Technical Memorandum

Preliminary Examination of the METROLift Automatic Vehicle Location System

September 1994

TECHNICAL MEMORANDUM

Preliminary Examination of the METROLift Automatic Vehicle Location System

This Technical Memorandum was prepared as part of the IVHS Research Center of Excellence at the Texas Transportation Institute. This project, which is examining the use of IVHS technologies to enhance specialized transportation services, is funded by the Federal Highway Administration (FHWA) and the Metropolitan Transit Authority of Harris County (METRO).

Prepared by
Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843-3135

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I. INTRODUCTION

Providing public transportation services that are accessible to individuals with disabilities has been an ongoing concern of federal, state, and local governments, transit operators, and advocacy groups. Current federal regulations require that transit systems provide both main line accessible service and paratransit or other specialized service to individuals with disabilities. Many transit systems in the U.S. are working to improve the responsiveness and timeliness of paratransit services, while at the same time maximizing the efficiency of these services. It appears that the use of AVL technologies may greatly enhance the ability of paratransit services to respond to changes in client travel schedules and to improve service productivity. Furthermore, when combined with advanced paratransit scheduling programs and other IVHS technologies, AVL systems may allow transit operators to provide dynamic paratransit scheduling and other service enhancements.

In October 1993, Texas Transportation Institute (TTI), a part of the Texas A&M University System, was notified by the Federal Highway Administration (FHWA) that it had been selected as one of three Intelligent Vehicle Highway Systems (IVHS) Research Centers of Excellence. Public transportation services represented one of the three major focus areas in TTI's application, which was supported and endorsed by a number of public and private organizations, including the Metropolitan Transit Authority of Harris County (METRO). METRO committed to providing a local match to support the public transportation focus area.

One of the projects included in the work program for the first year focused on the use of IVHS technologies to improve specialized transportation service delivery. This project includes an examination of an automatic vehicle location (AVL) system and advanced paratransit scheduling package with the METROLift fleet, an examination of the IVHS technologies to enhance specialized transportation services, and the analysis of potential expansion of the AVL system to other METRO vehicles.

Houston METRO provides specialized paratransit services to disabled individuals within

the METRO service area. The service, which is called METROLift, was initiated in 1978. METROLift provides pre-scheduled, curb-to-curb transportation for physically or mentally disabled persons who are unable to ride fixed-route METRO bus service. Approximately 2,300 daily trips are provided utilizing 129 vehicles. In 1993, METRO implemented a one year demonstration project using the AirTouch Teletrac automatic vehicle location (AVL) system. This is a radio-triangulation AVL system.

As noted, one of the major components of this research study is an examination of the METROLift AirTouch AVL system. The accuracy, performance, and data throughput of the system are being examined. The impact of AVL technology on the operations of the METROLift system is also being analyzed. METRO requested that a preliminary assessment be conducted of the AirTouch AVL system. This was accomplished through an initial test of the accuracy of the system on the METRO 2-Bellaire Route - Dairy Ashford Branch.

This Technical Memorandum presents the results of this preliminary assessment. It provides background information on the AirTouch system, the methodology used to conduct the initial tests, and the preliminary results. It also identifies areas where further testing and research are needed to fully analyze the system. These activities will be conducted as part of the more detailed assessment which will be conducted over the next several months. In addition, the comprehensive examination of the impact of the AVL system and the advanced paratransit scheduling package on the METROLift service are being examined.

II. BACKGROUND AND METHODOLOGY

In 1993, METRO initiated a one year demonstration project using the AirTouch Teletrac position system on the METROLift service. The AirTouch Teletrac AVL system is a subscriber-based radio location system which uses a network of 24 radio towers connected to a central computer. A small digital transceiver, called the vehicle location unit (VLU), is attached to each vehicle. The location of the vehicle is tracked using the Fleet Director software on a personal computer that is connected to a central computer via a telephone line. When the location of a vehicle is requested, the vehicle location unit receives the page and transmits a digital code back which is received at radio towers in the vicinity of the vehicle. Signals received by at least four towers are required to triangulate on the vehicle's position. For reasons of accuracy a higher number of radio towers are often used, however. The system can page and locate a single vehicle, a group of vehicles, or all vehicles within the service area. Figure 1 illustrates the AirTouch AVL service area in the region. AirTouch claims the vehicle location accuracy of the Teletrac system to be within 150 feet, at 2 sigma of the vehicle's actual position, at vehicle speeds of 0 to 100 miles per hour. A 2 sigma level of accuracy means that 95% of the location readings obtained from the system will be within the stated range (in this case, within 150 feet of the vehicle's actual location).

Three tests were conducted as part of this preliminary examination. The first test was performed to assess the locational accuracy of the AirTouch system for a stationary vehicle. This was accomplished by locating a vehicle at 24 known sites in the Houston area. In the second test, the time required by the AVL system to locate the entire fleet of METROLift vehicles was measured. The third test located a vehicle at 30-second intervals to identify the locational accuracy of the AVL system for a moving vehicle along a known bus route.

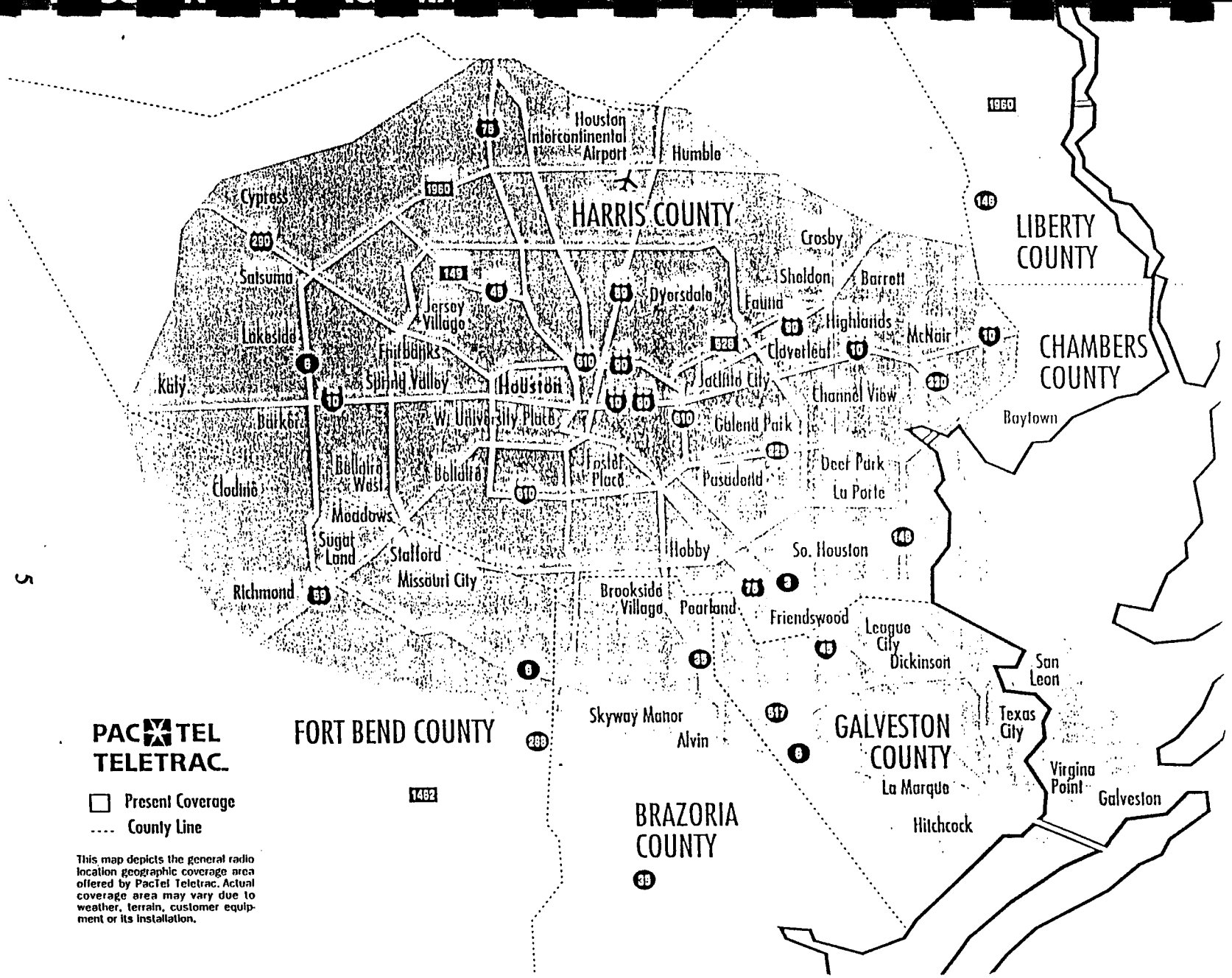
The AirTouch AVL system presents vehicle locations in terms of either latitude and longitude coordinates or street locations, as specified by the user. Examination of the locational accuracy of the system requires that measured coordinates be compared with some known coordinates. The focus of this preliminary test was to compute the distance between each

measured set of coordinates and the known coordinates for each of the 24 locations and to statistically analyze the computed distances.

GEOD is a software package developed by the United States Geological Service (USGS). The software, when given the appropriate parameters, computes the distance between any two sets of latitude and longitude coordinates by solving differential equations. The computations take into account the curvature of the earth and are accurate to within a few centimeters. The GEOD software is utilized by the USGS and is also available for use by other organizations.

TTI acquired the GEOD software from the USGS and installed it on a UNIX workstation. The data generated by the AirTouch Fleet Director software were converted into a format that could be read by the GEOD software. For each site the data file contained the known latitude and longitude and the latitude and longitude generated by the AirTouch AVL system. These values were expressed in degrees with minutes and seconds represented by a decimal fraction.

For each test site, the GEOD software compared the known latitude and longitude with the latitude and longitude generated by the AirTouch Fleet Director. The distance in meters between the two sets of coordinates was then computed. This distance was then compared with the claimed accuracy of the AirTouch system, which is 150 feet at 2 sigma.



Source: AirTouch Teletrac

Figure 1. AirTouch Teletrac Houston Coverage Map

III. PRELIMINARY TEST PROCEDURES

The procedures used to conduct each of the three preliminary tests are described in this section.

Test 1 - Accuracy of AVL system

Twenty-four locations with known latitudes and longitudes were selected for the initial test. The locations of these sites are identified in Table 1 and Table 2. Twenty of the sites are bus stops on the METRO 2 Bellaire Route - Dairy Ashford Branch and four are along freeways in other parts of the Houston area. The sites were selected to provide a mix of topography, including relatively open locations and downtown locations surrounded by tall buildings.

In order to perform the preliminary tests, the known latitude and longitude coordinates at each test site had to be determined. METRO provided the location values determined by E-SYSTEMS from another study for the sites along the 2 Bellaire Route--Dairy Ashford Branch. The latitude and longitude coordinates for the remaining four test sites were determined by TTI using a portable global positioning system (GPS) receiver. The nominal accuracy of the GPS receiver is 100 meters. For the purpose of this study the assumption was made that these values are correct, and they were used as base values for the accuracy comparison.

A portable vehicle location unit, connected to a 12-volt battery, was used to conduct this analysis. At each of the 20 locations along the bus route, the unit and antenna were placed next to the bus stop signpost. For the four other area-wide locations, the vehicle carrying the unit was positioned along the right side of the freeway shoulder adjacent to the structure used to determine the latitude and longitude. The antenna for the unit was placed on top of the vehicle. When the unit was in place at a site, a cellular telephone was used to call the TTI office, where a page of the unit was initiated. The AirTouch Fleet Director software on the personal computer in the TTI office was used to page the vehicle location unit at 10 second intervals. The location data received from each page was recorded. A comparison was then made of the known latitude and

longitude and the reading obtained from the AirTouch system.

Table 1. Locate Sites: 2 Bellaire Route - Dairy Ashford Branch

Site #	Bus Stop Location	Direction*	Longitude	Latitude
1	Bellaire-Dairy Ashford	IB	-95.60399°	29.70337°
2	Bellaire-Wilcrest	IB	-95.57168°	29.70379°
3	Bellaire-Gessner	IB	-95.53746°	29.70488°
4	Bellaire-Cannock	IB	-95.51142°	29.70381°
5	Bellaire-Transit Center (Northside)	IB	-95.46884°	29.70577°
6	Bellaire-Buffalo Speedway	IB	-95.42768°	29.70597°
7	Holcombe-Shamrock	IB	-95.40809°	29.70612°
8	Fannin-Bates	IB	-95.40254°	29.70732°
9	Fannin-TX Children's Hospital	IB	-95.40126°	29.70905°
10	Fannin-Ross Sterling	IB	-95.39780°	29.71342°
11	San Jacinto-Wheeler	IB	-95.38095°	29.73338°
12	Main-Calhoun	IB	-95.37025°	29.75006°
13	Main-Clay	IB	-95.36737°	29.75370°
14	Main-Dallas	IB	-95.36627°	29.75511°
15	Main-Texas	IB	-95.36260°	29.75976°
16	Congress-Smith	IB	-95.36377°	29.76417°
17	Preston-Milam	OB	-95.36343°	29.76269°
18	Fannin-Walker	OB	-95.36330°	29.75753°
19	Fannin-Calhoun	OB	-95.36933°	29.74984°
20	Fannin-Holman	OB	-95.37764°	29.73937°

*IB=Inbound direction (towards downtown)
OB=Outbound direction (away from downtown)

Table 2. Areawide Sites

Site #	Site Location	Longitude	Latitude
21	Barker Cypress Overpass on I-10 Katy Freeway Eastbound (18,000 block)	-95.68861°	29.78444°
22	Sign Structure East of Sam Houston Tollway on I-10 Katy Freeway Eastbound (10,600 block)	-95.56194°	29.78444°
23	Overhead Sign Structure No. RS45-52 2A on North Side of the I-610 Interchange on I-45 North Freeway Northbound (3,800 block)	-95.37861°	29.82222°
24	Overpass at the Interchange with the Hardy Toll Road on I-45 North Freeway (23,000 block)	-95.43556°	30.10472°

Test 2 - Response Time of AVL system

This test examined the time required by the AirTouch AVL system to locate vehicles. This was measured in two ways. First, a single vehicle was located 20 times at approximately one minute intervals. Second, the 144 vehicles or vehicle location units assigned to METRO were manually located 20 times. This includes the 129 METROLift vehicles equipped with the AVL system, 13 backup units in the METROLift fleet, and the 2 portable units used for this study. The time required to identify both the single vehicle and all 144 vehicles was measured and the results were analyzed.

Test 3 - Locating a Moving Vehicle

This test involved monitoring a vehicle along the length of the METRO 2 Bellaire Route-Dairy Ashford branch. A vehicle carrying a portable location unit was driven along the entire route and the Fleet Director software was used to page the vehicle at 30 second intervals. The resulting location information was compared with the known path of the bus, determined in a previous study by METRO. This information was graphed to illustrate any differences between the AVL polling locations and the actual bus route.

IV. PRELIMINARY RESULTS

Test 1 - Accuracy of AVL system

At each of the 24 locations, at least 20 tests of the AirTouch latitude and longitude coordinates were obtained. A larger number of observations were taken at two sites to assess potential statistical differences due to the size of the sample. Comparisons were then made between the known latitude and longitude and the latitude and longitude obtained from the AIRTouch system. The distance between the sets of coordinates was computed with the GEOD software. Table 3 presents the results of these tests in feet and Table 4 presents the same information in meters. The tables indicate the number of readings taken at each site and identify the minimum and maximum distance from the known coordinates, the mean (average) distance, and the standard deviation of the distance, which indicates the amount of variation between readings. A small standard deviation indicates that the readings at a test site were relatively close together, while a larger standard deviation indicates greater differences between readings for the site.

Table 5 identifies the number of measurements that met the stated accuracy of 150 feet (45.7 meters). The preliminary test results indicate that 8 of the 24 study sites, or 33 percent, had an average difference between the measured and known locations of less than 150 feet (45.7 meters). However, 19, or 79 percent, of the sites had at least one measurement within the 150-foot range. The additional observations at the two sites did not provide any greater indication of accuracy. As discussed in the last section of this technical memorandum, further tests and more detailed statistical analyses are needed before any specific conclusions can be drawn regarding the accuracy of the system.

