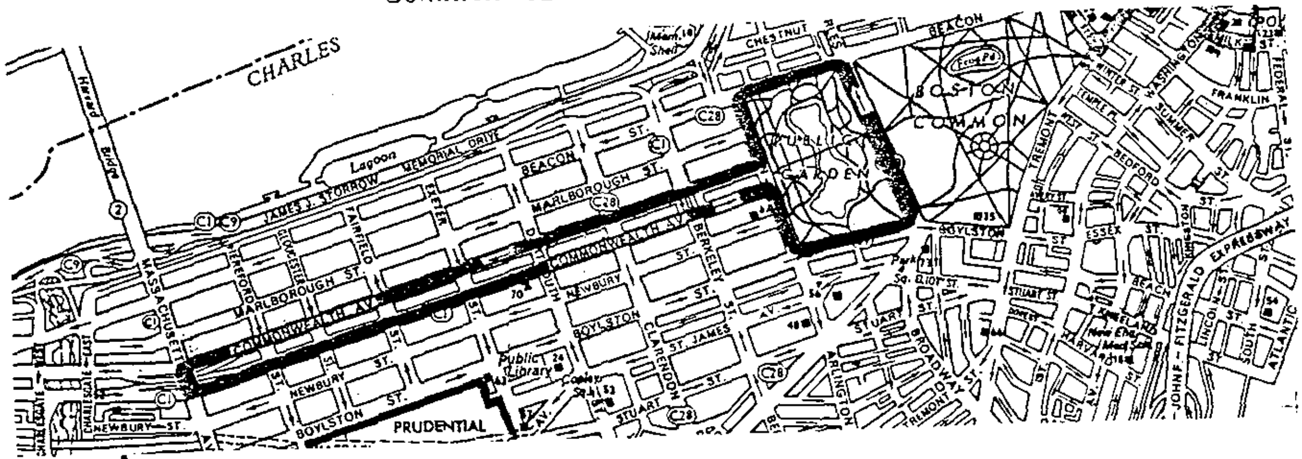
5.5.2 Commonwealth Avenue, Boston Run

Five Commonwealth Avenue runs were made with each receiver over the route comprising a perimeter around the Boston Public Garden combined with a return-trip run along Commonwealth Avenue. The test route was characterized by a continuous row of buildings on the outer perimeter of the route and a comparatively unobstructed view along the inner perimeter of the route. The four-story apartment buildings along Commonwealth Avenue have an average height of 65 feet and extended a shadowing angle of about 60 degrees from the building closest to the MTF and about 18 degrees from the buildings on the other side of the avenue. Along Arlington Street at the intersection of Commonwealth Ave, the Ritz-Carlton hotel provided a blocking angle approaching 80 degrees along the westerly direction.

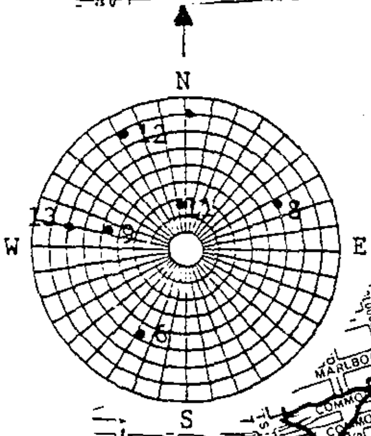
Figure 15 shows the GPS and LORAN-C (Accufix 600) navigation runs over the identical course. GPS operation was complicated by the LTN-700 attempting to lock onto alternate satellite configurations. This ocassionally resulted in loss of position lock when 'new' satellites were blocked from view by high buildings. The test run started with configuration SV6-8-9-11, switched to SV8-9-13, and later to SV6-8-9-13. The polar plot of satellite elevation and azimuth shows the locations of the six satellite during the course of the run.* While configuration SV6-8-9-12 was the preferred

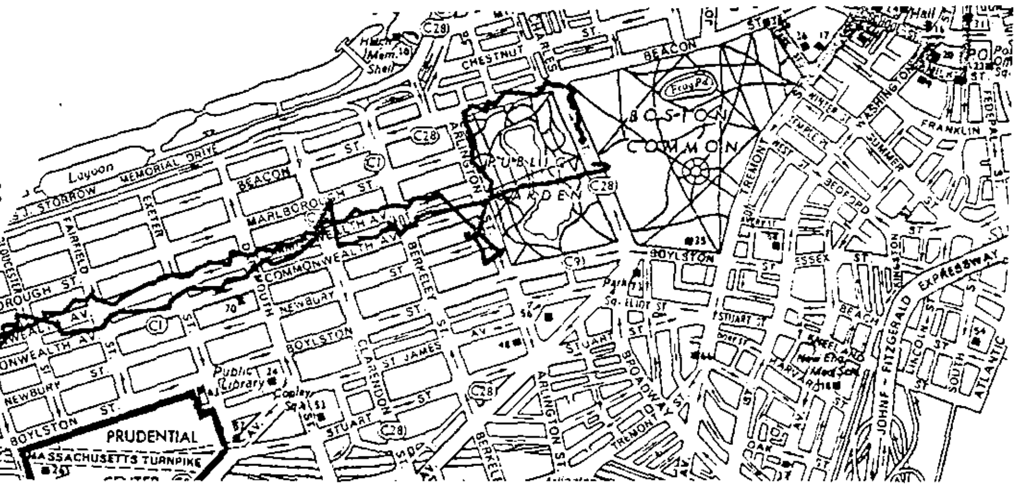
*The outer ring of the plot is zero elevation and the inner circles each represent 10 degree steps, with 90° (overhead) in the center.

Commonwealth Ave. Test Route



GPS





LORAN-C (Accufix 600)

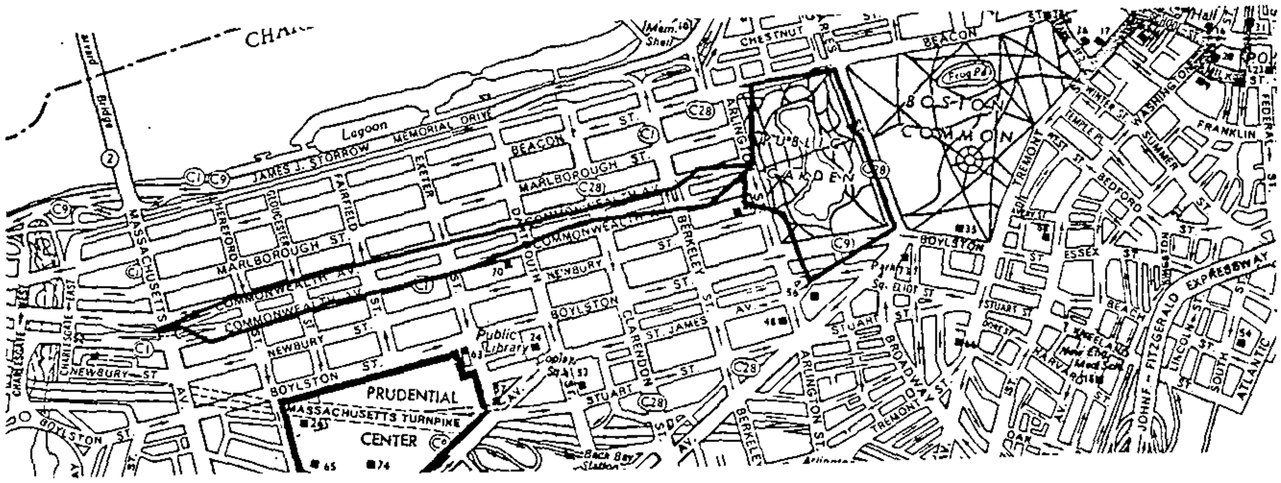


FIGURE 15. COMMONWEALTH AVE., BOSTON NAVIGATION PLOTS

configuration based on DOP, satellite SV12 was too low in elevation for effective GPS operation in the city. Best performance for the LTN-700 was obtained by shifting to a fixed altitude, three satellite solution. The T-Set automatically did this during the transit.

