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Equipment Systems Improvement Program – Development

Evaluation of an Automatic Direction Finder for Hijacked Truck Location

Prepared by
N. A. MAS
Engineering Science Operations

June 1973

DEVELOPMENT

Prepared for
LAW ENFORCEMENT ASSISTANCE ADMINISTRATION
U.S. DEPARTMENT OF JUSTICE

Contract No. F04701-72-C-0073

Law Enforcement Development Group
THE AEROSPACE CORPORATION

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EQUIPMENT SYSTEMS IMPROVEMENT
PROGRAM--DEVELOPMENT

EVALUATION OF AN AUTOMATIC DIRECTION FINDER FOR HIJACKED TRUCK LOCATION

Prepared

N. A. Mas
Communications and Digital
Subdivision

Approved

J. F. Carpenter, Director
Communications and Digital
Subdivision
Electronics and Optics Division
Engineering Science Operations

H. William Nordyke
Director, Law Enforcement and
Adjudication Systems
Law Enforcement Development Group

John O. Eylar, Jr.
Director, Law Enforcement Development Group

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SUMMARY

A short test program was completed to evaluate the use of an Automatic Direction Finder (ADF), tuned to commercial AM broadcast stations, to locate a hijacked truck in an urban environment. The measurements taken with the ADF in a test truck indicated that the errors were greater than an acceptable level. Measurements were made at numerous (17) sites, which ranged in character from downtown, with high-rise buildings, to some relatively uncluttered flat areas. The level of errors correlated with the complexity of the environment and indicated that buildings, power lines, and other potential reradiators strongly influence the electromagnetic field, even at wavelengths as long as 500 meters. On the basis of these tests, it is recommended that the use of a truck-installed ADF be eliminated as a candidate for hijacked truck location.

CHAPTER I. INTRODUCTION

Many radio techniques have been tested, and are being investigated, for the purpose of locating cooperative vehicles in an urban environment. A search of the current literature did not reveal any extensive testing performed to evaluate the use of radio-direction finding techniques in an equi- [illegible] environment. The technique has attractive features, such as the availability of existing high power transmitters distributed over the urban area, a wealth of operating experience in aircraft and ships, operation at a relatively long wavelength that should produce minimal reradiation effects, and commercially available, relatively compact low power equipment.

Therefore, a short test program was initiated to explore the feasibility of using an ADF to locate a hijacked truck. The experiment test bed was the demonstration truck developed by The Aerospace Corporation for LEAA. Photographs of the installation are shown in Figure 1-1.

The testing was performed while the test bed truck was being used for other tests; therefore, full time could not be allocated to that effort. No attempt was made to improve any performance specifications of the ADF from the factory characteristics, nor was there any attempt to optimize the installation to reduce errors. The results obtained here can, therefore, be taken as typical of a commercial installation.