Table 3. AirTouch Locates Along 2 Bellaire Route - Dairy Ashford Branch (Values in Feet)

Location	# of Trials	Minimum	Maximum	Mean	Standard Deviation
Bellaire - Dairy Ashford	21	91.87	226.70	172.90	30.531
Bellaire - Wilcrest	25	55.76	191.50	105.10	35.177
Bellaire - Gessner	20	48.49	213.80	104.30	37.891
Bellaire - Cannock	23	90.80	228.50	141.40	34.993
Bellaire - Bellaire Transit Center	22	123.30	253.20	201.40	34.071
Bellaire - Buffalo Speedway	22	105.60	207.20	157.20	27.185
Holcombe - Shamrock	20	186.60	268.00	225.50	20.201
Fannin - Bates	23	46.56	345.60	173.50	77.556
Fannin - Texas Children's Hospital	23	10.57	98.02	59.55	23.636
Fannin - Ross Sterling	118	48.04	505.60	271.90	81.637
San Jacinto - Wheeler	15	38.73	286.60	87.91	71.522
Main - Calhoun	20	87.77	383.20	191.20	68.545
Main - Clay	22	46.64	379.60	136.90	85.938
Main - Dallas	23	167.40	596.50	290.70	108.720
Main - Texas	45	79.47	433.90	170.30	60.308
Congress - Smith	23	168.10	626.90	445.10	91.894
Preston - Milam	24	646.40	828.10	730.50	45.995
Fannin - Walker	24	209.50	522.10	362.20	77.066
Fannin - Calhoun	21	58.78	277.90	124.20	65.244
Fannin - Holcombe	21	42.56	717.50	322.90	216.680
All Bus Route Sites	555	10.57	828.10	233.90	158.500
I-10 Katy - Barker Cypress	23	119.10	174.30	158.20	12.130
I-10 Katy - Sam Houston Tollroad	23	155.50	210.90	160.20	26.855
I-45 North Freeway - I-610	23	56.69	104.30	77.20	11.688
I-45 North Freeway - Hardy Tollroad	23	134.60	387.20	247.50	76.515
All Area-Wide Sites	92	56.69	387.20	160.80	72.990

Table 4. AirTouch Locates Along 2 Bellaire Route - Dairy Ashford Branch (Values in Meters)

Location	# of Trials	Minimum	Maximum	Mean	Standard Deviation
Bellaire - Dairy Ashford	21	28.00	69.09	52.71	9.305
Bellaire - Wilcrest	25	16.99	58.35	32.04	10.721
Bellaire - Gessner	20	14.78	65.18	31.79	11.549
Bellaire - Cannock	23	27.68	69.64	43.11	10.665
Bellaire - Bellaire Transit Center	22	37.57	77.18	61.37	10.384
Bellaire - Buffalo Speedway	22	32.18	63.17	47.92	8.285
Holcombe - Shamrock	20	56.88	81.69	68.74	6.157
Fannin - Bates	23	14.19	105.30	52.87	23.638
Fannin - Texas Children's Hospital	23	3.22	29.87	18.15	7.204
Fannin - Ross Sterling	118	14.64	154.10	82.86	24.882
San Jacinto - Wheeler	15	11.80	87.36	26.79	21.799
Main - Calhoun	20	26.75	116.80	58.26	20.892
Main - Clay	22	14.22	115.70	41.71	26.193
Main - Dallas	23	51.02	181.80	88.59	33.136
Main - Texas	45	24.22	132.20	51.90	18.381
Congress - Smith	23	51.23	191.10	135.70	28.008
Preston - Milam	24	197.00	252.40	222.70	14.019
Fannin - Walker	24	63.87	159.10	110.40	23.488
Fannin - Calhoun	21	17.91	84.71	37.85	19.885
Fannin - Holcombe	21	12.97	218.70	98.42	66.040
All Bus Route Sites	555	3.22	252.40	71.28	48.307
I-10 Katy - Barker Cypress	23	36.29	53.14	48.21	3.697
I-10 Katy - Sam Houston Tollroad	23	35.20	64.27	48.82	8.185
I-45 North Freeway - I-610	23	17.28	31.78	23.53	3.562
I-45 North Freeway - Hardy Tollroad	23	41.03	118.00	75.44	23.321
All Area-Wide Sites	92	17.28	118.00	49.00	22.246

Table 5. Location Measurement Deviation for Test Sites

Site #	Site Description	# of Trials	# of Trials <150 Ft. (45.7 m)	Average Trial <150 Ft. (45.7 m)
1	Bellaire-Dairy Ashford	21	4	No
2	Bellaire-Wilcrest	25	22	Yes
3	Bellaire-Gessner	20	17	Yes
4	Bellaire-Cannock	23	13	Yes
5	Bellaire-Transit Center (Northside)	22	2	No
6	Bellaire-Buffalo Speedway	22	9	No
7	Holcombe-Shamrock	20	0	No
8	Fannin-Bates	23	8	No
9	Fannin-TX Children's Hospital	23	23	Yes
10	Fannin-Ross Sterling	118	8	No
11	San Jacinto-Wheeler	24	22	Yes
12	Main-Calhoun	20	6	No
13	Main-Clay	23	16	Yes
14	Main-Dallas	23	0	No
15	Main-Texas	45	30	No
16	Congress-Smith	23	0	No
17	Preston-Milam	24	0	No
18	Fannin-Walker	24	0	No
19	Fannin-Calhoun	23	18	Yes
20	Fannin-Holman	21	5	No
21	Barker Cypress Overpass on I-10 Katy Freeway	23	4	No
22	Sign Structure East of Sam Houston Tollway on I-10 Katy Freeway	23	7	No
23	Overhead Sign Structure No. RS45-52 2A on North Side of I-610 Interchange on I-45 North Freeway	23	23	Yes
24	Overpass at Interchange with the Hardy Toll Road on I-45 North Freeway	23	2	No

Appendix A presents the scatter plots for each test site indicating the known latitude and longitude and the AirTouch latitude and longitude readings. Although a clustering of the test observations around the known locations could have been expected, at most sites the test

observations are clustered around an average which is different from the known location. In some cases, the clustering is in a narrow range, while in others there is a much wider variation. In addition, there seems to be greater variation in longitude than in latitude for most of the test sites. It appears that the narrow clustering is more frequently observed in areas which are relatively open and are not affected by tall structures, although this is not always the case. The wider variations appear more frequently in areas with tall structures, such as downtown.

The preliminary test data indicates a location accuracy for the system of approximately 550 feet at 2 sigma for the bus route sites and 306 feet at 2 sigma for areawide sites. These results are different than the stated range of 150 feet at 2 sigma.

The results of this preliminary test do not indicate a definite pattern for the differences between the known and observed readings. The results do point out a number of issues to be examined in more detail in the comprehensive assessment. These include the influence of tall buildings, the location of the radio towers, and the differences in variations in latitude and longitude. In addition, further tests are needed to ensure that vehicle location units are sited at the known coordinates.

Test 2 - Response Time of AVL System

This test examined the time required by the AirTouch system to locate the vehicles. Two different tests were conducted. First, a specific vehicle was located. Second, the 144 location units assigned to METROLift were located. Both tests were repeated a total of 20 times, with each test generating three separate values for "location time".

When a vehicle is paged by the Fleet Director, a *time stamp* is recorded indicating the time the page was initiated. Following this time stamp, there is a slight delay as the vehicle's location unit receives the page and transmits its response to the radio towers. When the unit's response is received by at least four towers, the unit/vehicle location is displayed both as an icon on the

on-screen street map and as a verbal description on the "data screen", which appears as a small window below the street map on the computer screen.

The *graphical screen time* represents the time it takes the Fleet Director software to locate and graphically display the location of all 144 vehicle location units on the street map. This was recorded with a stop watch by observing changes in the map. These readings may be slightly higher than actual time because there is a time lag of a few seconds before it can be observed that there are no more updates of the graphical screen. The *data screen time* represents the time required from the start of the locate operation until all of the unit locations are updated on the data screen. This was recorded with a stop watch by observing changes on the data screen. Similar to the graphical screen, this time may also be higher than actual time because of the time lag before it can be observed that there are no more updates. The results from these tests are presented in Table 6. Appendix B presents more detailed information on the observations for these tests.

As identified in Table 6, the time between the observations on the graphical and data screens did not differ appreciably in locating a single vehicle. As a result, only one time value was recorded for each observation. Three different times were recorded for each test in the second case, however.

Table 6. Location Time for Single Vehicle and for All Vehicles

	Single Vehicle	All Vehicles		
	(seconds)	Stamp (seconds)	Graphical Screen (seconds)	Data Screen (seconds)
Minimum	3.00	15.00	46.00	67.00
Maximum	5.29	30.00	73.00	100.00
Mean	3.89	20.95	57.45	80.60
Std. Dev.	0.64	4.82	10.08	12.44

Further research and analysis is needed to explain the difference between the graphical screen update time and the data screen update time. One possible explanation for this may be that the Fleet Director software updates the screen locations and then attaches the street location information and other status information before updating the data screen.

Test 3 - Locating a Moving Vehicle

In this test a TTI vehicle was monitored along the METRO 2 Bellaire Route - Dairy Ashford Branch. Readings were taken at 30-second intervals, and the screen was continuously monitored as the vehicle progressed along the route. Appendix C graphically presents the latitude and longitude coordinates recorded at 30 second intervals along the route.

As illustrated by the figures in Appendix C, some differences can be detected between the actual bus route and the test vehicle readings. For example, in one case the test vehicle was located about 2 blocks south of the actual bus route. In this case, it appears that the difference between the bus route and the test vehicle readings were approximately 1000 feet.

V. SUMMARY AND ADDITIONAL RESEARCH NEEDS

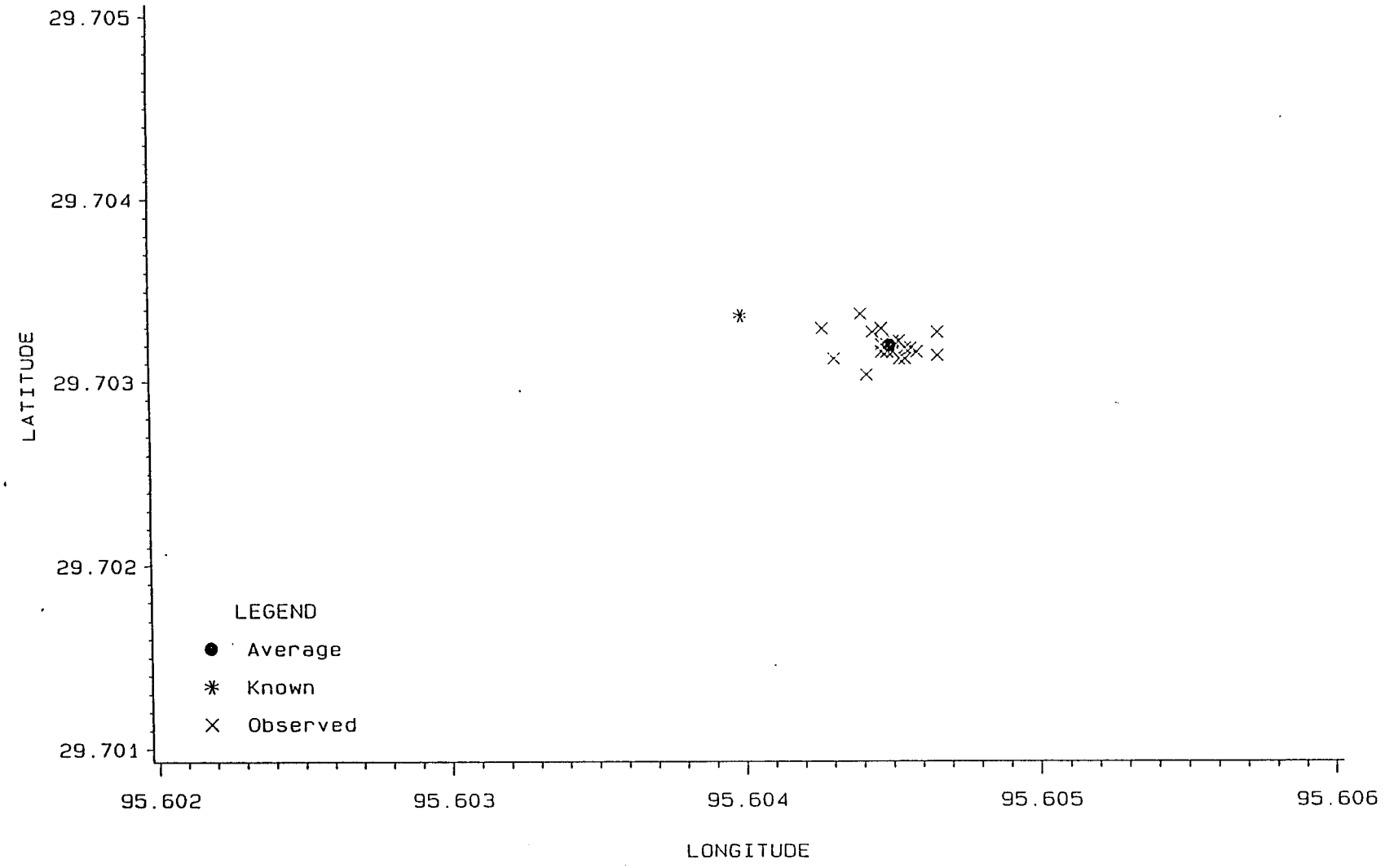
This technical memorandum presented the results of the preliminary assessment of the accuracy of the METROLift AirTouch AVL system. Information on the system was presented, along with the methodology and preliminary results from the three tests. The initial results indicate a good deal of inconsistency between readings. Further, a number of readings exceeded the 150 foot accuracy window. The average distance between the AirTouch Teletrac AVL system and known locations did not meet the 150 feet (45.7 meters) standard in 16 of the 24 sites studied. Both the average accuracy and the consistency between trials varied considerably from site to site through the Houston service area. The limited number of tests conducted during this preliminary assessment leave a number of issues unresolved, however. These need to be addressed in the more detailed examination to be conducted over the next few months.

The following issues should be considered in the more detailed assessment. First, the known coordinates should be rechecked and the test locations should be reexamined to ensure that they are as close to the known coordinates as possible. Second, additional tests should be conducted at these sites and at other locations throughout the METRO area. Third, the results from these tests should be examined to identify any variations due to the location of the radio towers, tall buildings, power lines, and other factors. The differences in the variation in latitude and longitude readings should also be assessed. Other tests addressing data throughput, vehicle speed, and the effects of underground and out-of-range locations will also be conducted.