GPS position accuracy was comparable to that of LORAN-C; however, GPS suffered from loss of position lock at the corner of Arlington Street and Commonwealth Avenue (caused by the Ritz-Carlton hotel) and as a result, became inoperative thereafter. LORAN-C maintained position fix throughout the run but exhibited course errors of some magnitude near Mass Ave and near the Boston Public Gardens.

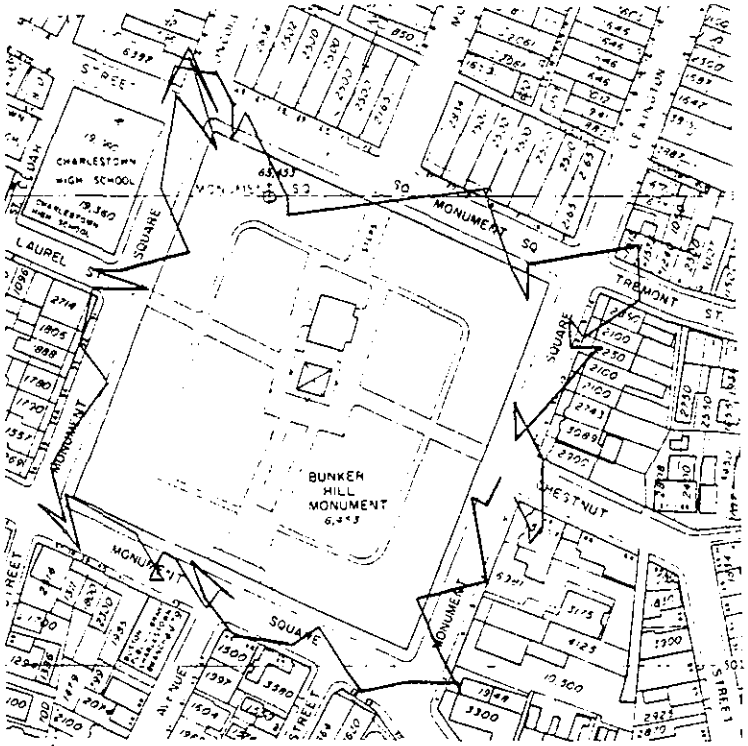
5.5.3 Bunker Hill, Boston Run

Four test runs of 2 minutes duration each were made on Monument Square, a route circumscribing the historic Bunker Hill Monument. Positioned at the apex of the monument was the geodetic site known as Bunker Hill Monument 1846. Four-story apartment dwellings surround the outer perimeter of Monument Square producing average blocking angles of about 45 degrees along the outer perimeter.

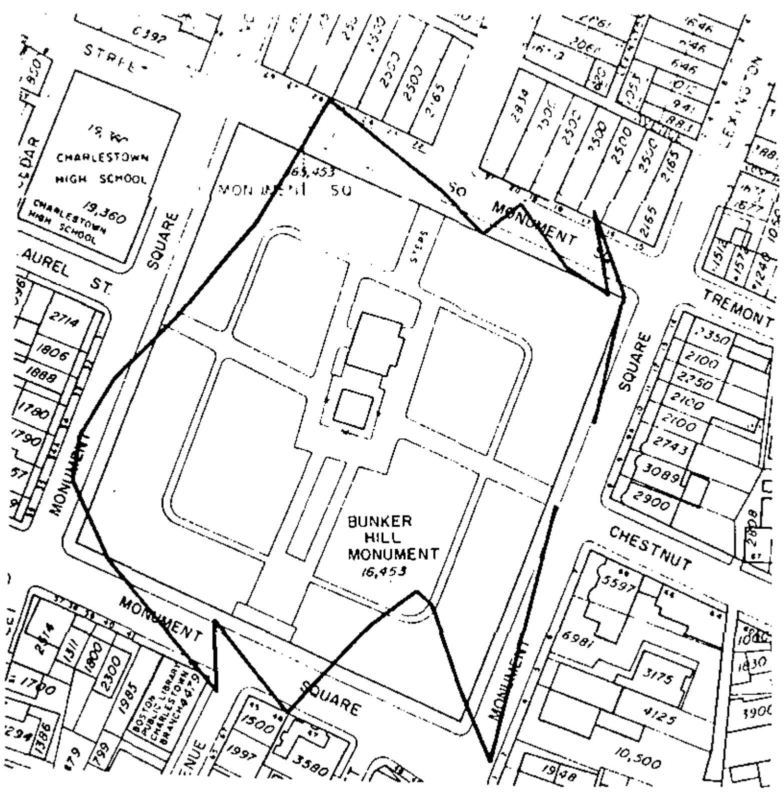
Figure 16 presents a typical GPS navigation plot using satellite configuration SV6-8-9-11 at about 19:19 sidereal time. Except for the northern corner of the test route, the GPS plot was a reasonable representation of the actual test route. The polar elevation-azimuth angle plot shows the satellite positions at the time of the measurement. At the northern corner, satellites SV9-11 were blocked from view, causing momentary loss of position fix. Similar GPS performance was observed on the other test runs. The LORAN-C (Northstar) navigation plot followed the test route, though with somewhat less accuracy than the GPS run. However, the LORAN-C maintained position lock throughout the run.

Figure 17 shows LTN-700 scatter data taken at four positions around Monument Square corresponding to the street intersections at Chestnut St., Monument Ave., Laurel St., and Monument St. The scatter data illustrated the resolution/accuracy obtained at the respective locations. The large scatter at the Laurel Street intersection was consistent with the reduced satellite visibility along this section of the test route.

GPS



LORAN-C (Northstar 7000)