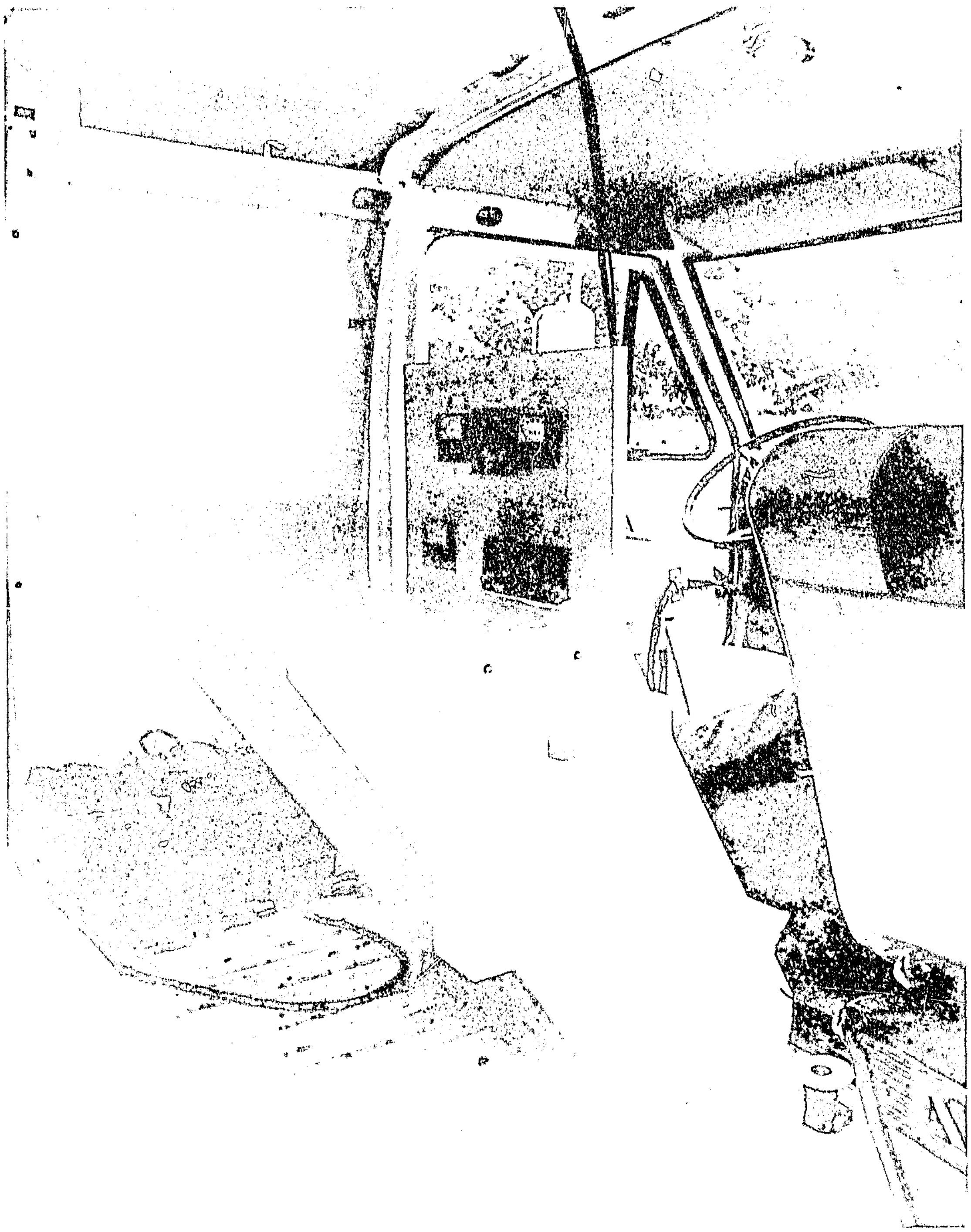

Fig. 1-1(b). Interior View ADF Installation and Panel

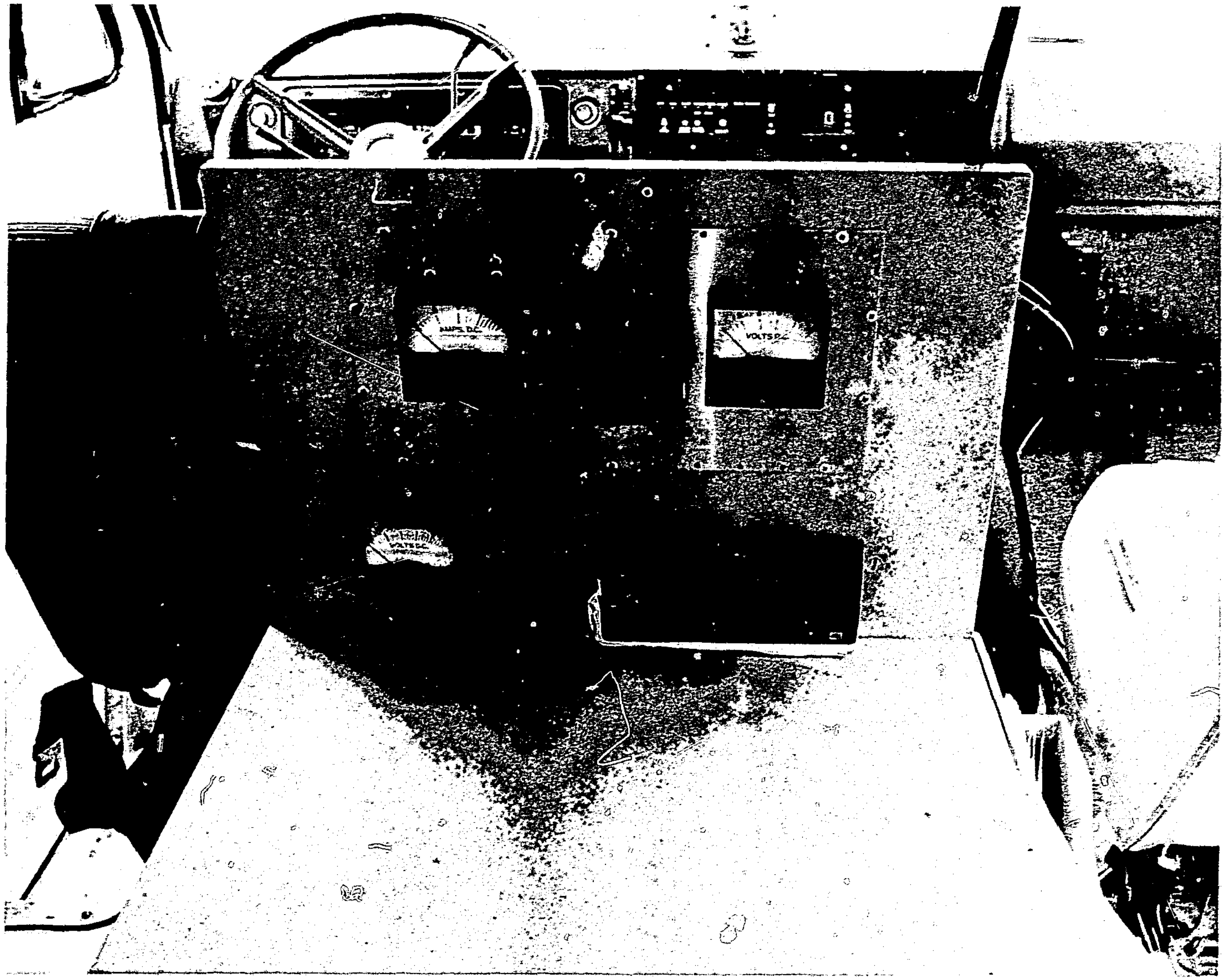

Fig. 1-1(b). Interior View ADF Installation and Truck.

Measurements were taken using 17 AM broadcast stations distributed throughout the band from 0.57 to 1.58 MHz. Locations for the measurements included downtown Los Angeles, San Fernando Valley, seaside, and both hilly and flat terrain in the Los Angeles basin. The spectrum of locations encompassed the various residential, commercial, and industrial locales that are encountered in any urban area. Figure 1-2 shows a map with the test site and transmitter locations.

A candidate algorithm for computing a two-dimensional location from the ADF angle data is presented. This algorithm does not contain the capability to discard all of the improper, ambiguous solutions that arise from the ADF data. However, the algorithm was tested and found adequate in all other respects.

The ADF errors were evaluated in the measured data (angles) domain by comparing the set of readings taken with the truck stationary against a set of true bearings computed from the known locations of the truck and the radio transmitters. Since the true headings of the truck were unknown, but constant, the means of the differences of those two sets were not zero, but equal to the mean headings of the truck. Variances from these means were then used to evaluate the ADF data.

In addition to the data taken with the truck stationary at discrete locations, observations were made with the truck in motion along surface and freeway roads either directly toward, away from, or tangential to a specific transmitter. These observations, though qualitative in nature, were very