Appendix A

Bellaire @ Dairy Ashford

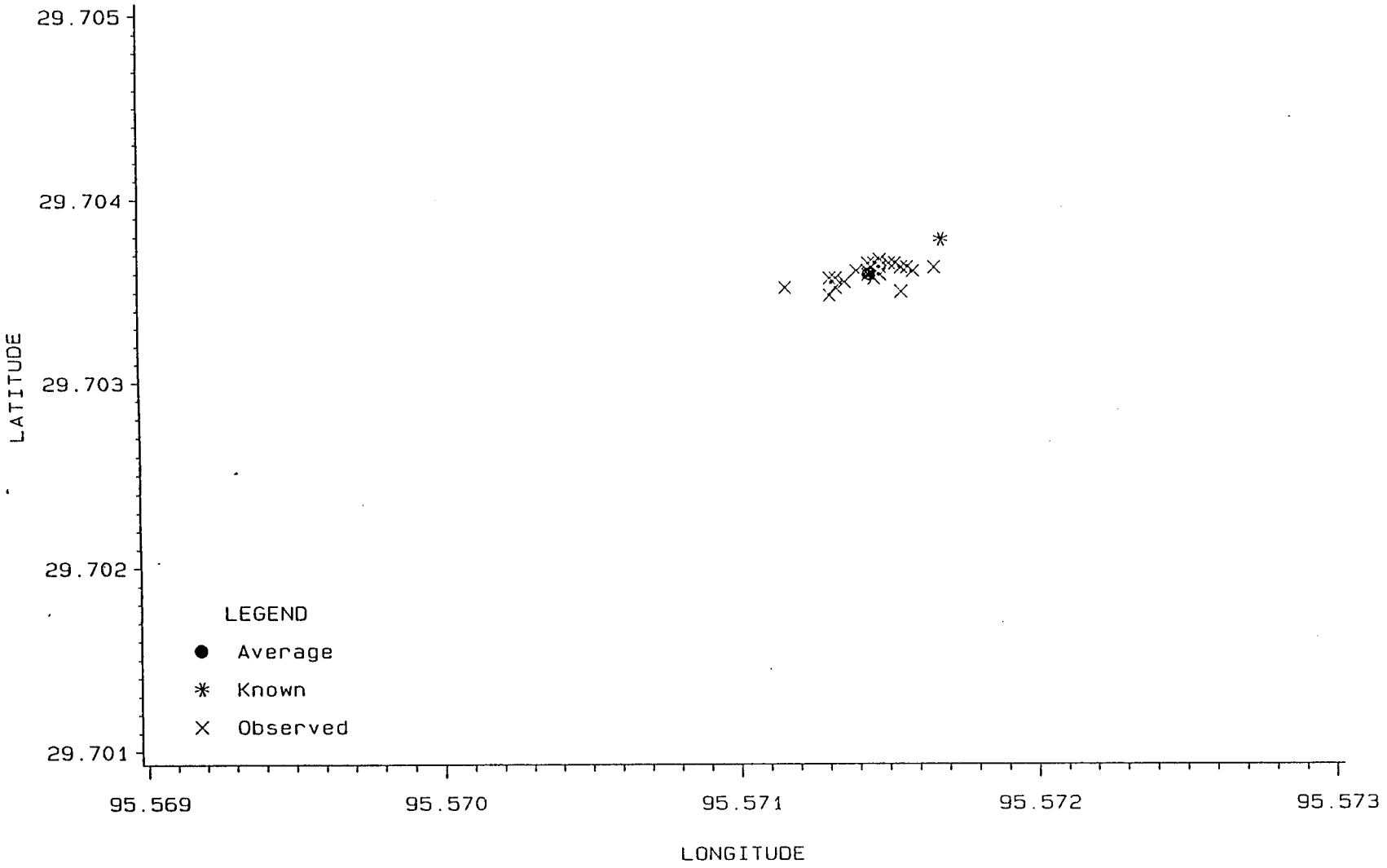
Latitude = 29.703370 Longitude = 95.603992



Average distance from known to observed = 172.9 ft (52.7 meters)

Bellaire @ Wilcrest

Latitude = 29.703792 Longitude = 95.571683

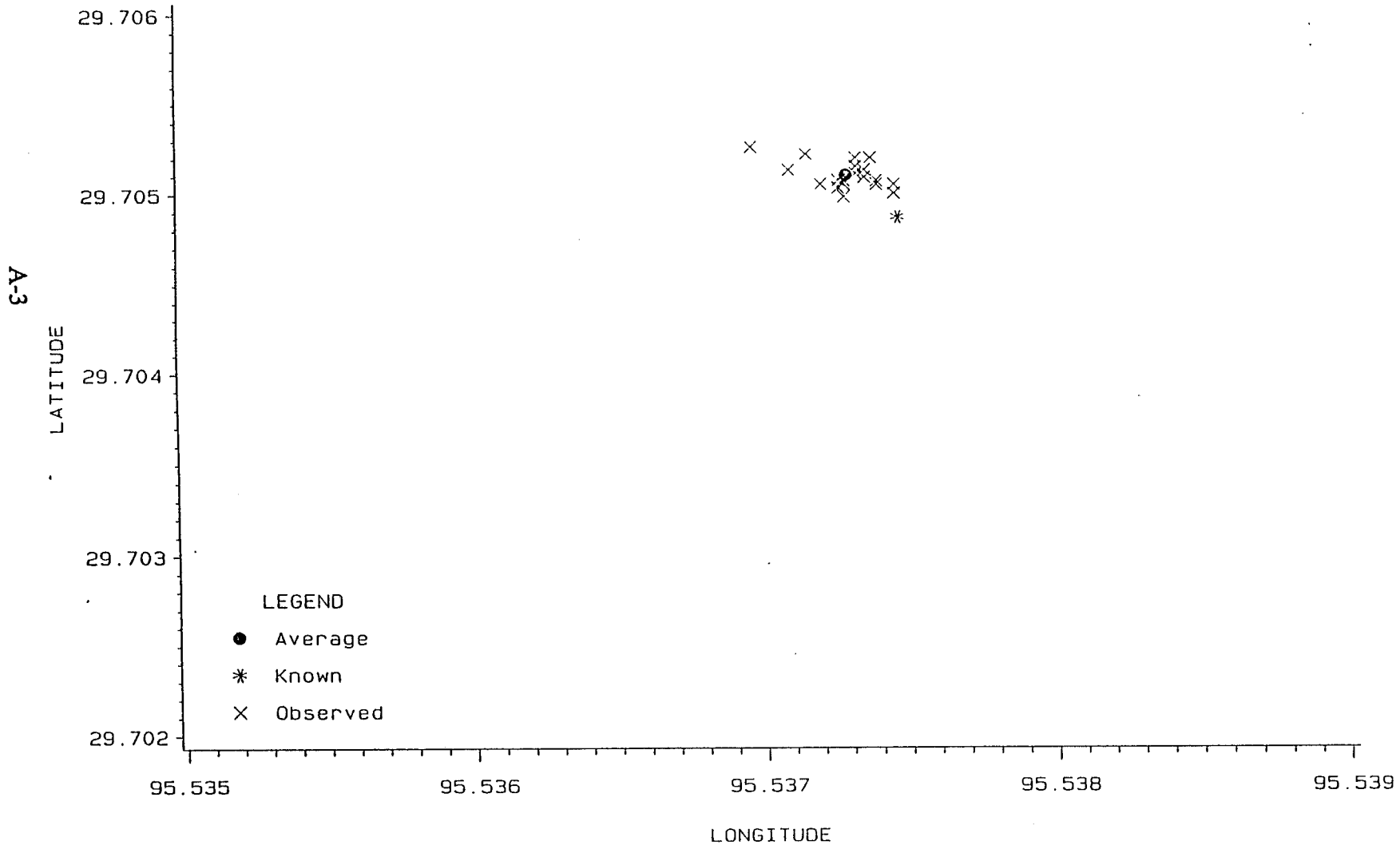


Average distance from known to observed = 105.1 ft (32.0 meters)

A-2

Bellaire @ Gessner

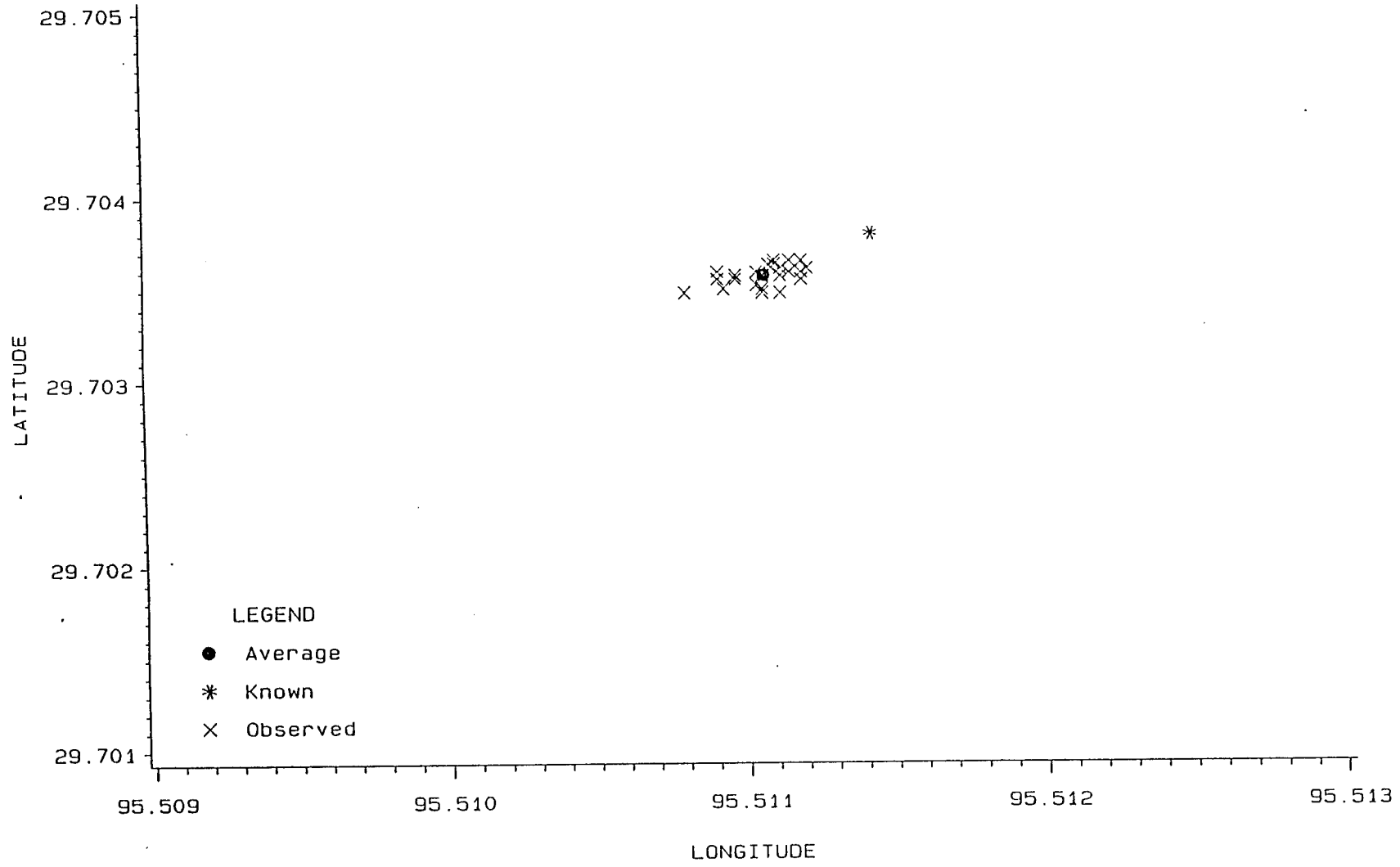
Latitude = 29.704877 Longitude = 95.537461



Average distance from known to observed = 104.3 ft (31.8 meters)

Bellaire @ Cannock

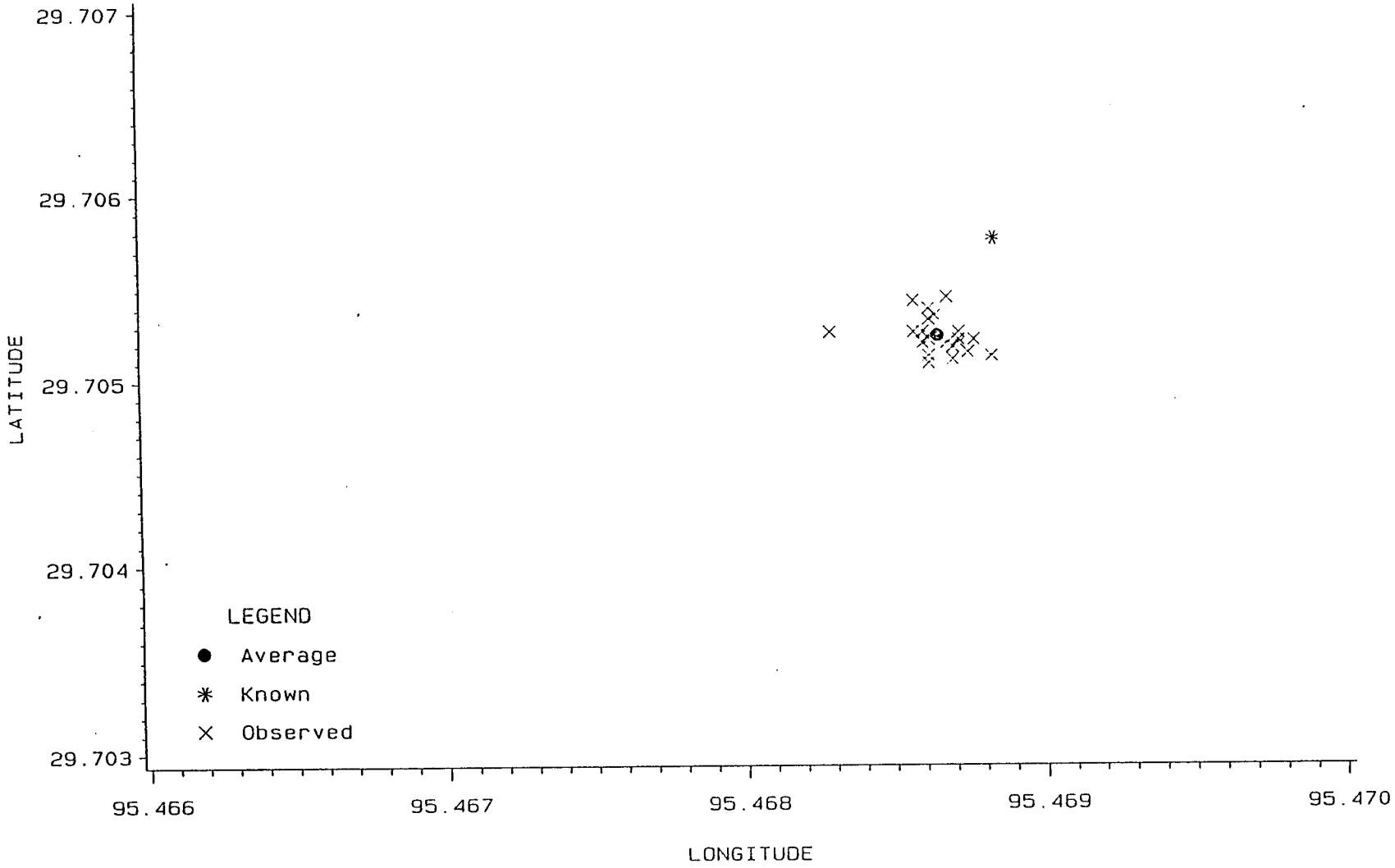
Latitude = 29.703806 Longitude = 95.511422



Average distance from known to observed = 141.4 ft (43.1 meters)

Bellaire @ Bellaire Transit Center

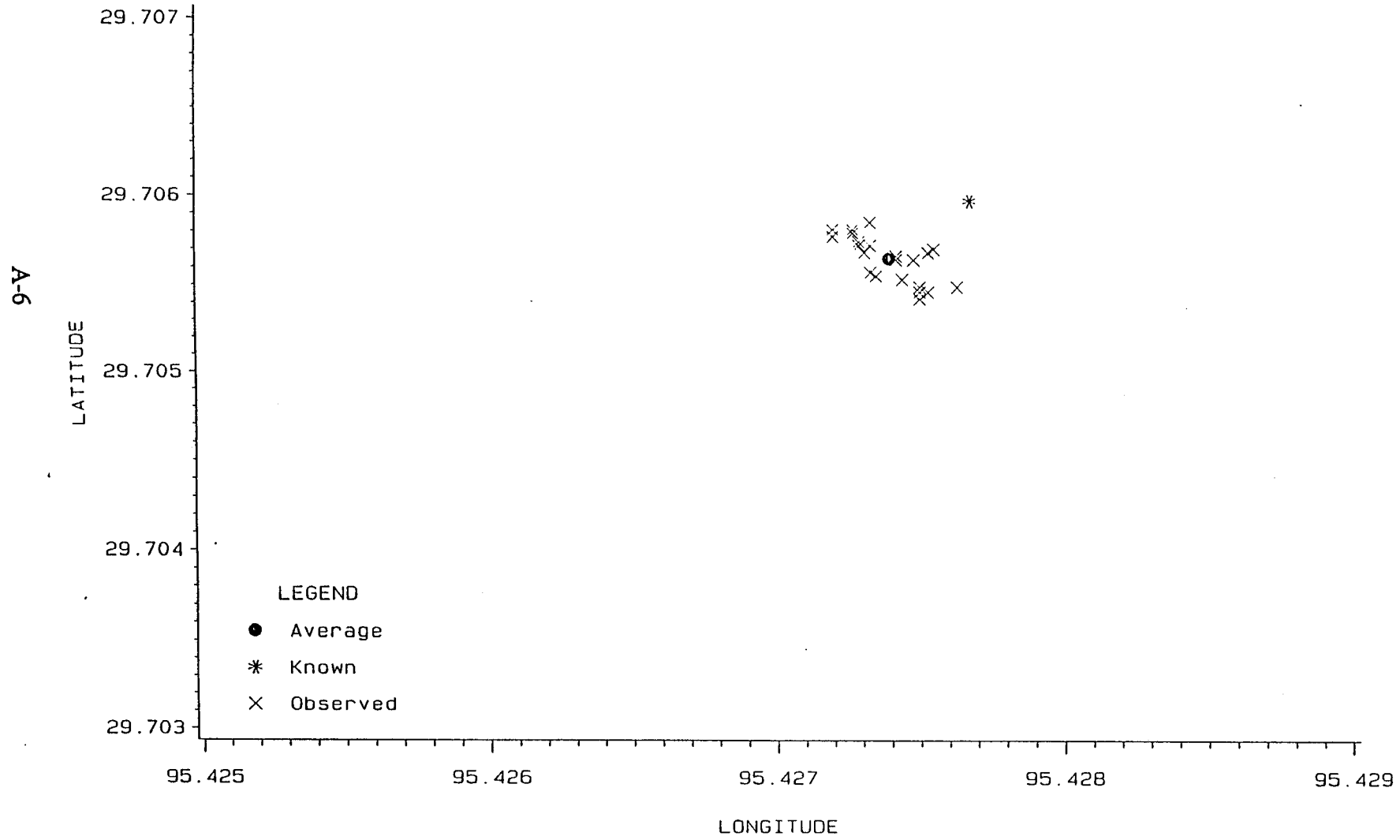
Latitude = 29.705770 Longitude = 95.468837