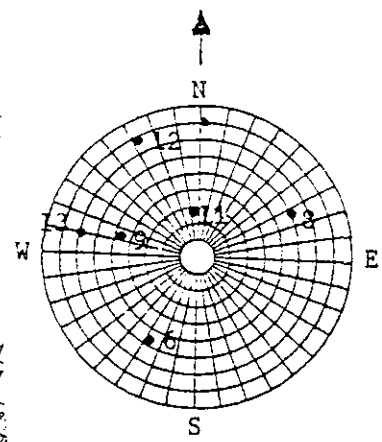


FIGURE 16. BUNKER HILL, BOSTON NAVIGATION PLOTS

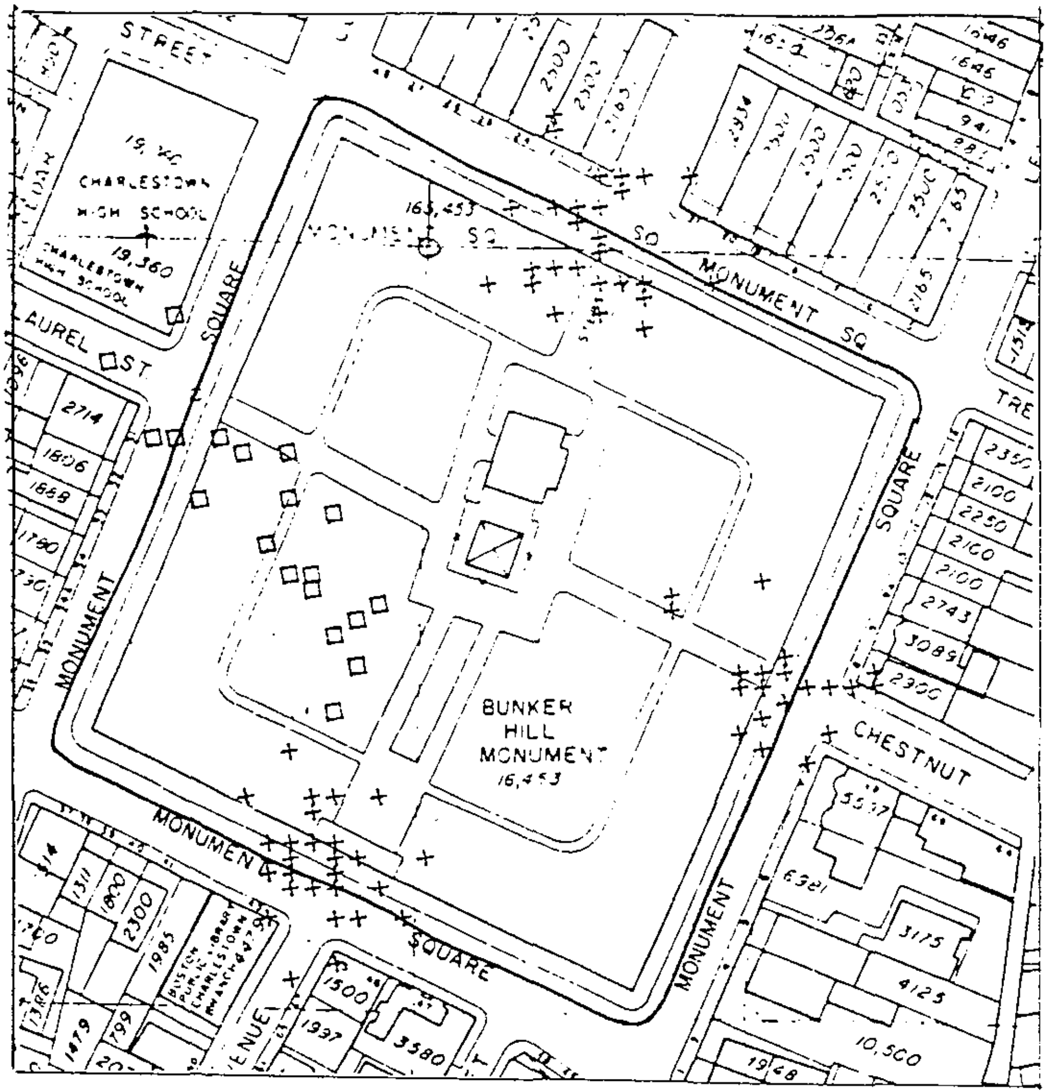


FIGURE 17. MONUMENT SQUARE, GPS SCATTER PLOTS AT BUNKER HILL

5.5.4 Bedford Common Run

The Bedford Common run was selected to study land navigation in a (semi) rural environment where signal reception was unimpeded by obstructions in the immediate surroundings. Throughout the 2-minute test runs, the LTN-700 maintained position 'fix' with the SV6-8-11-13 configuration.

A typical GPS navigation plot for the Bedford Common run is shown in Figure 18. Except for some data scatter at the western sector of the run, the indicated receiver position closely followed the actual route. The signal-to-noise of SV13 dropped momentarily to low values at two positions along the route, presumably due to signal blockage by nearby buildings. While configuration SV6-8-11-13 was the optimum one based on DOP, it did not represent the best choice in terms of satellite visibilities.

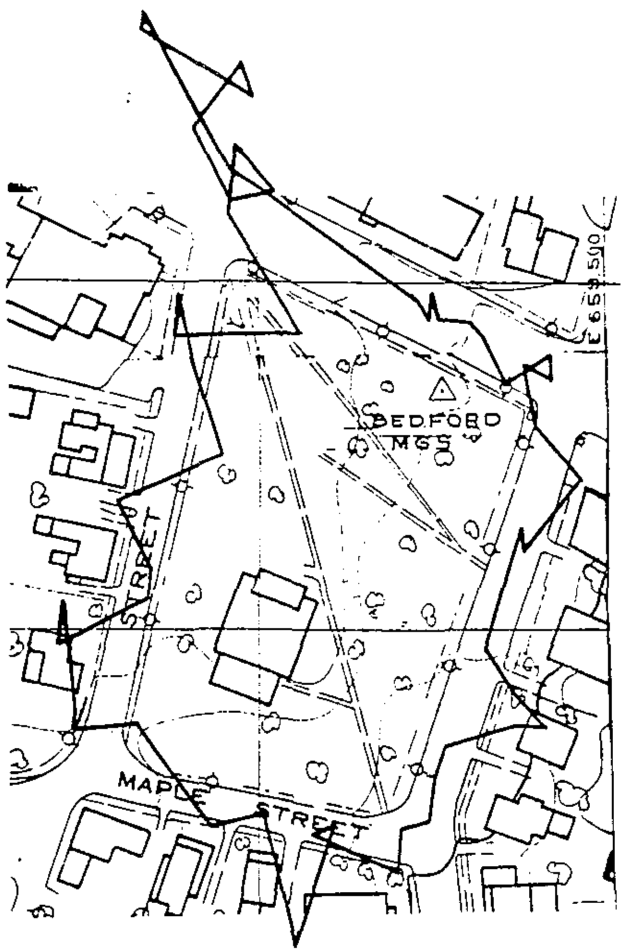


FIGURE 18. GPS NAVIGATION PLOT, BEDFORD COMMON

The LORAN-C navigation plots for the Bedford Common run proved totally inaccurate with large deviations extending far beyond the test route. The adverse weather conditions which existed during the test run could possibly have contributed to the poor measurement results. These problems were not noted during the run. Since reasonably accurate tracking data was available for other tests, the Bedford runs were not duplicated.

5.5.5 Salem City Run

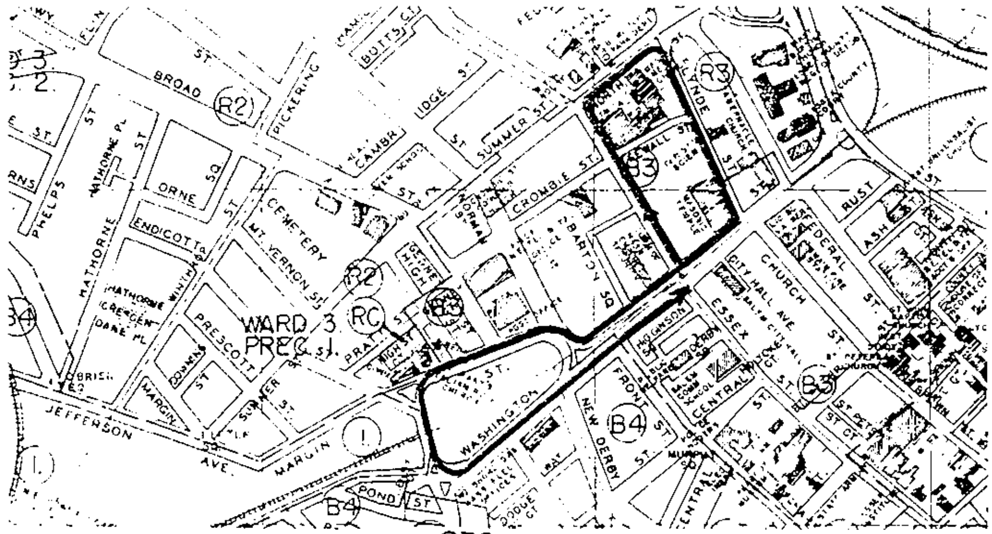
The Salem City tests covered a path through a section of downtown city characterized by four story buildings. The test route followed a figure eight pattern, beginning and ending at a location where signal reception was moderately good. An underground railroad line ran under Washington Street. Figure 19 shows the navigation plots using GPS and LORAN-C(Northstar 7000). The plot was typical of GPS operation in an environment with moderately high buildings. Of the total distance traveled, the LTN-700 tracked three or more satellites only for 20 percent of the test route. The loss of position fix shortly after the beginning of the run resulted in large errors in the receiver position. Once having lost position lock, the receiver did not reaquire four satellites until the end of each run.

The LORAN-C navigation plot was superior to that of the GPS receiver and displayed a pattern similar to the actual route itinerary. Whereas GPS was totally unable to function over most of the trip run, LORAN-C maintained a position fix throughout the run. This was demonstrated by the ability of the LORAN-C receiver to follow changes in user direction which occured four times during the run. No attempt to stop the MTF was made throughout each run. The position offsets in the LORAN-C plot may have been caused by residuals in the tracking loops.