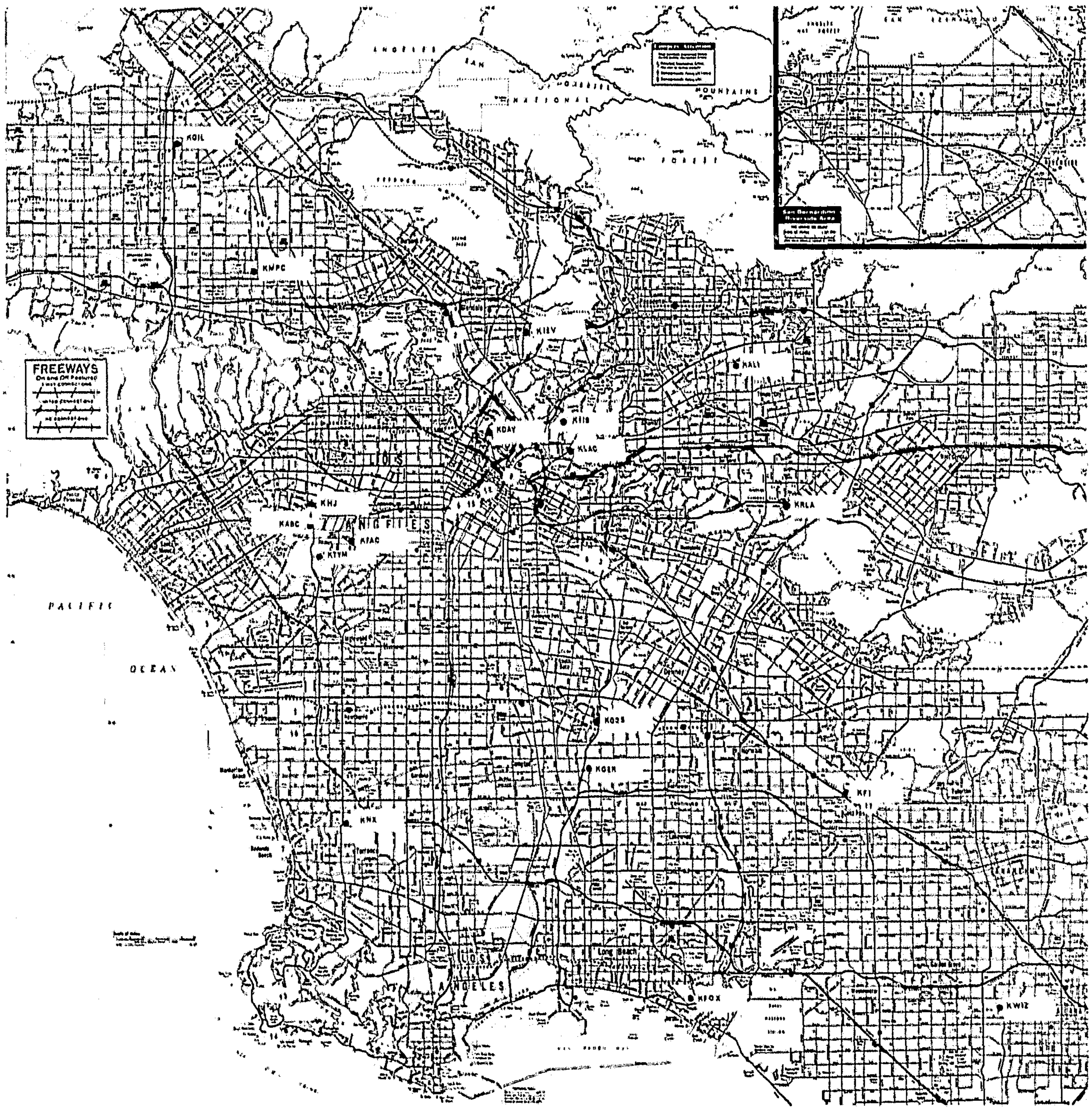

Fig. 1-2. Map of Test Site and Transmitter Locations

revealing as to the nature of errors arising from the environment. Data was also taken to evaluate the direct effect of the truck itself on the antenna system with two antenna configurations. These errors, called quadrantal errors in an aircraft installation, could possibly have been minimized with some effort, but that effort was not taken, since their effect is small in comparison with the environmental errors.

CHAPTER II. OBJECTIVES AND SCOPE

The primary objective of the test program was to evaluate the feasibility of utilizing ADF equipment to locate a hijacked truck in an urban environment. A secondary purpose would have been to integrate the ADF into an antihijacking system if the test data warranted such a step.

The effort was constrained to the use of commercially available equipment installed per manufacturer's instructions. No modifications, except as required for test instrumentation, were performed. If, in fact, the test results had indicated that instrumental error was a controlling error source, it was planned to attempt to reduce that source of error.

Another constraint placed on the purchased equipment was that the ADF be designed to minimize the remote tuning, and to telemeter the output data. A further restriction was that only signals from AM broadcast stations be used, since only that band is generally available in all urban areas.

CHAPTER III. EQUIPMENT

A search of the available ADF equipment was made. Table 3-1 presents a summary of the characteristics of the candidates considered.