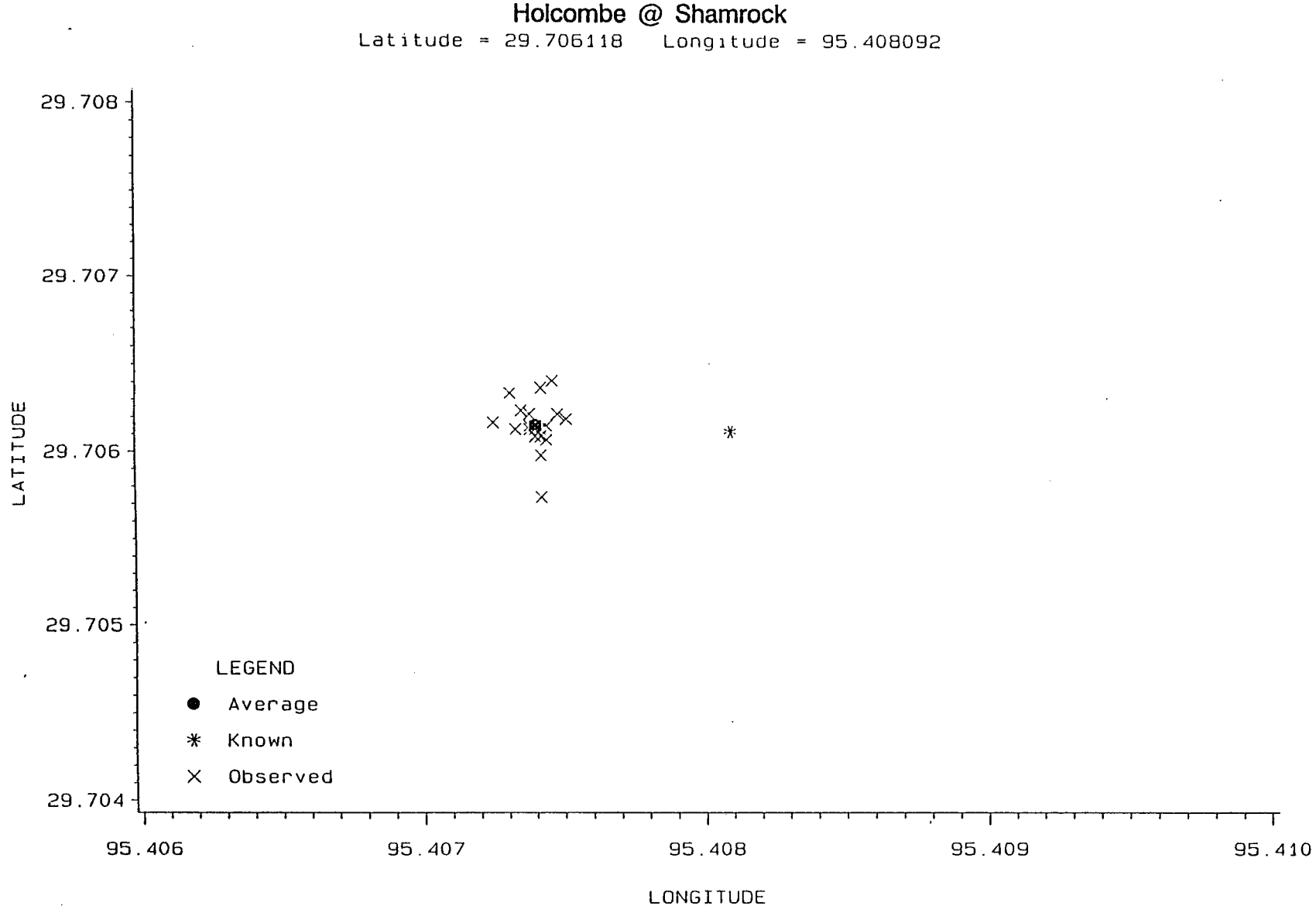
Average distance from known to observed = 201.4 ft (61.4 meters)

Bellaire @ Buffalo Speedway

Latitude = 29.705969 Longitude = 95.427675



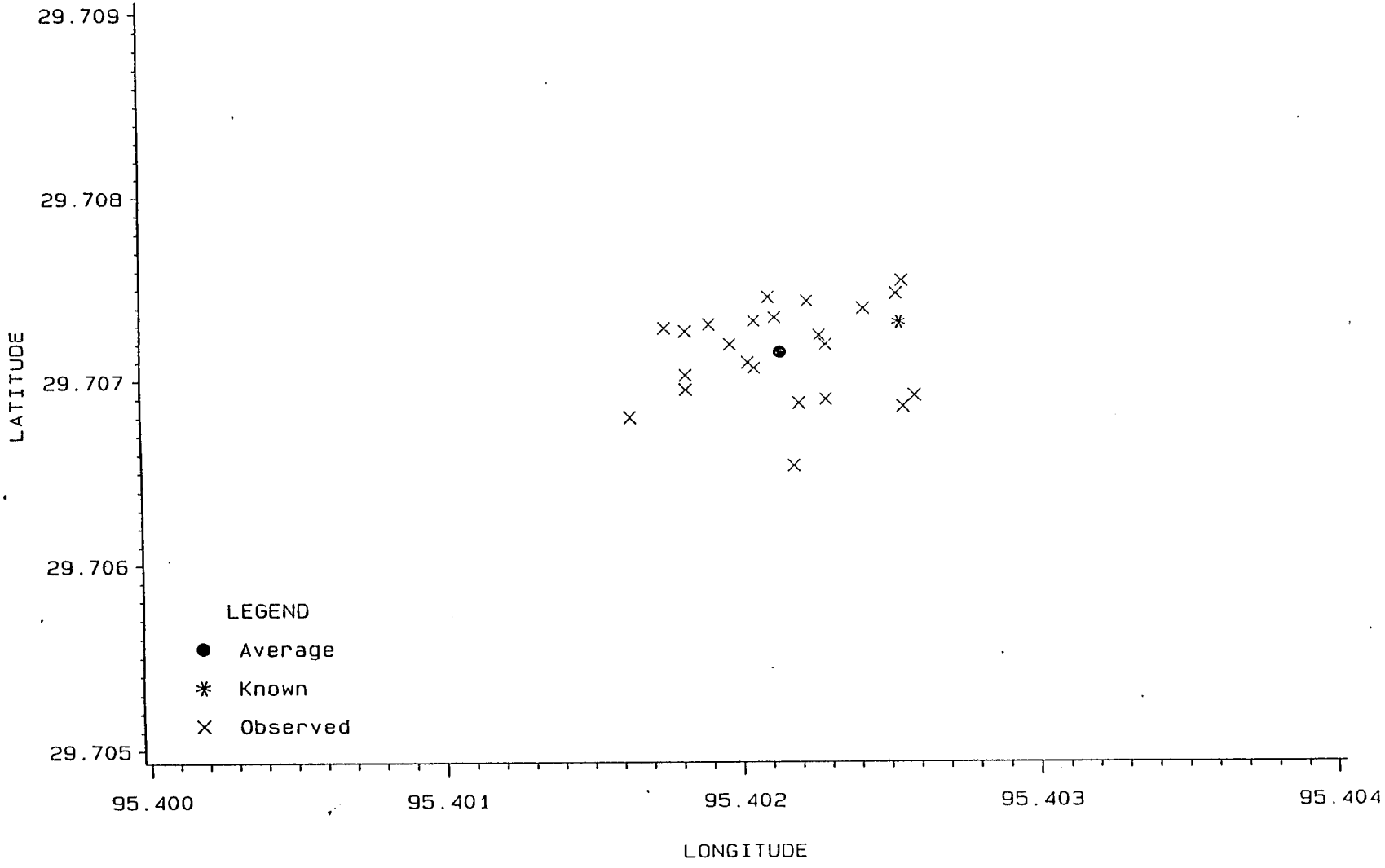
Average distance from known to observed = 157.2 ft (47.9 meters)



Average distance from known to observed = 225.5 ft (68.7 meters)

Fannin @ Bates

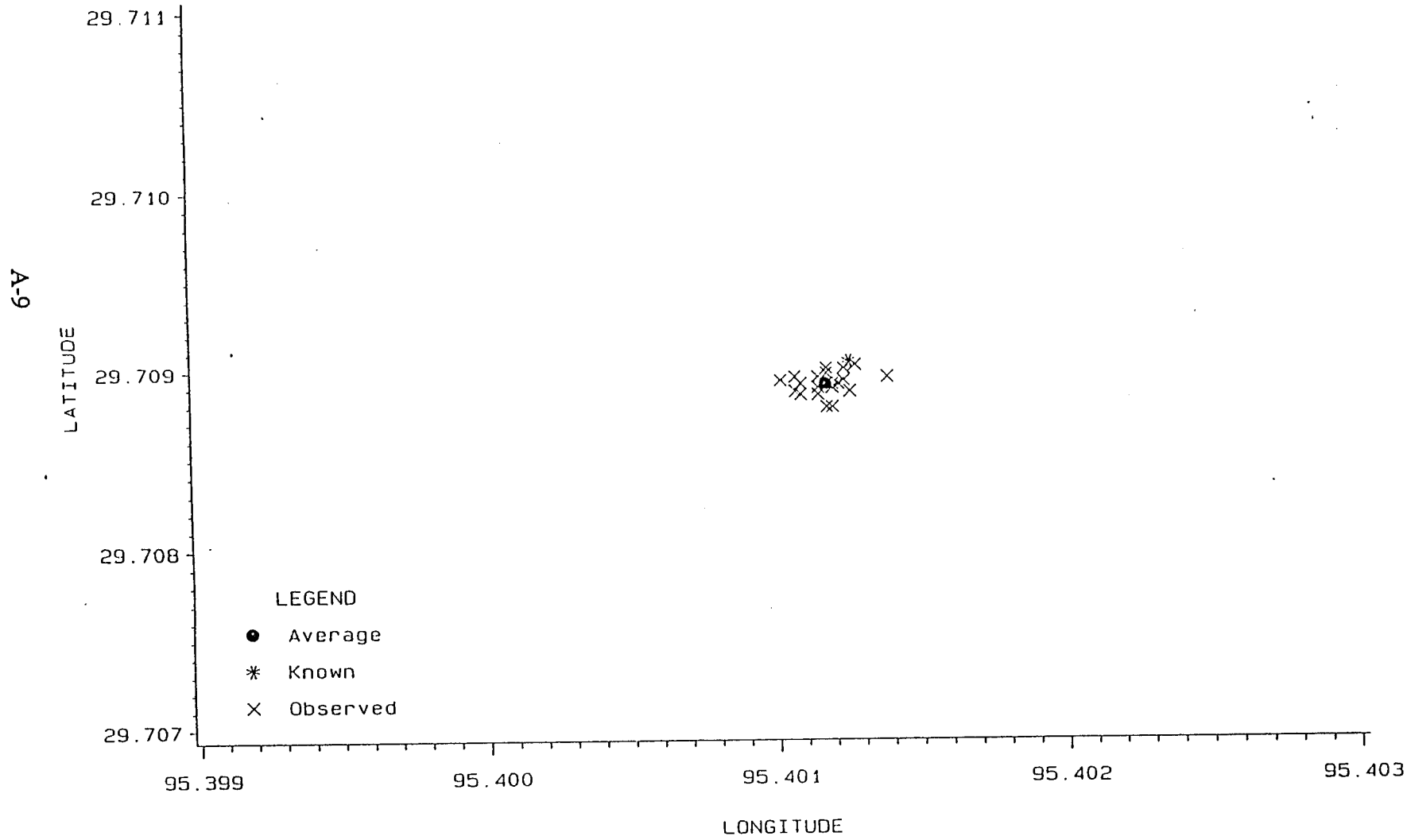
Latitude = 29.707324 Longitude = 95.402538



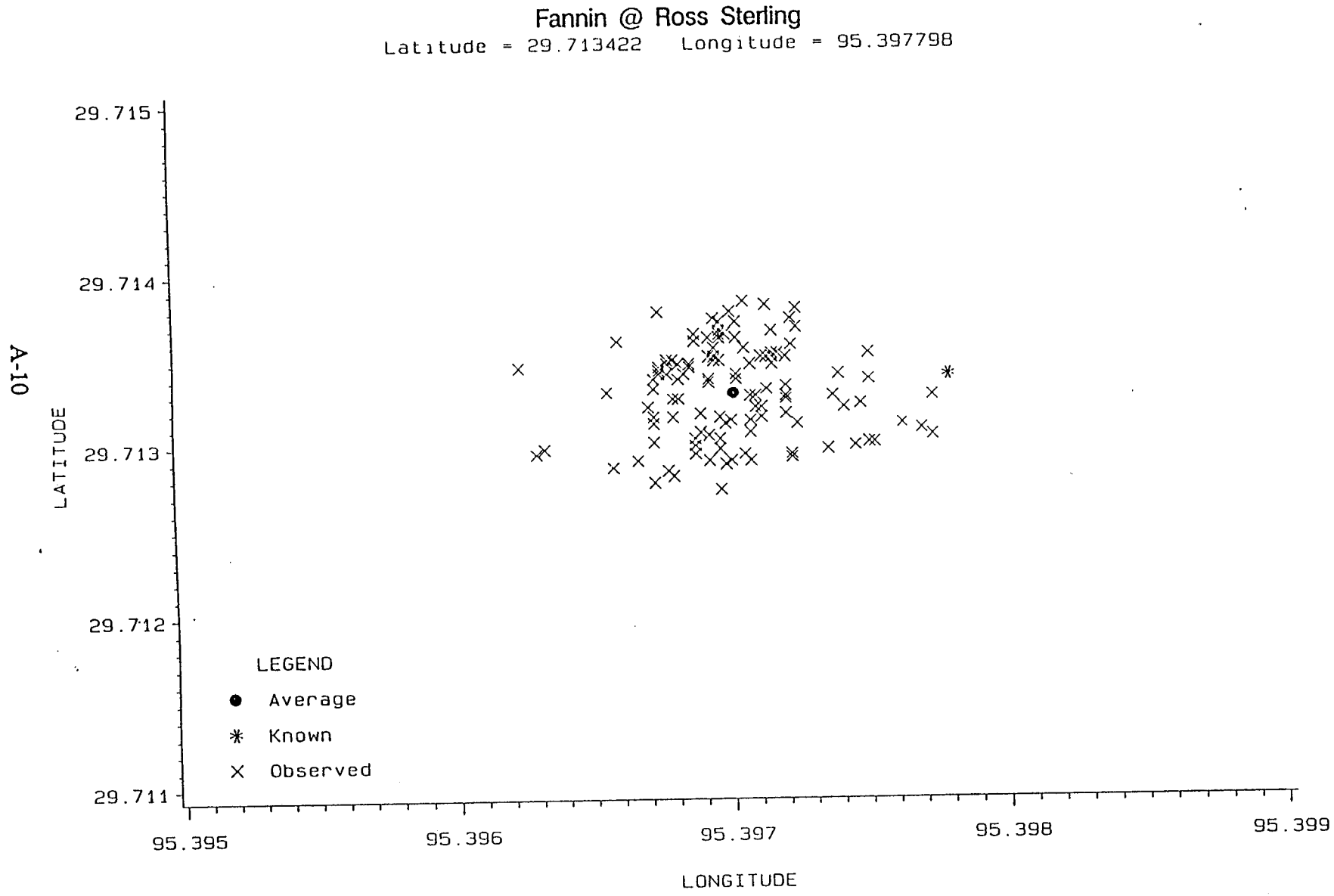
Average distance from known to observed = 173.5 ft (52.9 meters)