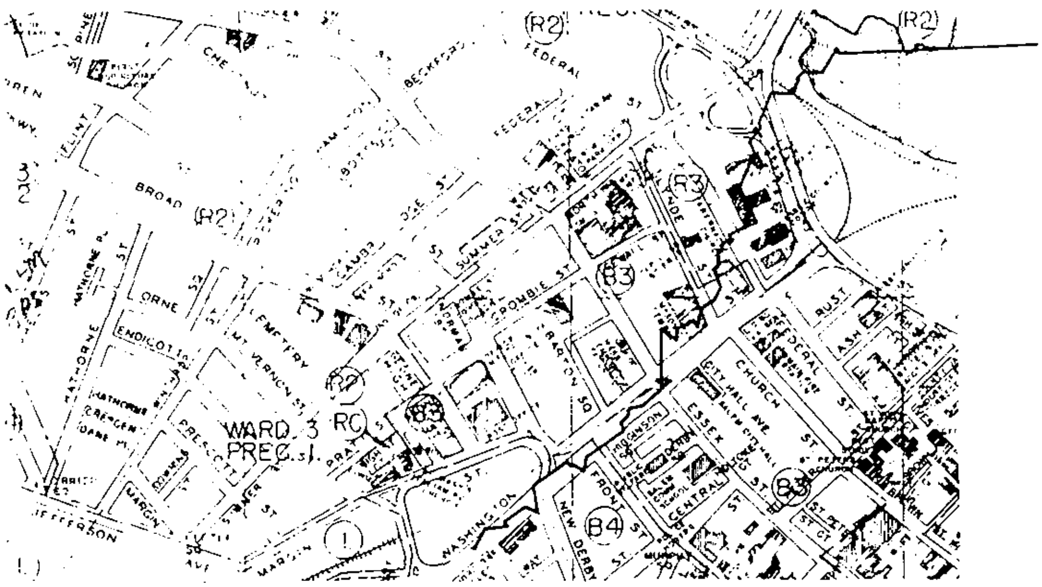
5.5.6 Route 95 Test Run

Several test runs were made over a 3-mile section of interstate highway located 20 miles north of Boston. No power or telephone lines were located near the highway. This test route was selected to provide a straight section of highway for studying the receivers' navigation characteristics under fairly optimum conditions. Test runs were made in the north- and south-bound directions.

Salem City Test Route



GPS



LORAN-C (Northstar 7000)

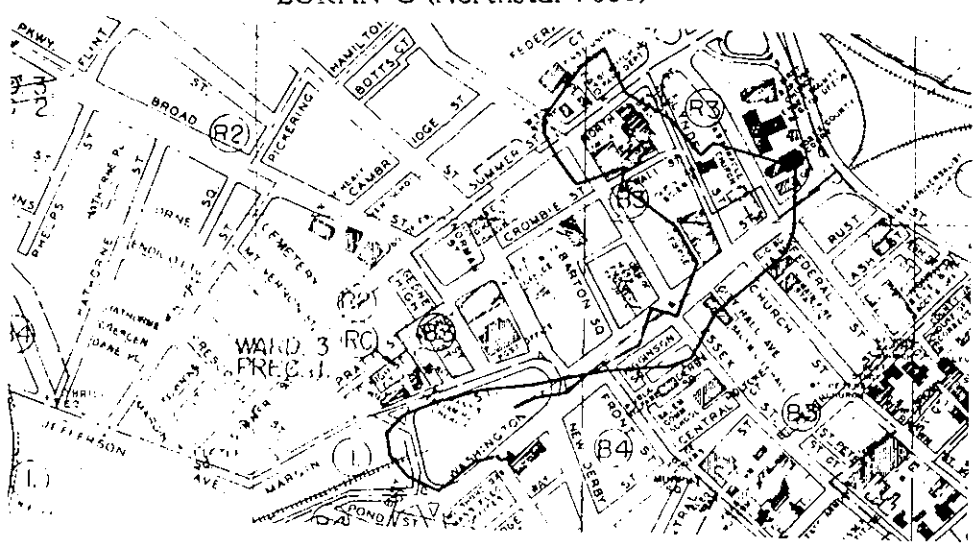


FIGURE 19. GPS AND LORAN NAVIGATION PLOTS, SALEM CITY

Figure 20 shows the northbound GPS and LORAN-C runs beginning at an overpass and ending at the next cloverleaf exit. Both navigation plots show a close correspondence with the actual route itinerary. Thus, in this instance, GPS and LORAN-C perform equally well with both systems yielding good results.

5.5.7 Ipswich Rd-East Run

The Ipswich Rd test run followed a typical rural road in northeastern Massachusetts. In contrast to the fixed direction of the previous run, the Ipswich Rd run had frequent changes in both direction and elevation. Local utility lines, both power and telephone, were present along the road. The navigation plot in Figure 21 shows that GPS can track route itineraries of this kind. LORAN-C plots showed greater variation, but followed the road with reasonable accuracy.

5.6 ELECTRICAL INTERFERENCE TESTS

Susceptibility of the LTN-700, the Northstar 7000 and the Accufix 600 to three types of electrical interference was examined; power line modulation, VHF/UHF television transmissions and modular telephone transmissions.

5.6.1 Power Substation Radiation

The MTF was operated in the vicinity of the Massachusetts Electric Company "Medway 65" electrical power substation at West Medway. This is the largest substation in New England and presents a severe RF radiation environment. The LORAN-C receivers lost lock and indicated low SNR when within 400 feet of the substation, but recovered as the MTF left the area. The LTN-700 was unaffected.

5.6.2 VHF/UHF Television Stations

The MTF was driven adjacent to transmitting towers in the immediate vicinity (up to 2 miles) of several TV stations (channels 2, 4, 5, 7, 25, 38 and 56). None of the receivers gave any indication of malfunction.

5.6.3 Modular Telephone Transmitters

The modular telephone networks which are being implemented throughout the United States operate in the 800 mHz band, close to a harmonic of the L1 GPS carrier

GPS LORAN-C(Northstar 7000)

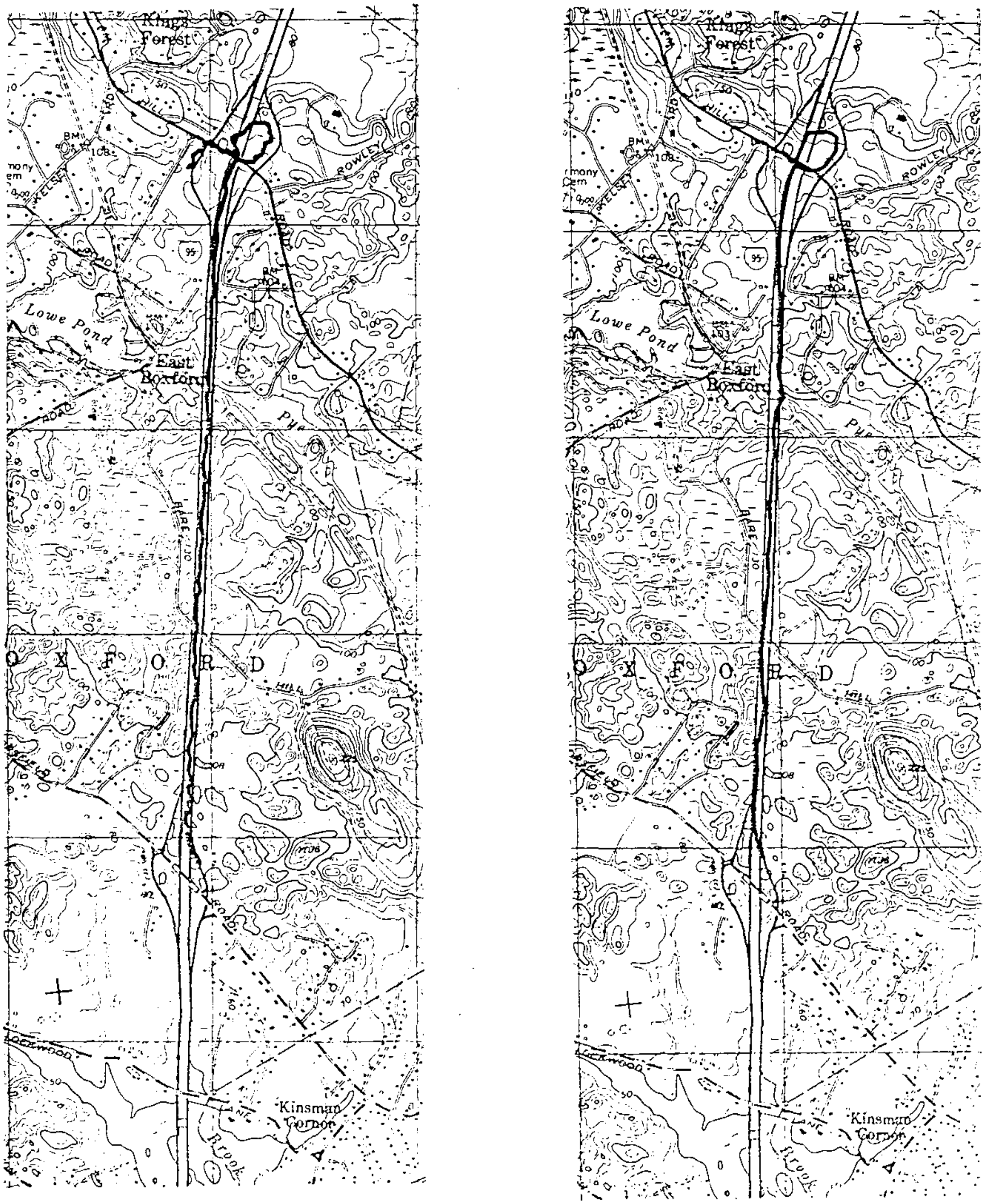
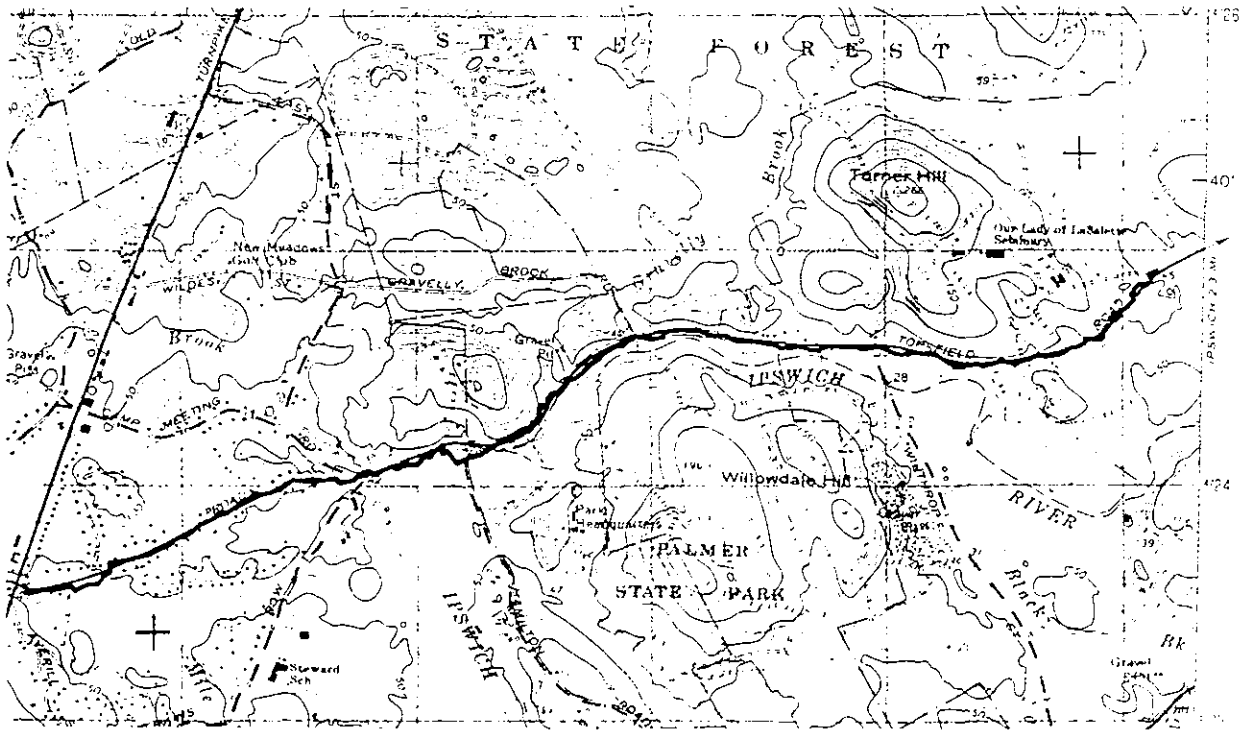


FIGURE 20. GPS AND LORAN-C NAVIGATION PLOTS, ROUTE 95-NORTH

GPS



LORAN-C (Northstar 7000)

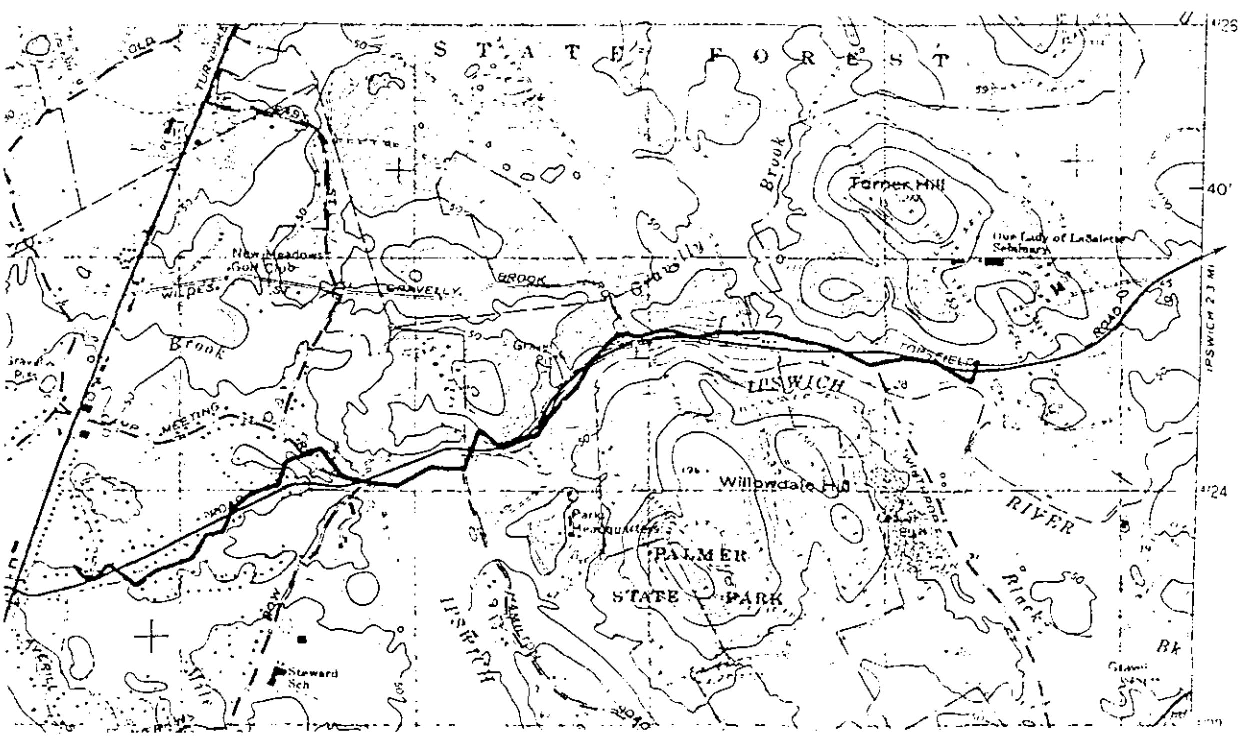


FIGURE 21. GPS AND LORAN-C NAVIGATION PLOTS, IPSWICH RD-EAST

frequency. In Boston, "Cellular 1" operates at 100 watts in the 870-880 mHz band. The MTF was operated in close proximity to the transmitting station and also adjacent to an automobile with a 3-watt transceiver installed. Again, none of the receivers was affected.