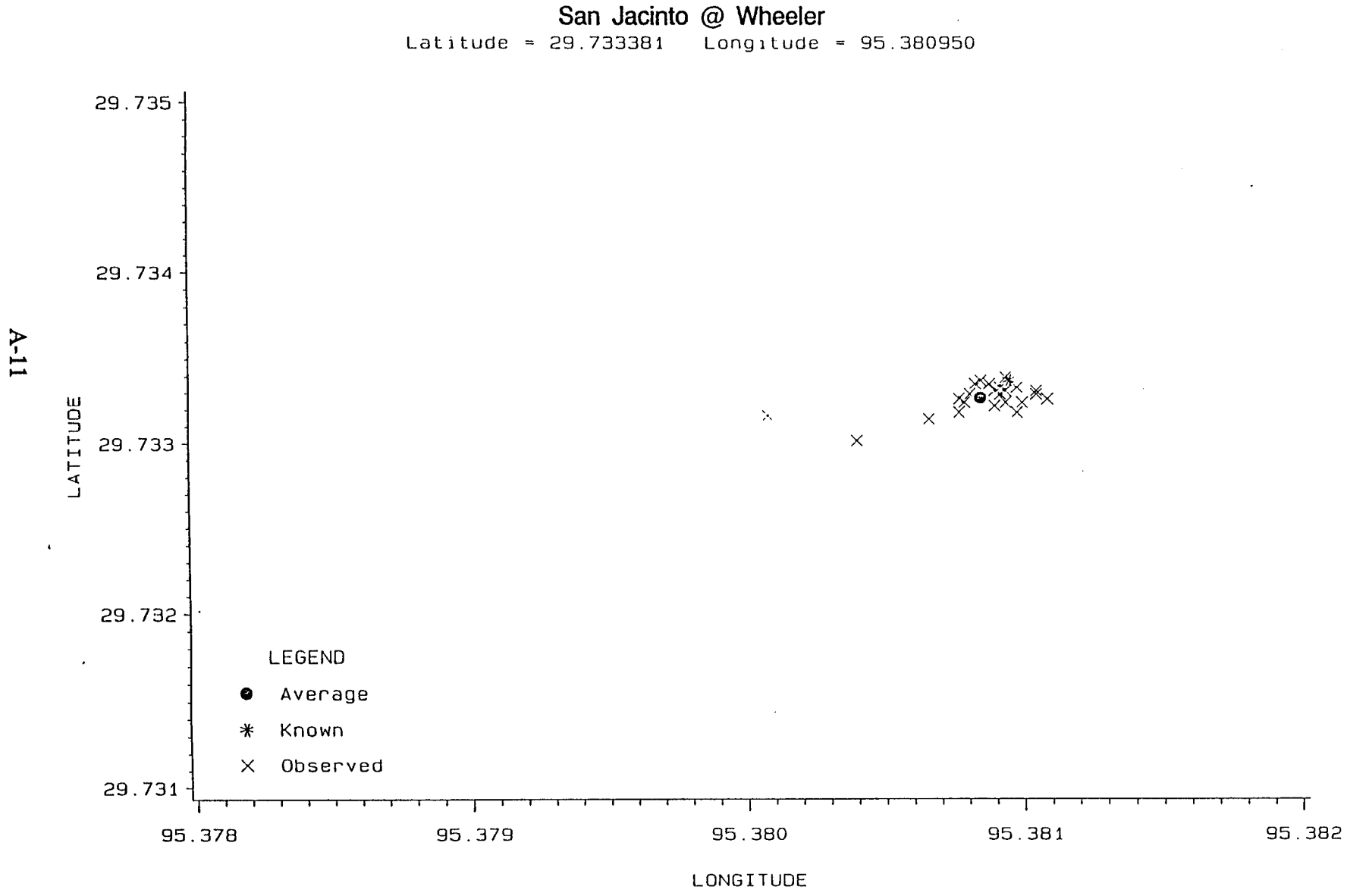
Fannin @ Texas Childrens Hospital

Latitude = 29.709051 Longitude = 95.401257



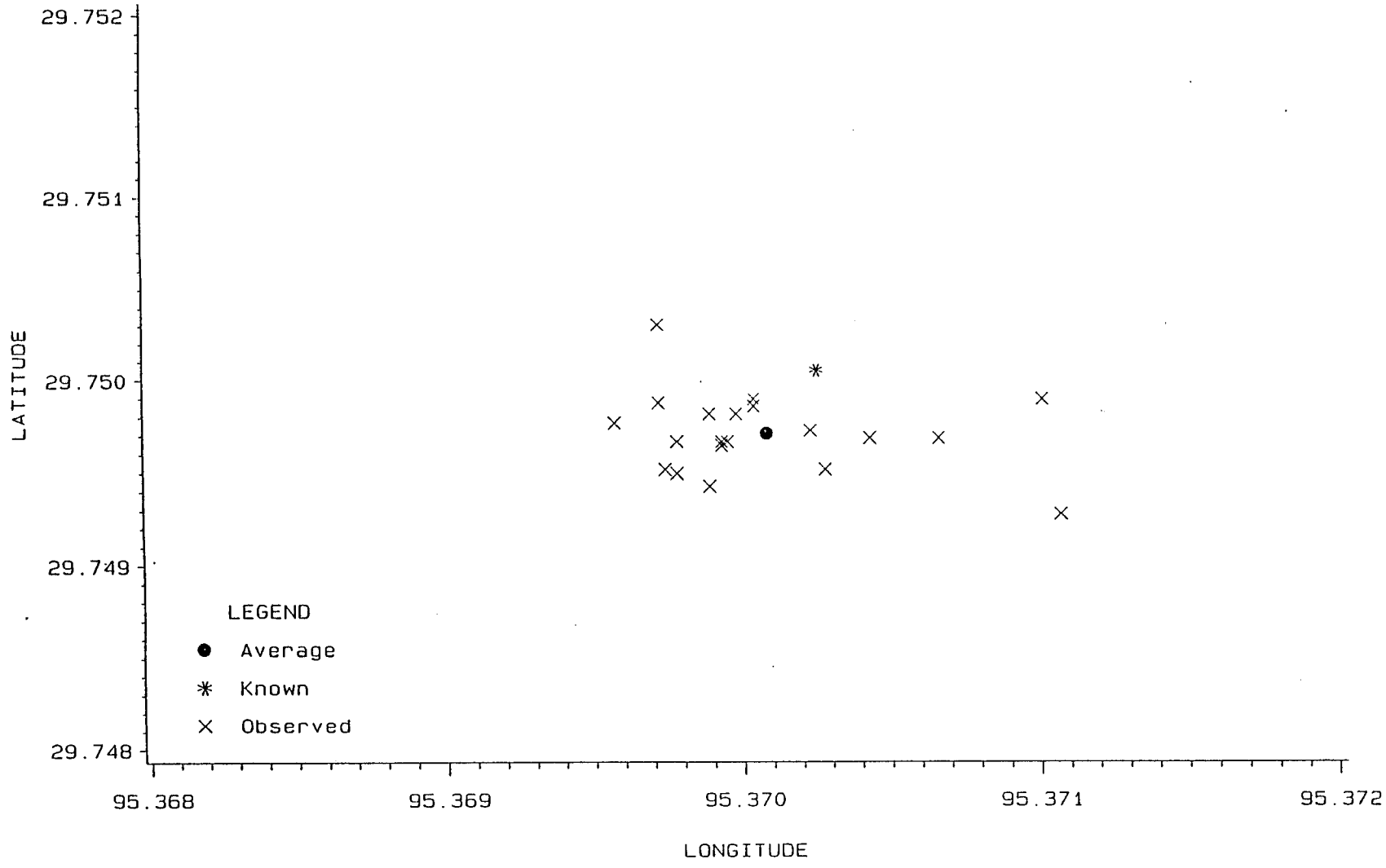
Average distance from known to observed = 59.6 ft (18.2 meters)


Fannin @ Ross Sterling
Latitude = 29.713422 Longitude = 95.397798
29.715
29.714
29.713
29.712
29.711
LATITUDE
A-10
LEGEND
Average
Known
Observed
95.395
95.396
95.397
95.398
95.399
LONGITUDE
Average distance from known to observed = 271.9 ft (82.9 meters)


San Jacinto @ Wheeler
Latitude = 29.733381 Longitude = 95.380950
29.735
29.734
29.733
29.732
29.731
LATITUDE
LEGEND
Average
Known
Observed
95.378
95.379
95.380
95.381
95.382
LONGITUDE
Average distance from known to observed = 87.9 ft (26.8 meters)

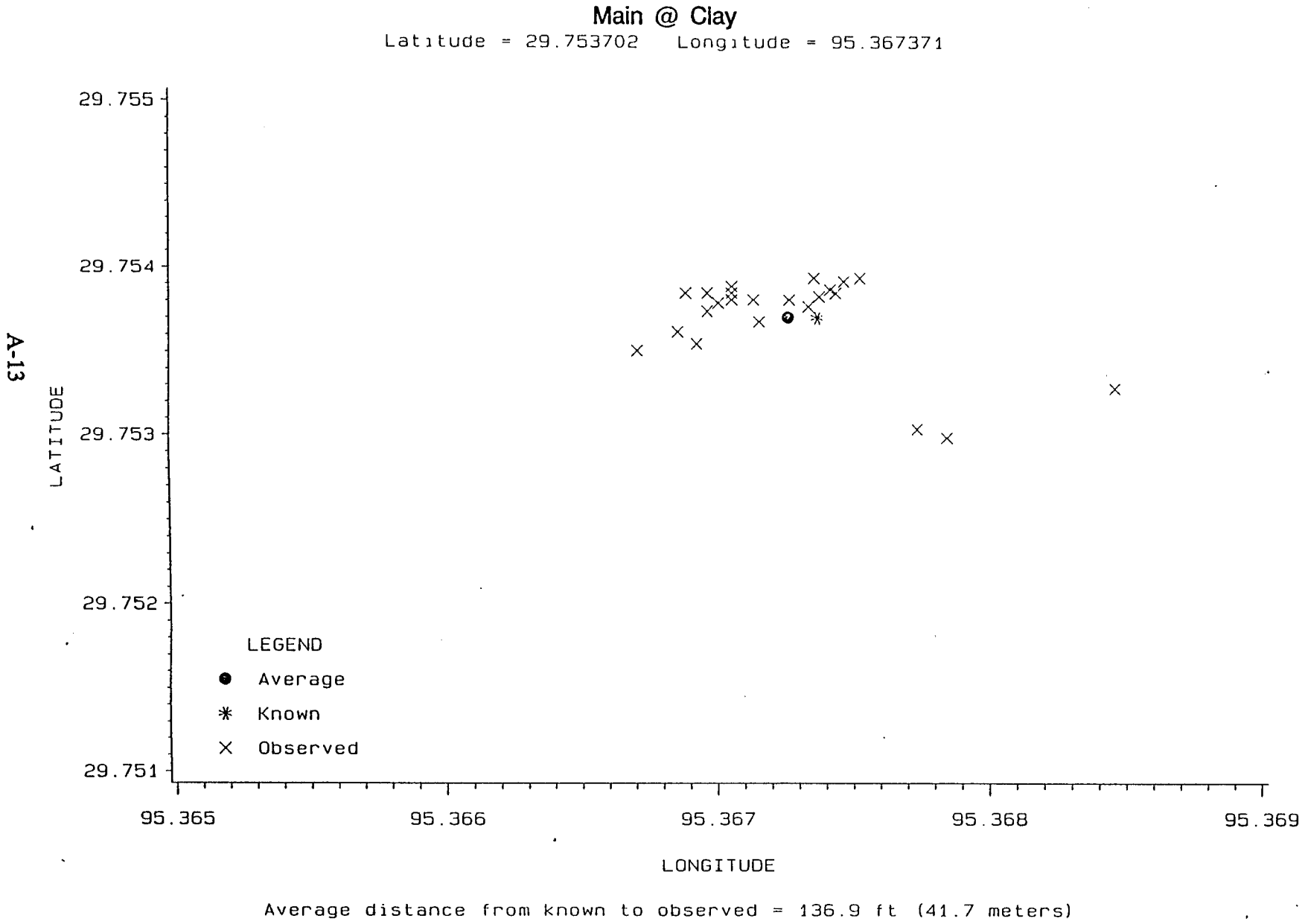
Main @ Calhoun

Latitude = 29.750055 Longitude = 95.370252



A-12

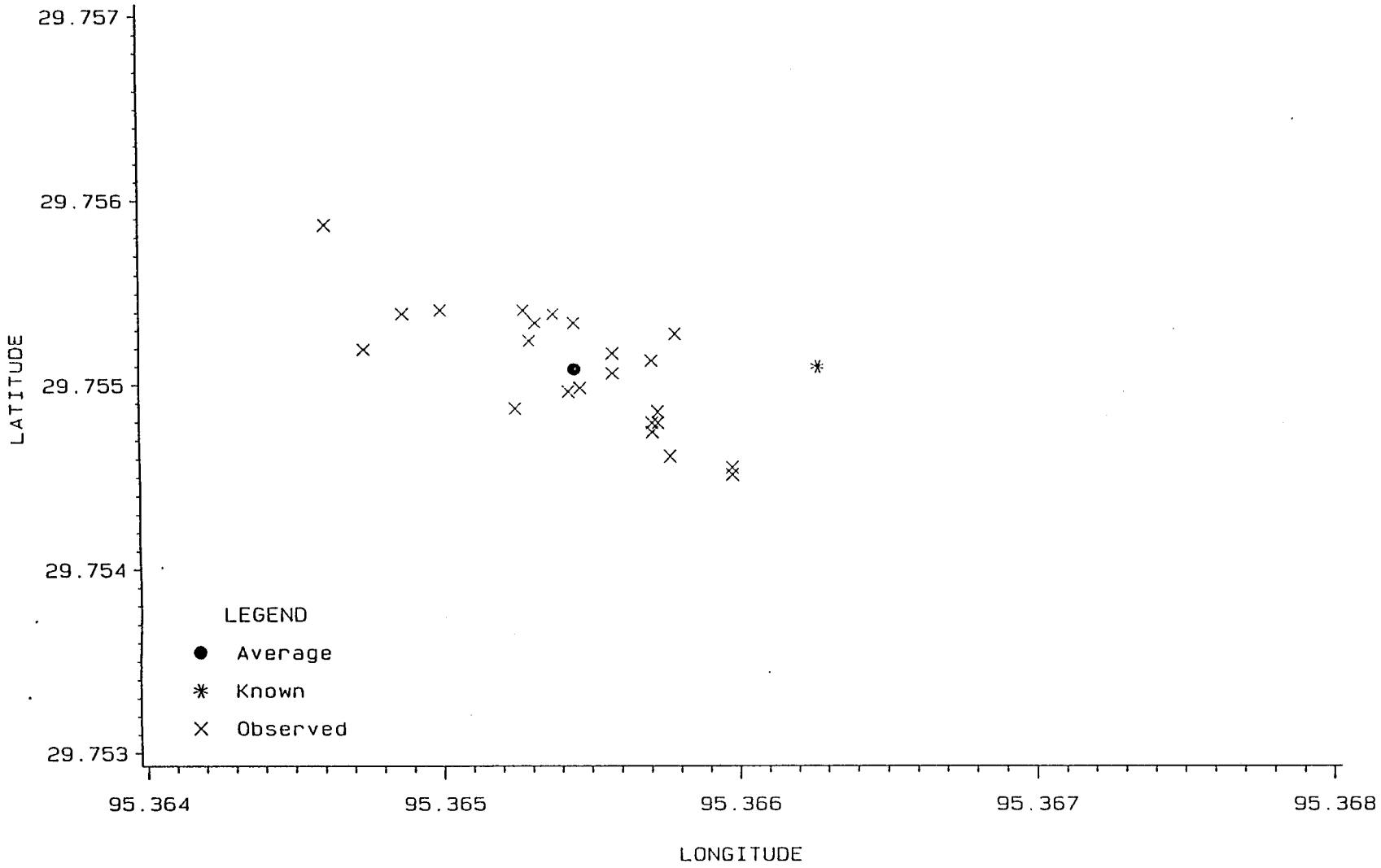
Average distance from known to observed = 191.2 ft (58.3 meters)