5.7 GPS MULTIPATH TESTS

Static GPS tests were conducted to study the susceptibility of the LTN-700 to multipath errors. In general, multipath errors can be anticipated in environments where satellite signal reflections are likely to occur. Examples of such environments include areas with extended water surfaces and locations in cities with surrounding high buildings.

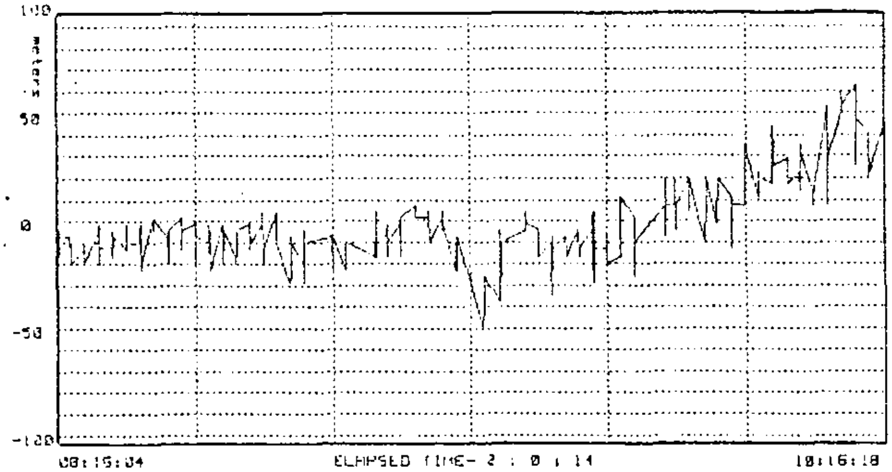
The LTN-700 is designed to minimize multipath errors through software which seeks out satellite signals with the shortest path. Thus, the multipath signals with delayed arrival at the receiver are supposed to be rejected in favor of the primary signals. To study the receiver response to possible multipath signals, tests were conducted in a flat marshy region near the coastline where signal reflections from low elevation satellites might occur.

Figure 22 shows plots of position variation with time, measured with satellite configuration SV9-11-12-13. The test period was chosen to include the time during which satellite SV9 was descending to the horizon. Figure 22a presents the latitude variation observed at the marsh site while Figs. 22b, and 22c give the corresponding latitude variations obtained with the LTN-700 antenna located on the roof of TSC. Data in Figures 22a and 22b exhibit the same steady increase in latitude with time and hence ruled out multipath effects. Data in Figure 22c obtained using newly acquired receiver software exhibited no anomolies. A review of other test data also failed to show any confirmed evidence of multipath effects during the test program.

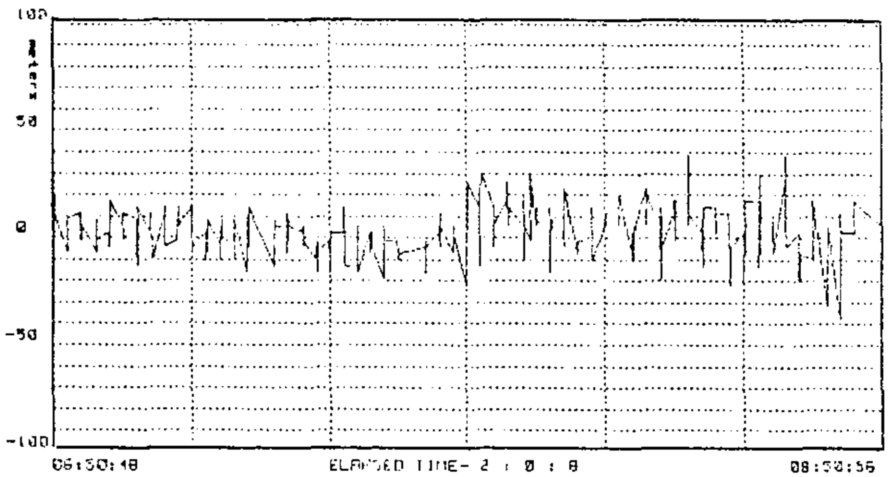
5.8 GPS FOLIAGE TESTS

Past studies conducted at the Army's J. E. Rudder Ranger Camp, Florida, using a GPS Manpack set with three satellites, showed evidence of signal attenuation due to foliage (Ref. 5). Those tests were carried out in a variety of wooded regions in the presence of both deciduous and coniferous (evergreen) foliage. The L Band signal attenuation was reported to vary between 0.7 and 1.1 dB/meter for deciduous foliage and 0.3 and 0.5 dB/meter for coniferous foliage.

a. MARSHES 3-19-85



b. BASELINE 4-10-85



c. BASELINE 5-9-85

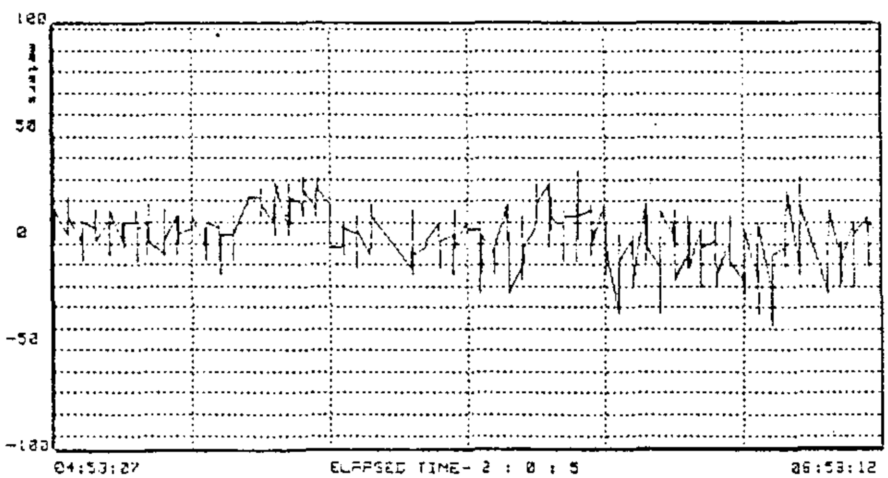


FIGURE 22. GPS MULTIPATH TESTS, LATITUDE VERSUS TIME

Except for evergreen trees, there was no foliage of significance available in Massachusetts when the LTN-700 was tested. Unpredictable road conditions and night time signal availability required postponement of foliage observations.

The brief availability of the T-set in August permitted a quick examination of foliage effects on the GPS signals. These were made on Lockwood Lane in Topsfield, MA; a 17-foot wide secondary road near the Interstate 95 highway. Baseline observations were made with the receiver at an overpass with clear visibility when the first three satellites were visible. The MTF was then repositioned to two sites on the lane. One site was bounded by trees, 3 feet off the road, about 10 trees deep on either side, with a clear overhead view. The second site had similar stands of trees alongside the road, but the leaves formed an arch. The trees were a mix of oak, maple, ash and fir. A sketch of the conditions is shown in Figure 23 and a picture of the conditions in shown in Figure 24.

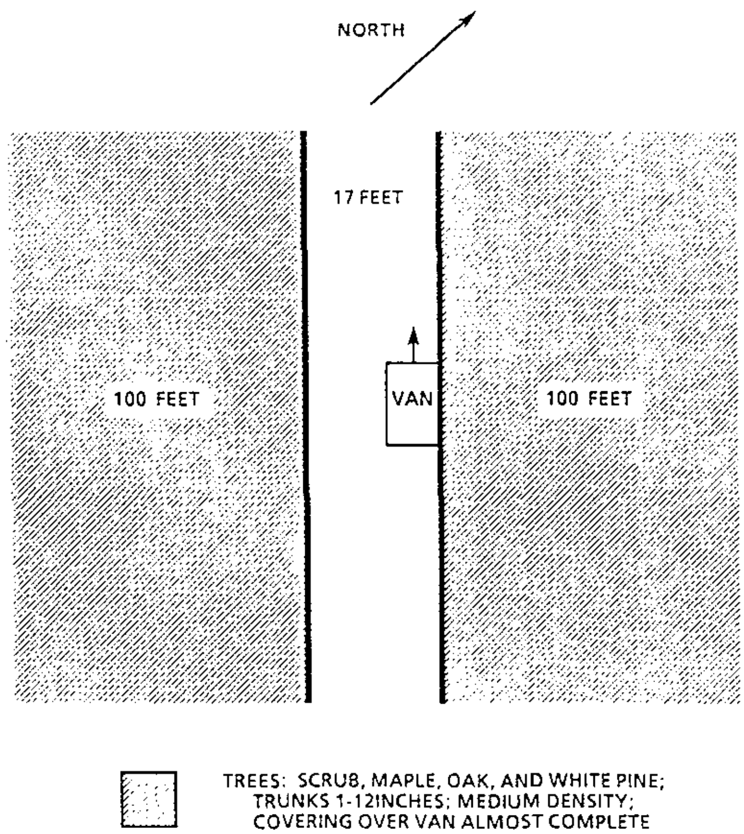


FIGURE 23. MOBILE TEST FACILITY (MTF) LOCATION DURING T-SET FOLIAGE TESTS

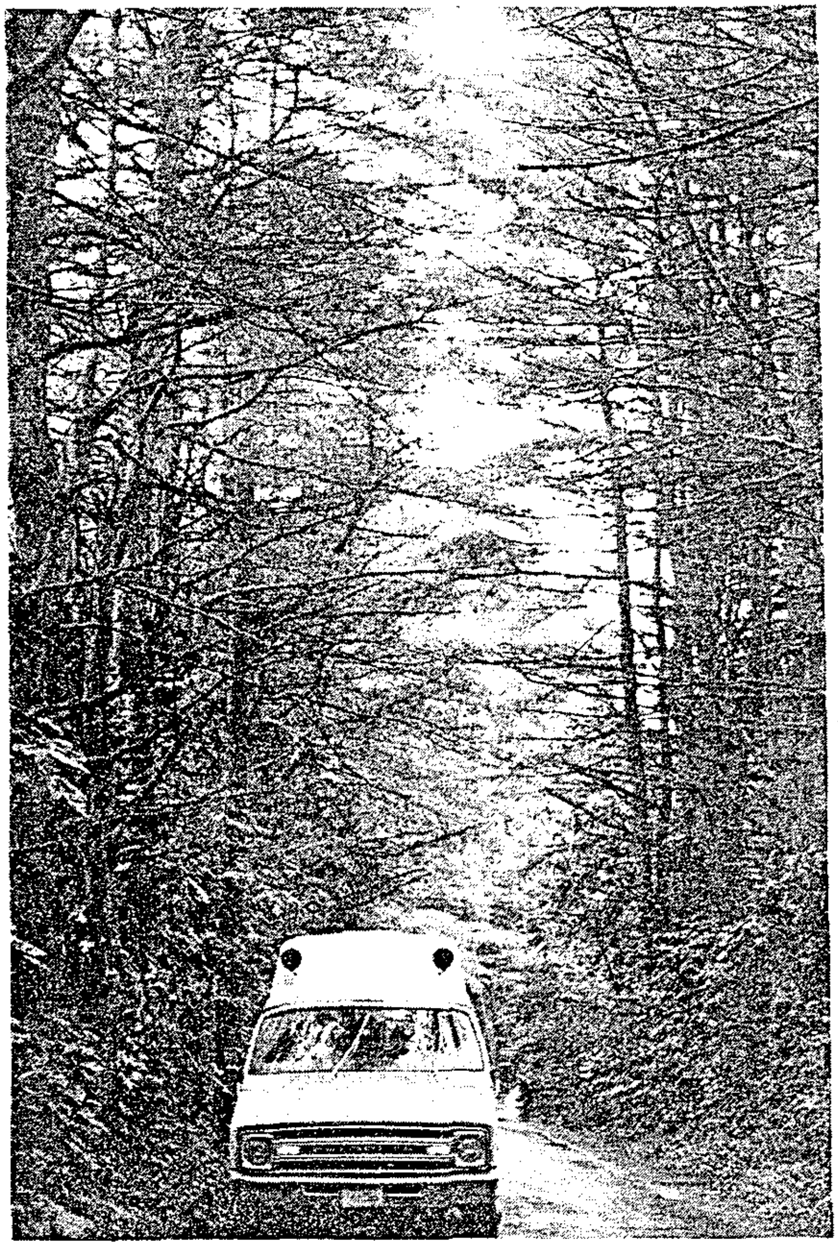


FIGURE 24. PHOTO OF MOBILE TEST FACILITY (MTF) DURING T-SET FOLIAGE TESTS

The GPS signals were obviously attenuated. The attenuation varied, dependent upon satellite elevation, typically 7 to 10 dB. Temporary blockage was occasionally noted, apparently due to satellites going behind trees. Rising satellite acquisition was delayed due to the signal attenuation. For one satellite, SV9, the signal was not acquired until the satellite elevation reached 22 degrees versus previously observed acquisition at 7.5 degrees.

The navigation output of the receiver reflected the problems of satellite visibility. The receiver made numerous satellite transitions, attempting to maintain adequate signal lock under these adverse conditions.

At the time of these tests, data output from the T-set did not include satellite azimuth and elevation information. As such, comparison of satellite information in foliage conditions and at clear locations was difficult. Limited receiver availability prevented multiple days of observations. Quantitative tests were therefore rescheduled for future evaluations when two GPS receivers can be used for simultaneous observations.

6.0 DISCUSSION OF RESULTS AND CONCLUSIONS

Comprehensive tests of the GPS and LORAN-C were conducted over a 4 month period, providing a large amount of information and data. The results of the individual tests permit assessment of the suitability of the SPS to provide a navigation reference for terrestrial users and permit a comparison of the two systems.

6.1 STATIC ACCURACY

Both GPS receivers demonstrated the capability to provide position determination within 20 meters of surveyed points during periods when HDOP was less than 2.0. This performance is representative of that reported by receivers using the SPS. Positions with LORAN-C showed reasonably constant ASF in Boston, but there was over a 100 meter variation when all sites were considered. While the LORAN accuracy is adequate for marine applications, the ASF variation would cause difficulties in identification of individual streets. Multiple ASF calibration points might permit use of the system in the Boston area.

6.2 UNDERWAY FIELD TESTS

6.2.1 Rural/Suburban

Both the GPS and LORAN-C receivers provided navigation information which correctly showed the position of the MTF. Here again, ASF compensation and calibration of the LORAN-C grid is necessary. While no problems were encountered with the LORAN-C receivers due to primary power lines during these tests, the results should not be interpreted as indicative that primary power does not affect LORAN-C. Reference (6) provides detailed information concerning this problem.

6.2.2 Urban Transits

6.2.2.1 GPS Navigation in Urban Environments - Examination of the fixing capabilities of the GPS receivers confirmed other tests, indicating that both receivers were performing to the limits of the system. Except during instances when signals were blocked, the receivers provided exceptional position references. An analysis of GPS signal availability from the operational system was made for the Boston area. Figure 25 shows the number of satellites visible during a 24 hour period for the 18 satellite configuration. Calculations were made at 30 minute intervals. Three or more satellites are available if the receiver encounters an unobstructed horizon of 30 degrees. For four satellites a clear horizon to the 20 degrees level is required. Some improvement is noted for the 21 satellite constellation situation and this is shown in Figure 26.

The results noted in these tests are therefore representative of the final system and it must be concluded that a "stand-alone" GPS will not provide continuous navigation in urban environments, because a sufficient number of satellites will not be visible for tracking. It appears that external sensors, supplying altitude, direction and speed will be necessary for unambiguous, continuous navigation in urban environments.

6.2.2.2 LORAN-C Navigation in Urban Environments - The LORAN-C receivers maintained signal lock throughout practically all the tests. Position locations were affected due to changes in ASF (see Section 6.1). The loss of signals in the Government Center area of Boston indicates that LORAN-C navigators could also use supplemental, external sensors to improve urban performance. It would appear that inputs of direction and speed, plus use of multiple calibration points, might permit continuous, stand-alone tracking in Boston.