Main @ Clay
Latitude = 29.753702 Longitude = 95.367371
29.755
29.754
29.753
29.752
29.751
LATITUDE
LEGEND
Average
Known
Observed
95.365
95.366
95.367
95.368
95.369
LONGITUDE
Average distance from known to observed = 136.9 ft (41.7 meters)

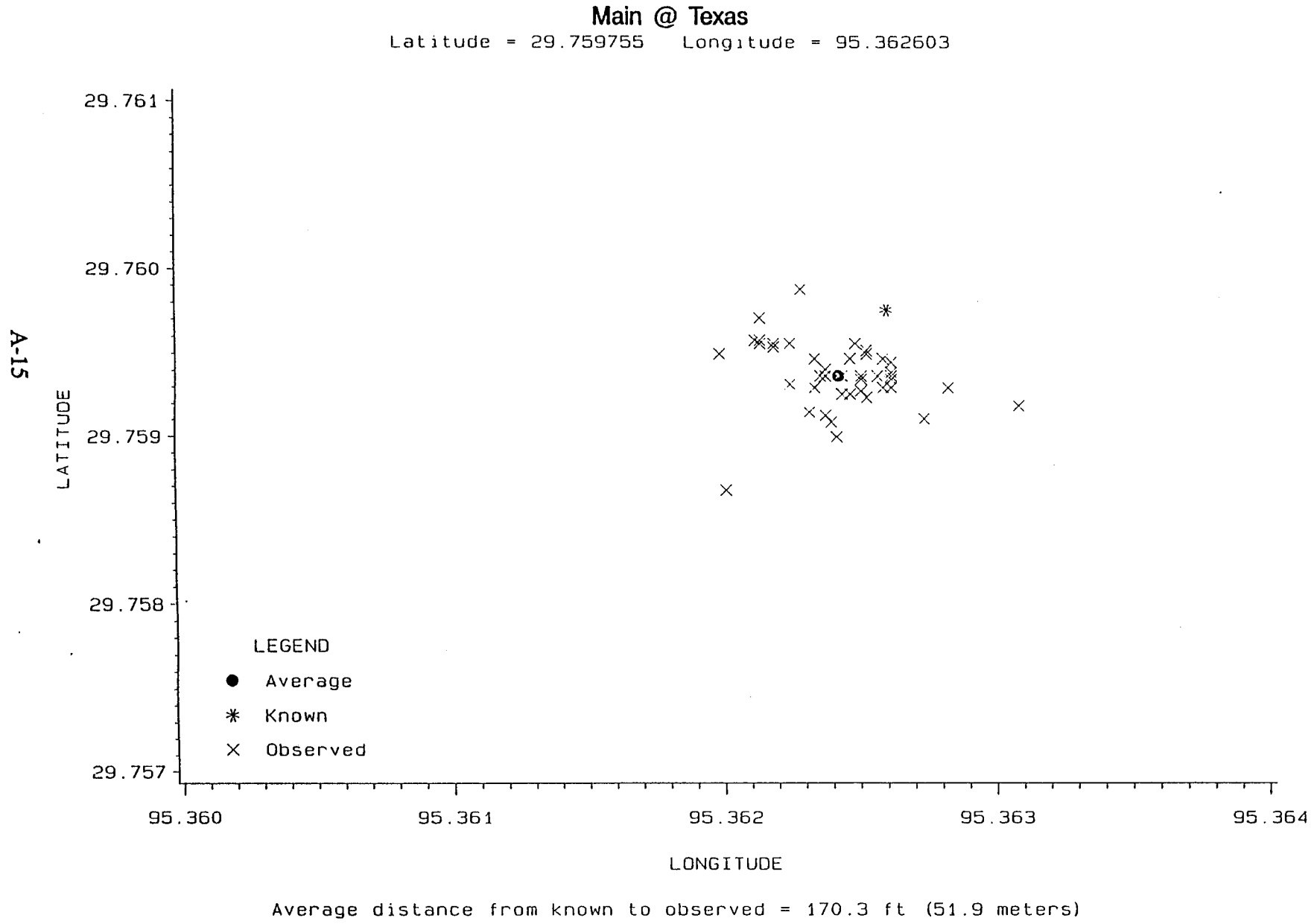
A-13

Main @ Dallas

Latitude = 29.755107 Longitude = 95.366274

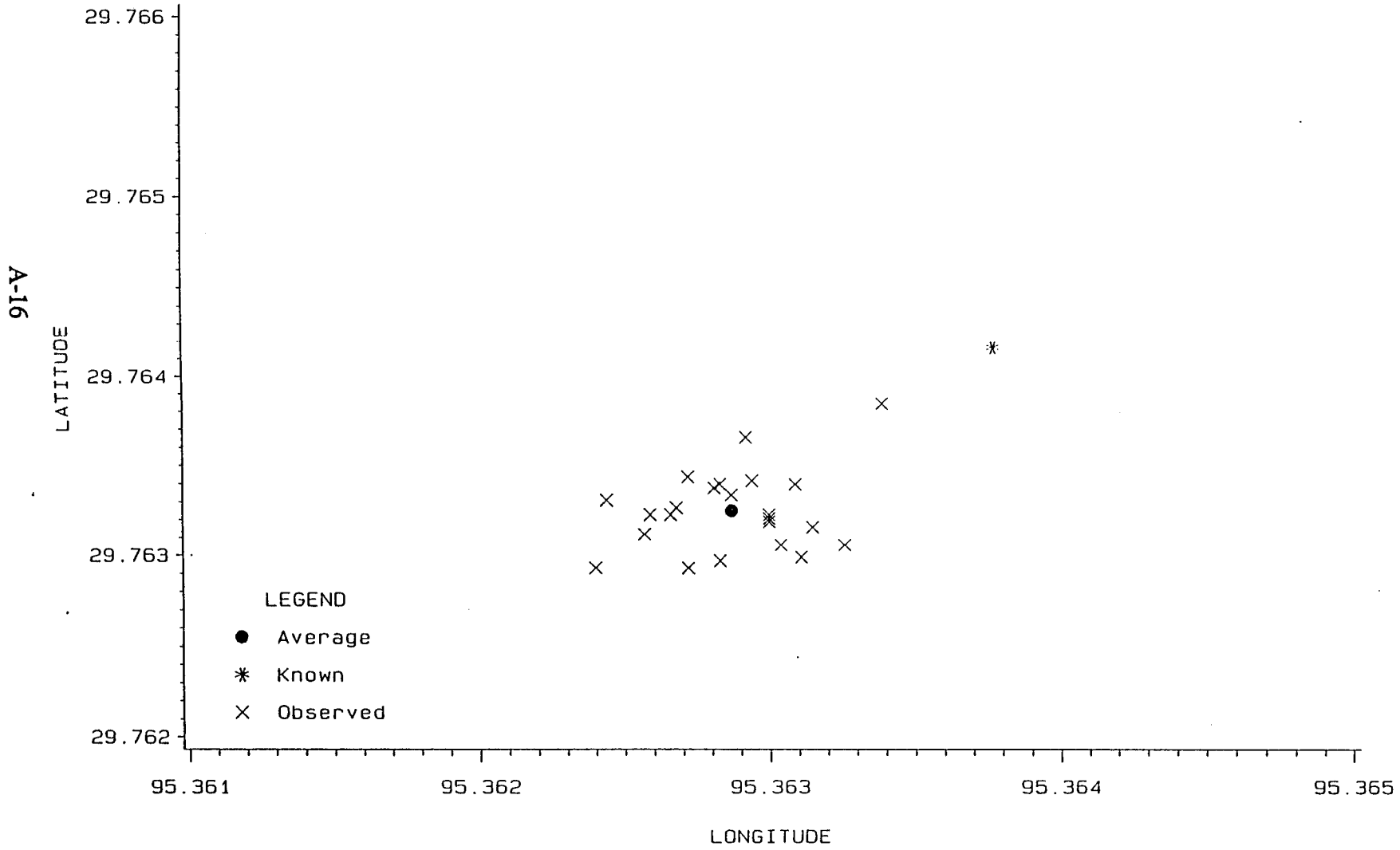


Average distance from known to observed = 290.7 ft (88.6 meters)


Main @ Texas
Latitude = 29.759755 Longitude = 95.362603
29.761
29.760
29.759
29.758
29.757
LATITUDE
95.360
95.361
95.362
95.363
95.364
LONGITUDE
LEGEND
Average
Known
Observed
Average distance from known to observed = 170.3 ft (51.9 meters)

Congress @ Smith

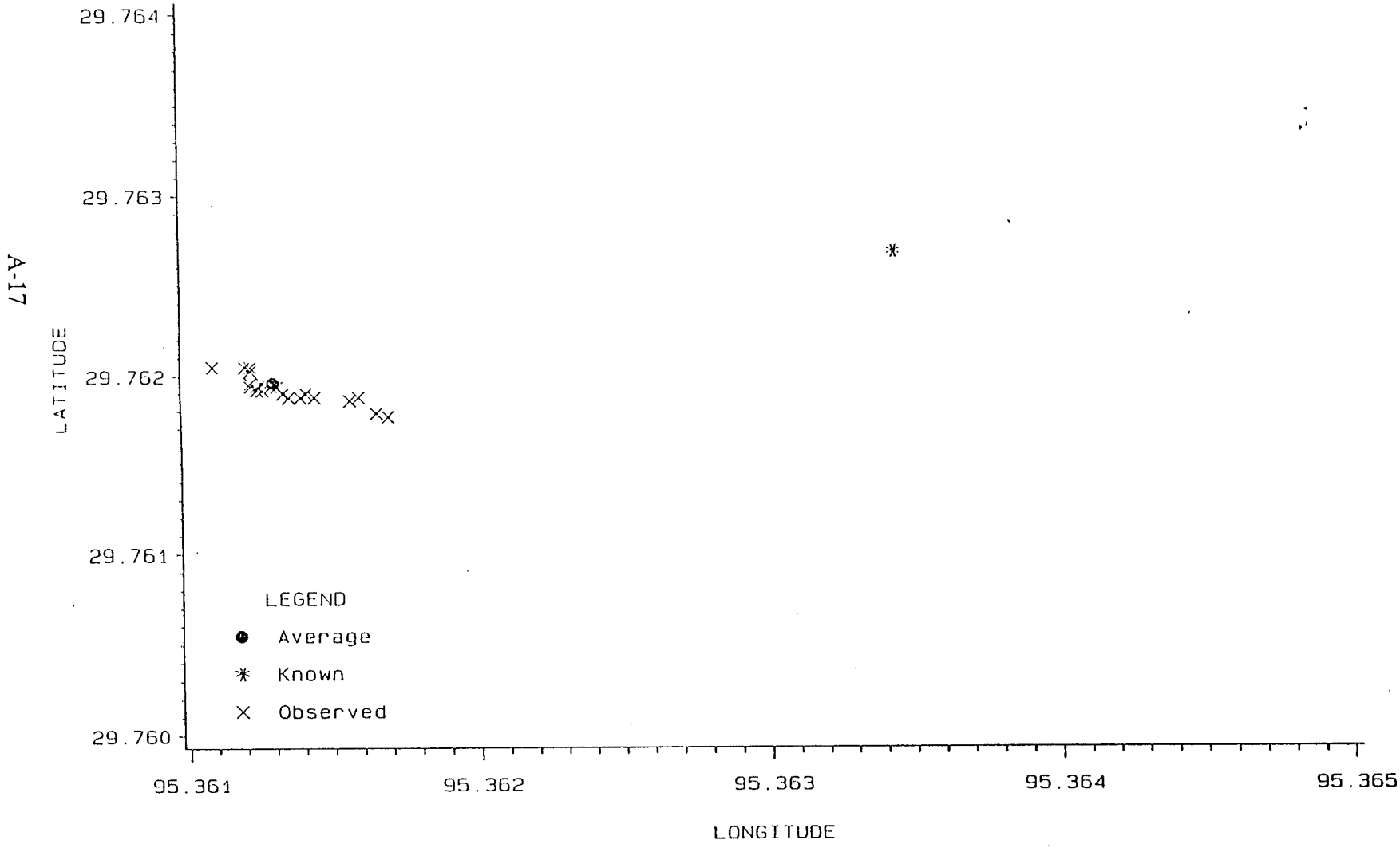
Latitude = 29.764172 Longitude = 95.363770



Average distance from known to observed = 445.1 ft (135.7 meters)

Preston @ Milam

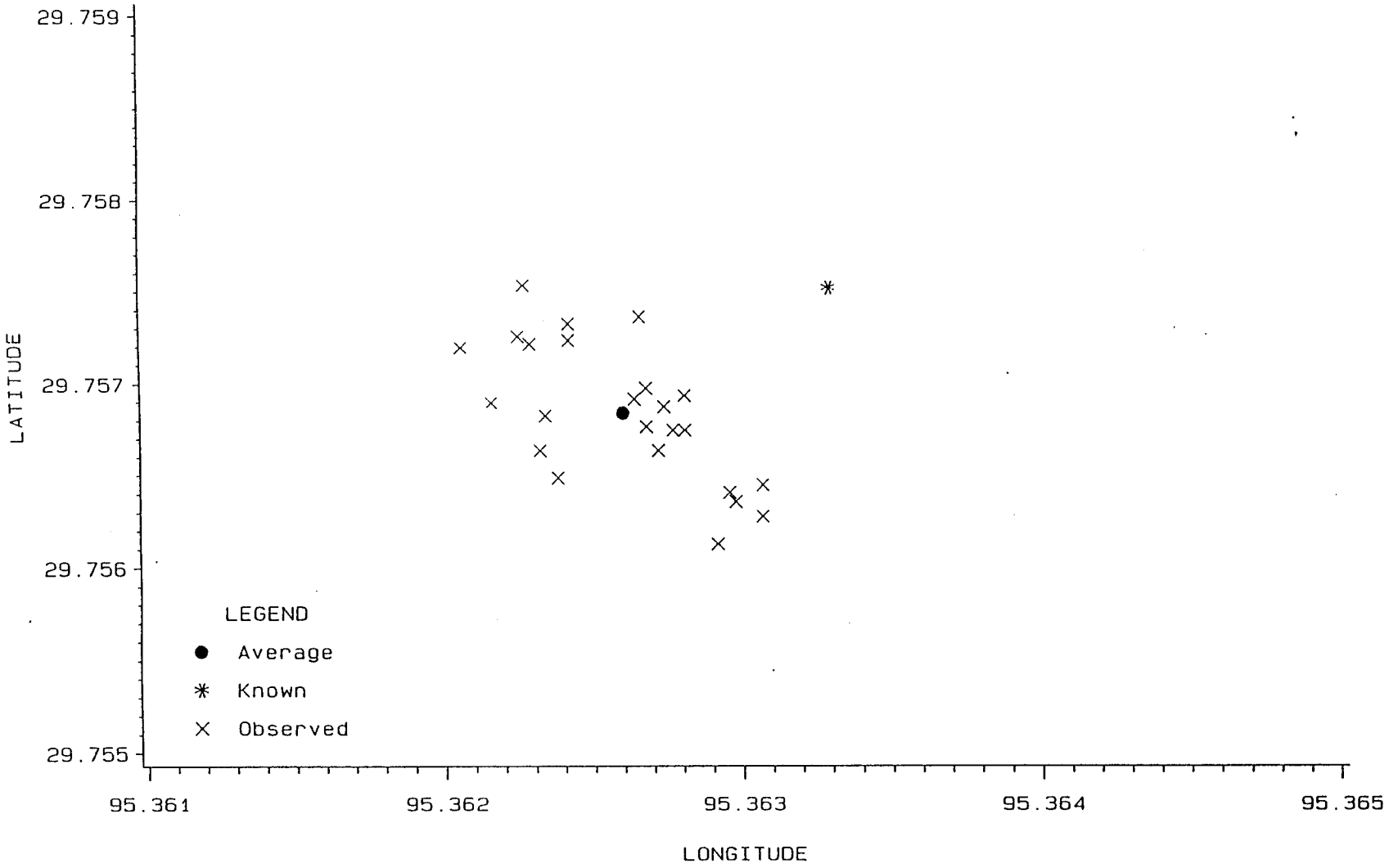
Latitude = 29.762690 Longitude = 95.363433



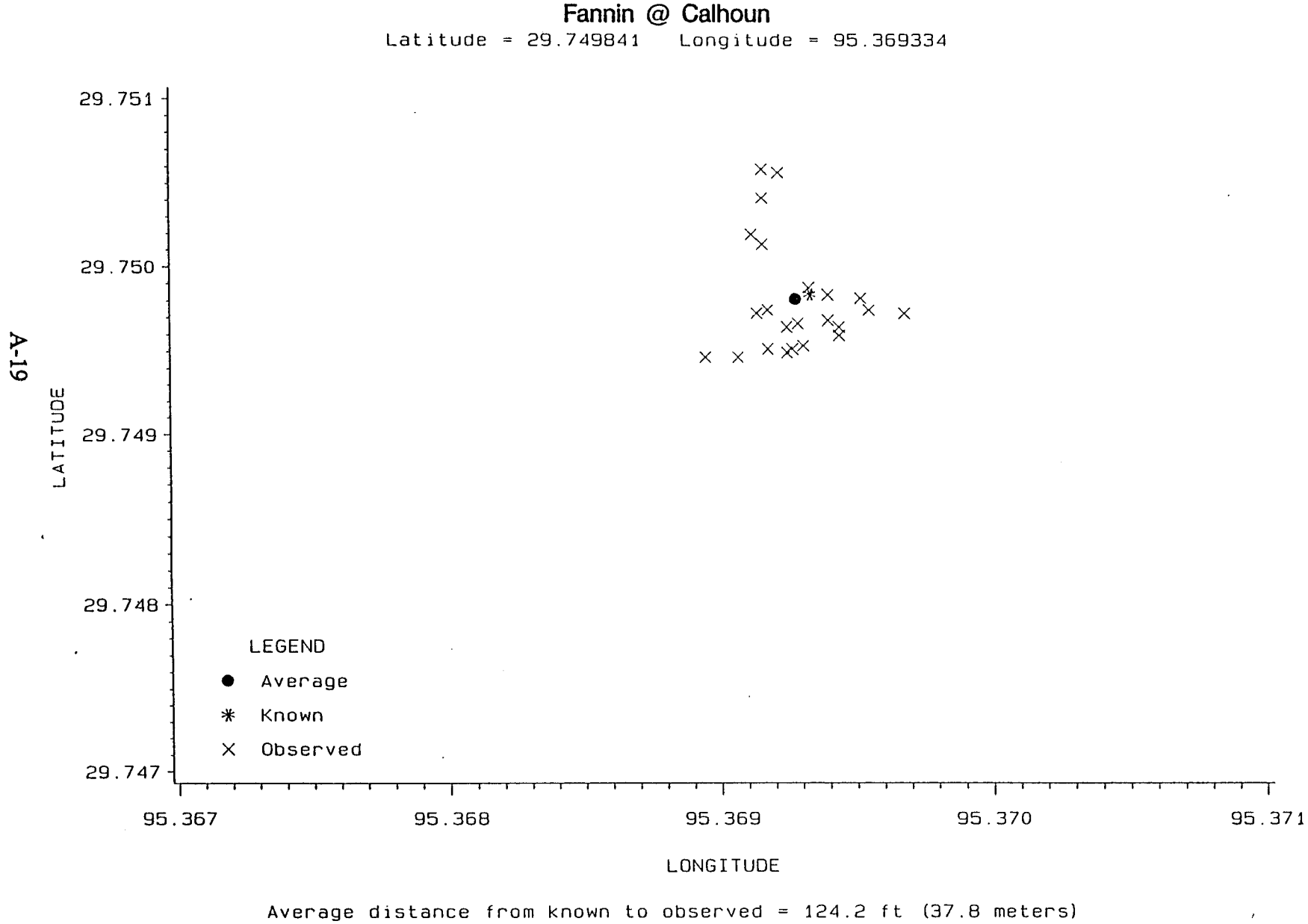
Average distance from known to observed = 730.5 ft (222.7 meters)

Fannin @ Walker

Latitude = 29.757528 Longitude = 95.363295

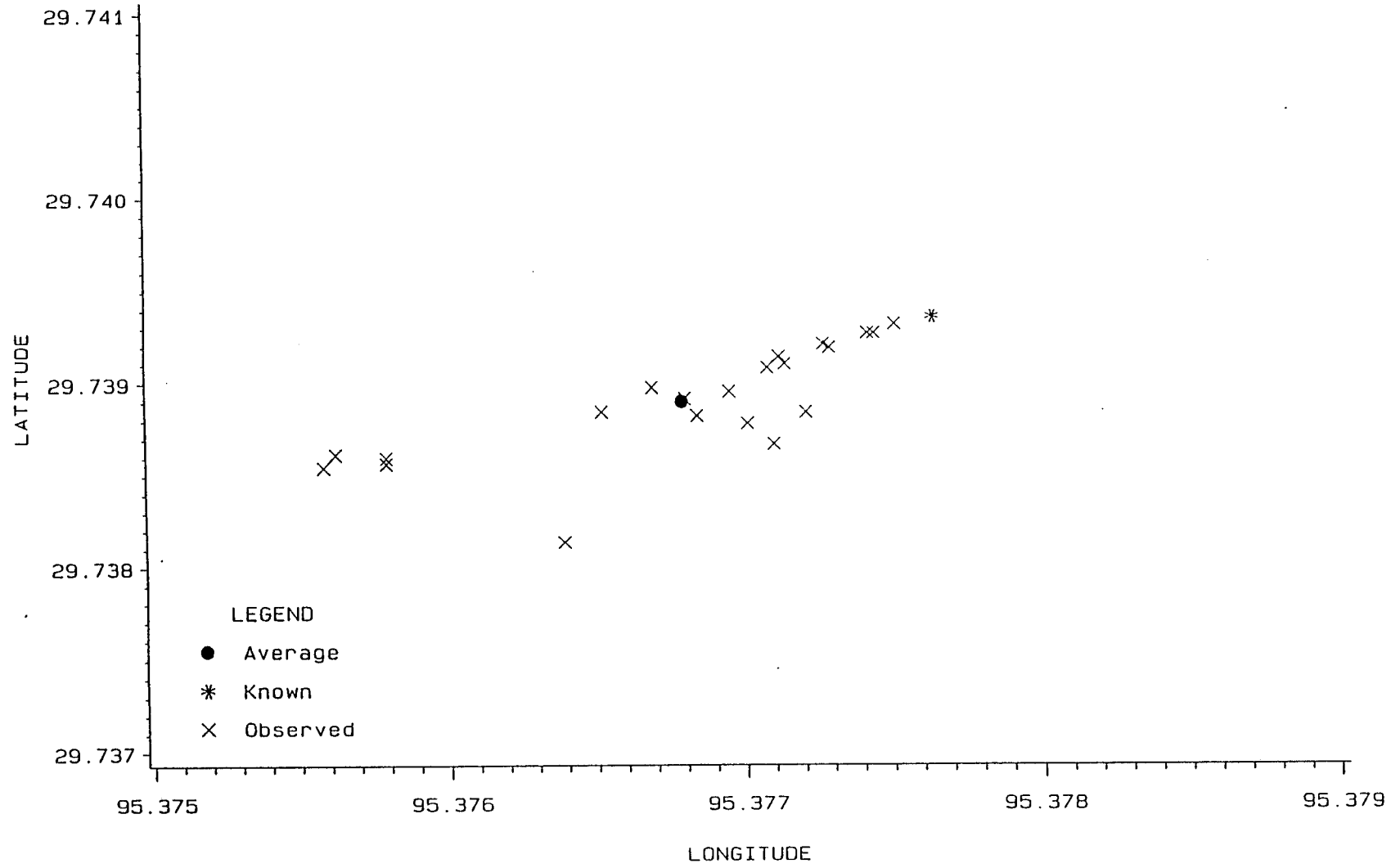


Average distance from known to observed = 362.2 ft (110.4 meters)

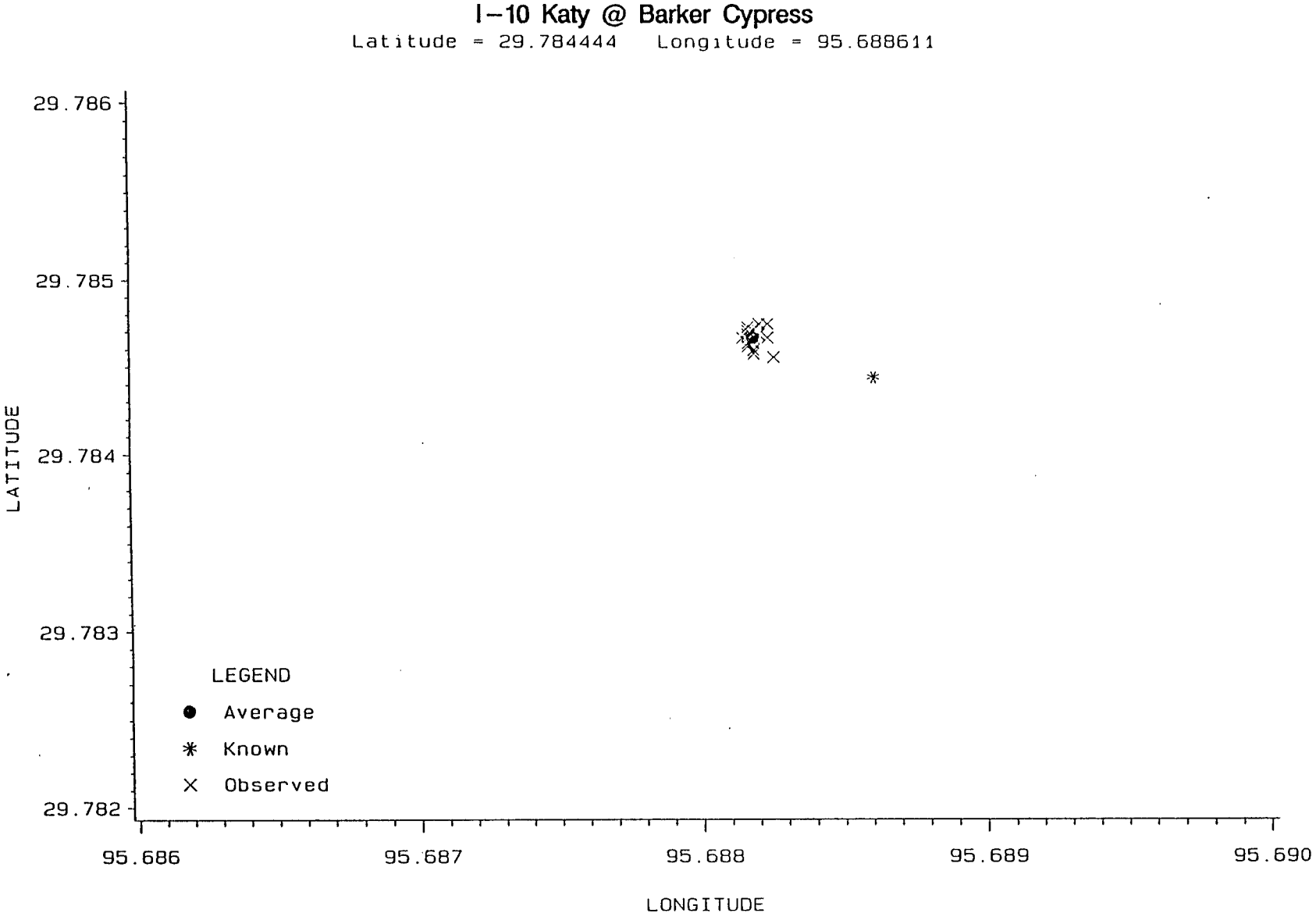

Fannin @ Calhoun
Latitude = 29.749841 Longitude = 95.369334
29.751
29.750
29.749
29.748
29.747
LATITUDE
LEGEND
Average
Known
Observed
95.367
95.368
95.369
95.370
95.371
LONGITUDE
Average distance from known to observed = 124.2 ft (37.8 meters)

Fannin @ Holcombe

Latitude = 29.739370 Longitude = 95.377636

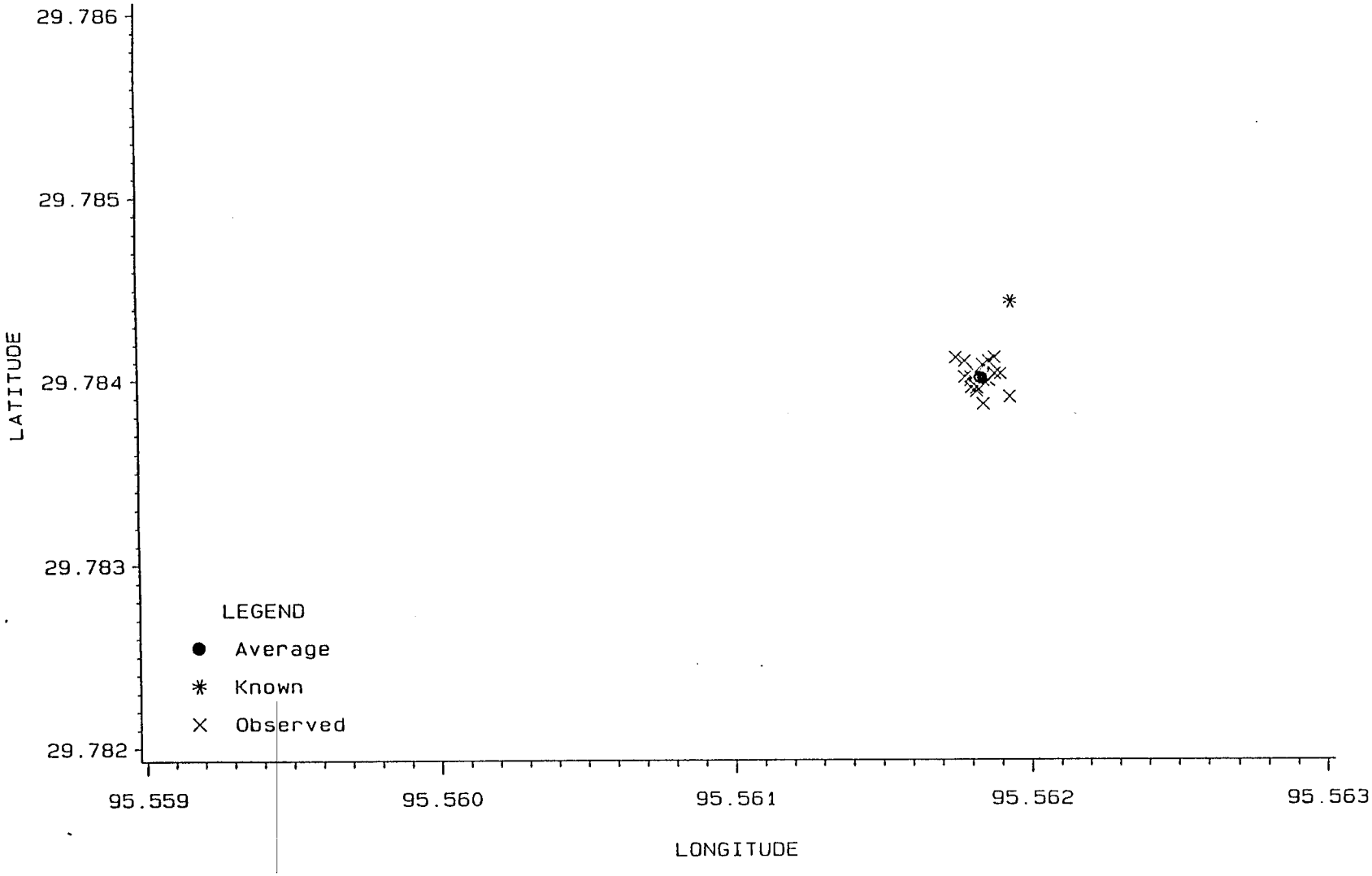


Average distance from known to observed = 322.9 ft (98.4 meters)