6.3 FOLIAGE TESTS

The T-set tests confirmed the Army tests and reinforced the fact that GPS signals are attenuated by foliage. The operational system will eventually provide more satellites, with increased elevation angles. Figures 25 and 26 show that three or more satellites are available with angles above 20 degrees, approximately the angle where rising satellites were detected. Additional, carefully controlled tests may show that the final system will provide sufficient satellites at high enough altitudes and required DOP to allow navigation in areas with foliage.

6.4 INTERFERENCE TESTS

The GPS receivers showed no degraded operation in rural and suburban environments when subjected to power line, television and modular telephone interference. This result is encouraging and the system is superior to LORAN-C which has a documented history of susceptibility to power line interference.

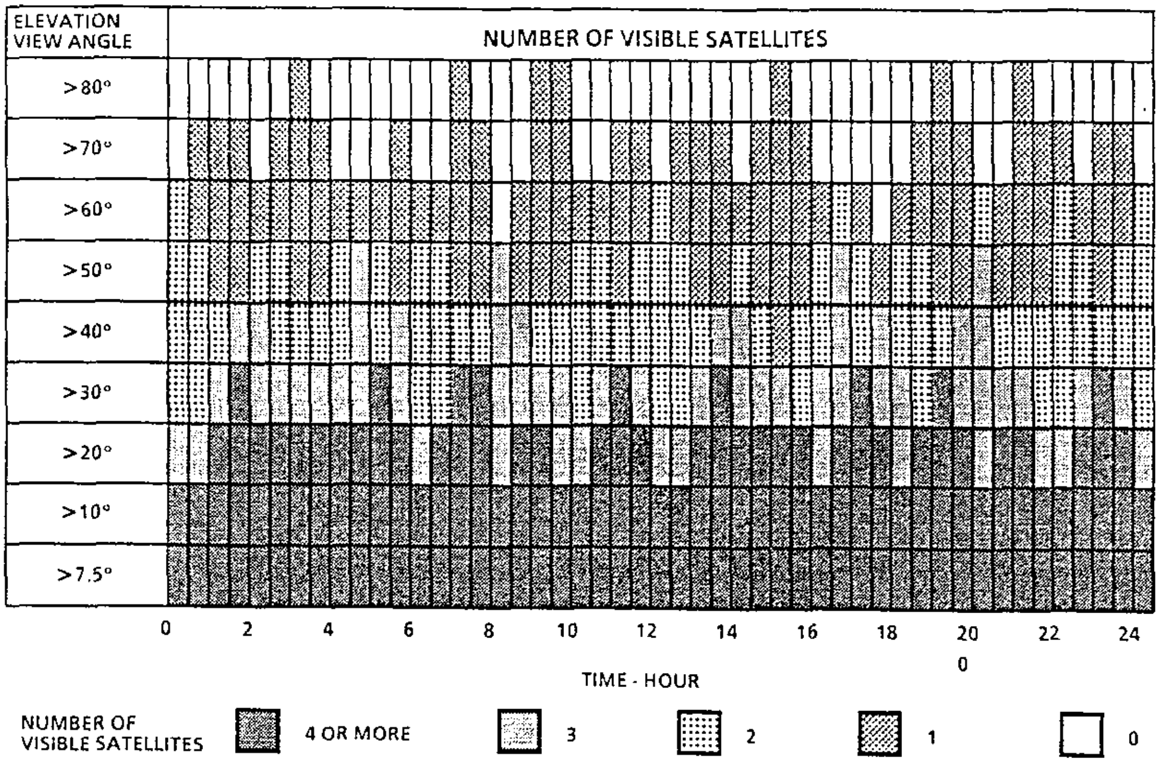


FIGURE 25. GPS SATELLITE VISIBILITY IN BOSTON - 18 SATELLITE CONFIGURATION

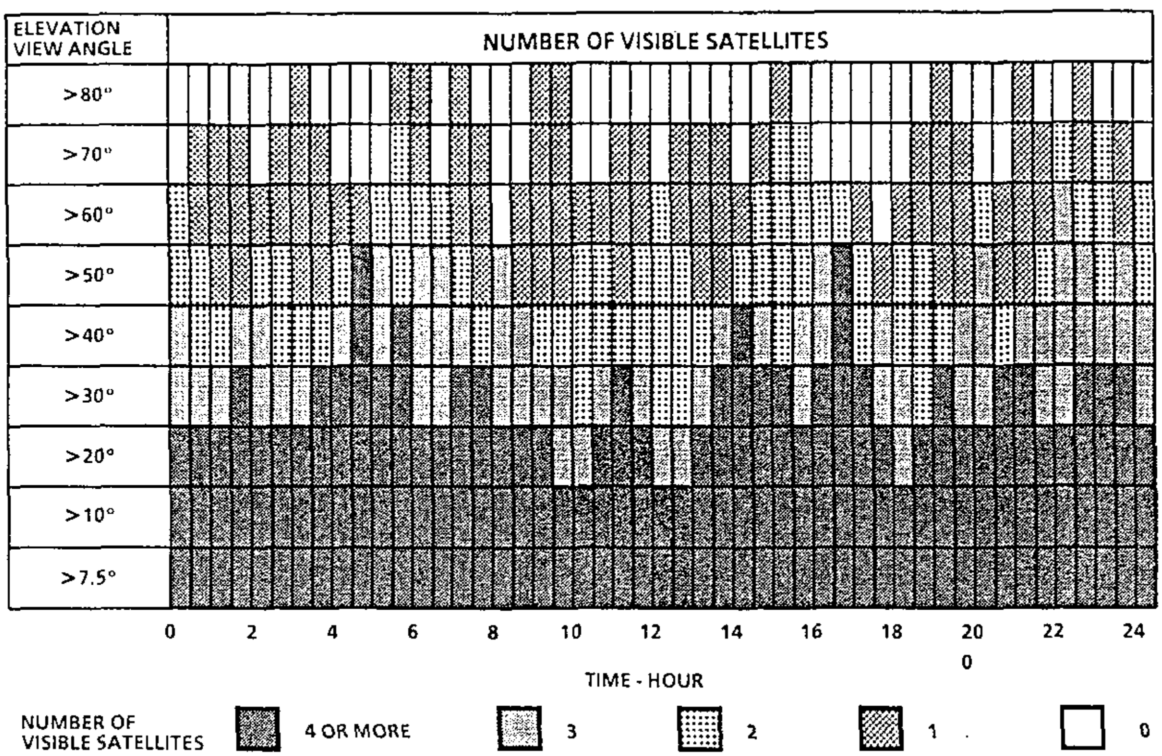


FIGURE 26. GPS SATELLITE VISIBILITY IN BOSTON - 21 SATELLITE CONFIGURATION

6.5 MULTIPATH TESTS

The tests conducted during this evaluation gave no identifiable indication of multipath interference problems. Multipath interference may have caused some of the navigation problems encountered during urban transits. It appears that signal obstruction is a more significant problem.

6.6 CONCLUSIONS

These tests provide additional information regarding the capabilities of the GPS and LORAN-C systems. Each system has attributes which reflect the radio frequencies used to broadcast the navigation signal. It appears that supplemental sensor inputs are required as part of the navigation solution for either system if stand-alone urban navigation is desired.

7.0 REFERENCES

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2. Claire, Charles N., "State Plane Coordinates bv Automatic Data Processing", U.S. Department of Commerce, Publication 62-4.

3. Couselman, III, Charles, Earth, Atmosphere and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, private communication.

4. DOP plot furnished by the Aerospace Corporation, Box 92957, Los Angeles, CA 90009.

5. "Foliage Attenuation, Multipath and Evaluation of the NAVSTAR Manpack Set in Different Foliage Environments," Navstar Global Positioning System Space and Missile Systems Organization, Los Angeles, CA 90009, 1979.

6. Mauro, Peter, and John D. Gakis, "The Effects of Primary Power Transmission Lines on the Performance of LORAN-C Receivers in Experimental Terrestrial Applications," DOT-TSC-RSPA-79-8, U.S. Department of Transportation, Research and Special Programs Administration, Washington, DC 20590.