I-10 Katy @ Barker Cypress
Latitude = 29.784444 Longitude = 95.688611
29.786
29.785
29.784
29.783
29.782
LATITUDE
LEGEND
Average
Known
Observed
95.686
95.687
95.688
95.689
95.690
LONGITUDE
Average distance from known to observed = 158.2 ft (48.1 meters)

I-10 Katy @ Sam Houston Tollroad

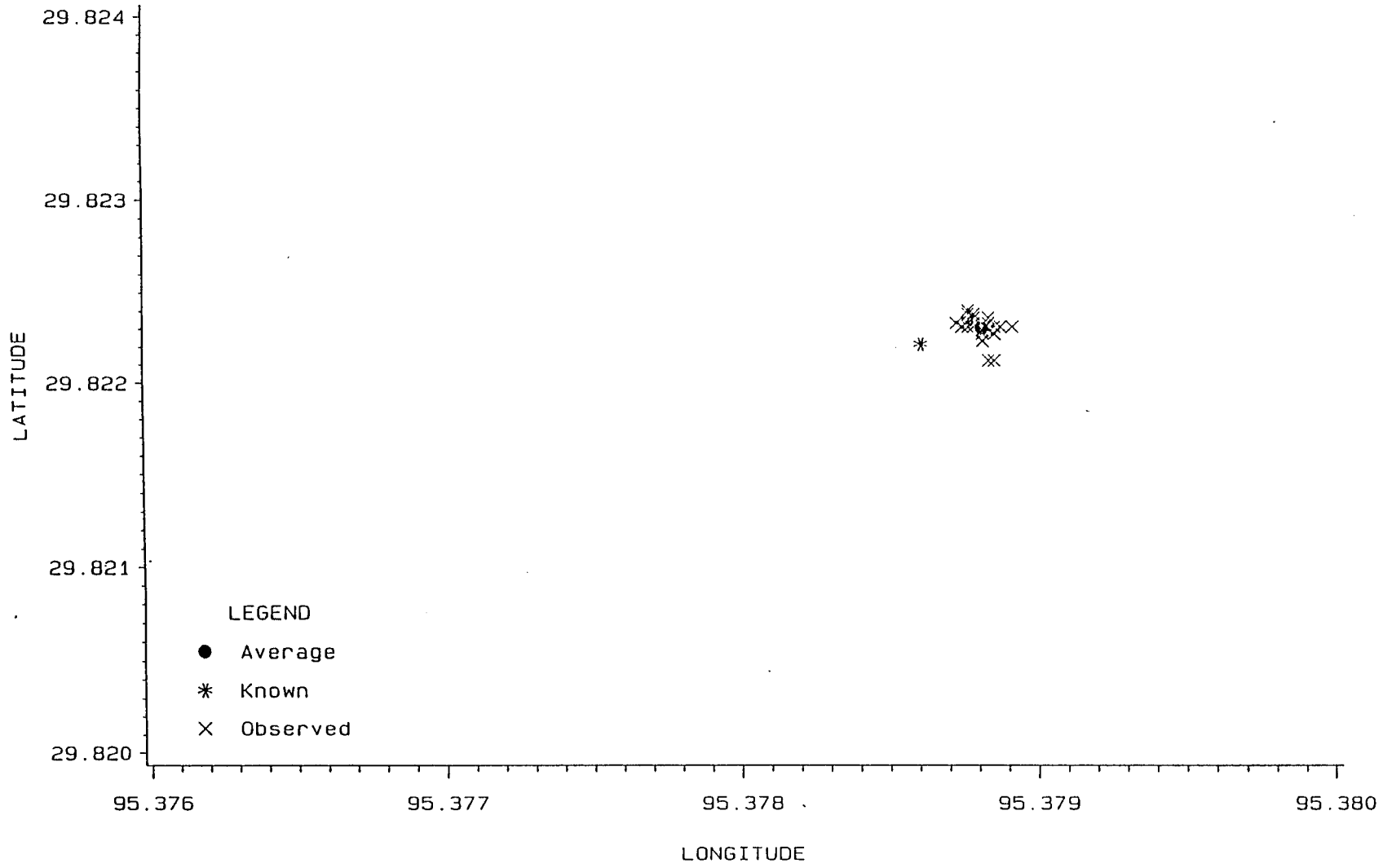
Latitude = 29.784444 Longitude = 95.561944



Average distance from known to observed = 160.2 ft (48.8 meters)

I-45 North Freeway @ I-610

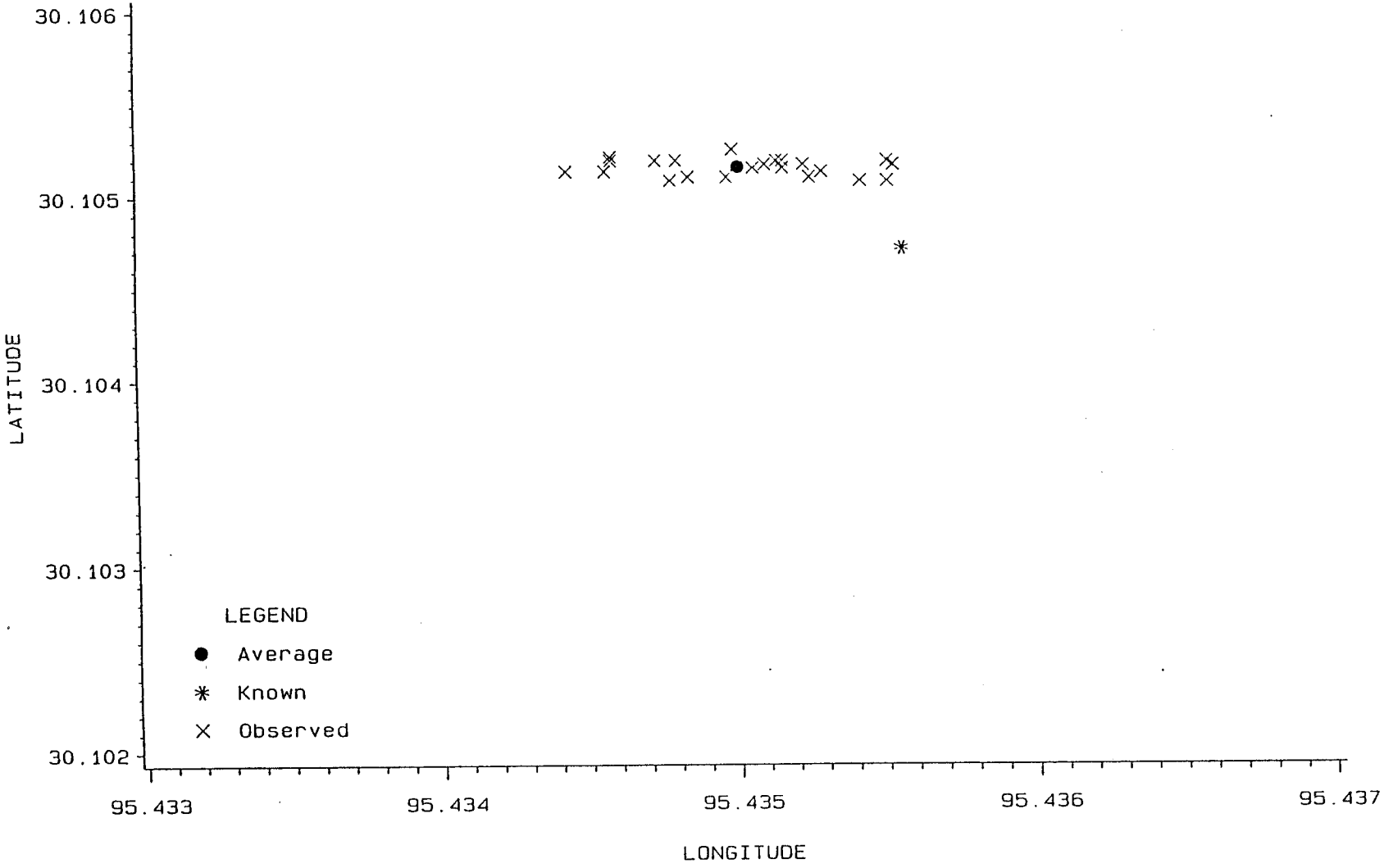
Latitude = 29.822222 Longitude = 95.378611



Average distance from known to observed = 77.2 ft (23.5 meters)

I-45 North Freeway @ Hardy Tollroad

Latitude = 30.104722 Longitude = 95.435556



Average distance from known to observed = 247.5 ft (75.4 meters)

Appendix B

Location Time Observations

Trial #	Single Vehicle	All Vehicles		
	(seconds)	Stamp (seconds)	Graphical Screen (seconds)	Data Screen (seconds)
1	3.03	17	67	93
2	4.13	15	65	96
3	4.03	17	73	97
4	3.00	20	70	96
5	4.01	18	70	96
6	4.10	19	76	100
7	3.98	23	67	92
8	4.88	16	54	76
9	4.18	15	49	69
10	4.12	18	50	71
11	3.12	26	51	71
12	3.03	26	49	70
13	4.11	17	54	79
14	3.01	16	47	67
15	4.07	23	61	88
16	5.29	25	56	77
17	4.21	29	46	68
18	3.13	30	48	69
19	4.13	23	49	70
20	4.19	26	47	67

Appendix C

Latitude and Longitude Coordinates for Test #3 (Locating A Moving Vehicle)

29.70351	-95.60732
29.70287	-95.60575
29.70349	-95.60565
29.70319	-95.60459
29.70319	-95.60313
29.70336	-95.59783
29.70330	-95.59623
29.70351	-95.59462
29.70345	-95.58996
29.70362	-95.58704
29.70353	-95.58245
29.70353	-95.57666
29.70364	-95.57219
29.70371	-95.56807
29.70394	-95.56301
29.70413	-95.55850
29.70426	-95.55704
29.70448	-95.55256
29.70484	-95.54874
29.70482	-95.54425
29.70476	-95.53958
29.70474	-95.53709
29.70471	-95.53273
29.70469	-95.53134
29.70480	-95.52958
29.70474	-95.52529
29.70506	-95.52233
29.70501	-95.51823
29.70461	-95.51372
29.70383	-95.50803
29.70463	-95.50460
29.70512	-95.50074
29.70235	-95.49529
29.70512	-95.49325
29.70538	-95.48992
29.70568	-95.48825
29.70512	-95.48469
29.70531	-95.48085
29.70540	-95.47617
29.70549	-95.47233
29.70542	-95.47229
29.70534	-95.46932
29.70538	-95.46718

29.70551 -95.46274
29.70549 -95.45825
29.70568 -95.45319
29.70562 -95.45021
29.70583 -95.44488
29.70583 -95.44259
29.70572 -95.43909
29.70568 -95.43729
29.70577 -95.43426
29.70564 -95.42971
29.70574 -95.42759
29.70581 -95.42439
29.70577 -95.41894
29.70594 -95.41838
29.70598 -95.41377
29.70609 -95.40909
29.70598 -95.40830
29.70585 -95.40527
29.70581 -95.40504
29.70589 -95.40345
29.70690 -95.40261
29.70920 -95.40124
29.70989 -95.39961
29.71085 -95.39982
29.71192 -95.39675
29.71255 -95.39806
29.71463 -95.39562
29.72218 -95.39109
29.72302 -95.38894
29.72342 -95.38854
29.72688 -95.38579
29.72900 -95.38420
29.73151 -95.38223
29.73420 -95.38032
29.73600 -95.37854
29.73885 -95.37643
29.74143 -95.37395
29.74398 -95.37240
29.74617 -95.36998
29.74804 -95.37004
29.74855 -95.37120
29.75014 -95.37010
29.75048 -95.36905
29.75256 -95.36755

29.75417 -95.36648
29.75683 -95.36626
29.75651 -95.36463
29.75694 -95.36450
29.75883 -95.36266
29.76085 -95.36167
29.76164 -95.36077
29.76218 -95.36092
29.76301 -95.36270
29.76409 -95.36435
29.76507 -95.36474
29.76501 -95.36528
29.76407 -95.36418
29.76177 -95.36249
29.76151 -95.36111
29.76110 -95.36107
29.76267 -95.36264
29.75965 -95.36206
29.75904 -95.36281
29.75660 -95.36292
29.75435 -95.36543
29.75177 -95.36665
29.75065 -95.36817
29.74885 -95.36989
29.74589 -95.37219
29.74293 -95.37401
29.74098 -95.37575
29.73881 -95.37731
29.73602 -95.37933
29.73366 -95.38184

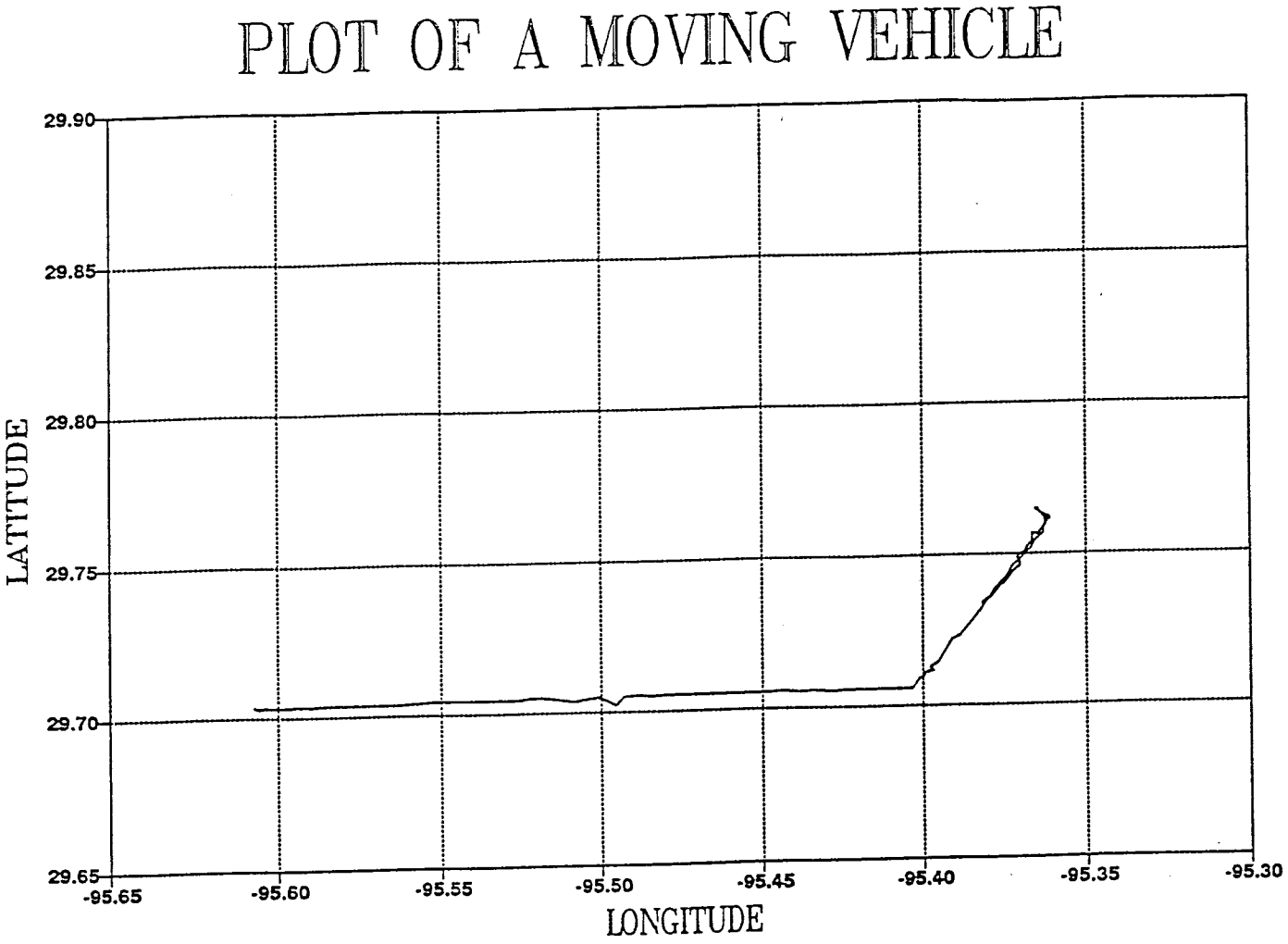


Figure 2. Graph Using 30-second AirTouch Coordinates for METRO Route #2