From these candidates, the KR-85 was chosen, primarily because of the open wiring in the digital tuning area, and because of its excellent reputation in aircraft service. The performance characteristics of that receiver and of the accompanying indicator have been excerpted from the manufacturer's literature and are presented as Table 3-2. Upon receipt of the equipment, the receiver was checked out in the laboratory and the manufacturer's claimed performance was seen to be met or exceeded.

At the same time, a curve of automatic gain control (AGC) voltage versus input signal was generated to evaluate the signal levels that would be encountered in the experiment. In addition, power monitor meters (input voltage and current) were added to the installation with the AGC meter. Power was taken directly off the truck dc bus.

Two sense antenna configurations were checked for operation. One used an 8-ft whip, which was considered unwieldy; it was replaced with a simple automobile 5-ft telescoping antenna. Quadrantal errors were evaluated with both antenna configurations.

Table 3-1. Automatic Direction Finder Receiver ADF

Company	Model	Service	Tuning Frequency	Output Bearing Angle	Angle Accuracy	Settling Time (sec)	Power	Weight (lb)
Bendix Avionics Mr. J. Ahmann 117 E. Providencia Ave. Burbank, California 91503	DFA-74A $(3,000)	ARINC Continuous tuning	Digital tuning 190 KHz - 1749.5 KHz	Servo Drive	$\pm 2^{o}$ 50 μV/m to 0.5 μV/m	4	27.5 Vdc 1.1 a 26 Vrms 0.18 a 400 Hz	9.8
(213) 843-4600	ADF-T-12D $(1,000)	General Aviation Three bands	Digital tuning 200 KHz - 1600 KHz	Servo drive Goniometer in indicator	$\pm 3^{o}$ 20 μV/m threshold	7 max	14 Vdc - 1.2a	7.4
Collins Radio Company Mr. F. B. Jacobus 9841 Airport Blvd Los Angeles, California 90045	DF-206 $(6,500)	ARINC Continuous tuning	BCD Digital tuning 190 KHz - 1750 KHz	Servo drive	$\pm 2^{o}$ 70 μV/m to 0.5 μV/m	6	27.5 Vdc - 1.2a 26 Vrms 0.6a 400 Hz	16.2
(213) 670-2970	DF-203 $(5,300)	General Aviation AN/ARN-83	Servo 190 KHz - 1750 KHz	Servo drive	$\pm 3^{o}$ 30 μV/m to 100,000 μV/m	10	27.5 Vdc 1.7a 26 Vrms 0.63a -27 Vdc 1.0a	18.1
General/Aviation Electronics, Inc. Mr. Lowell Atkinson 4141 Kingman Dr. Indianapolis, Indiana 46226	SIGMA/1500 $(1050)	General Aviation Continuous tuning	Digital tuning 190 KHz - 1699 KHz	Servo drive	$\pm 3^{o}$	≈7	14 Vdc - 1.2a	6.0
(317) 546-1111								
King Radio Corp. Mr. Charles Demaree 400 North Rogers Rd. Olathe, Kansas 66061	KR 85/KI 225 $(1295)	General Aviation Continuous tuning	Digital tuning 200 - 1699 KHz	Servo drive	$\pm 3^{o}$	7	14 Vdc 1a	8.1
(913) 782-0400	KDF-800 $(3250)	General Aviation	Digital tuning 200 - 1699 KHz (separate tuning head)	Servo drive (two indicators)	$\pm 3^{o}$	7	14 Vdc 1.1a	13.8
Narco Avionics Ft. Washington, Pennsylvania 19034 (215) 643-2900	PLF-35	General Aviation One band	Digital tuning 200 KHz - 415 KHz	Servo drive	$\pm 2^{o}$ $\pm 3^{o}$ at 45^{o} bearings	3	14 Vdc 0.8a	6.5
John DiBello 1005 Marian Lane Newport Beach, Calif.	Under development		Digital tuning 200 KHz - 1699 KHz					

Table 3-2. Performance Characteristics of KR-85 Receiver and Accompanying Indicator

Function and/or Mode of Operation	Off, ADF, ANT, BFO
Controls	Function Selector switch, Volume Control, single Tuning Knob, concentric double Tuning Knob.
Frequency Range	200 kHz to 1699 kHz in one continuous action, with 1 kHz spacing in 3 bands
ADF Bearing Accuracy	±3° from 70 μv/m to 0.5 v/m rf input signal level.
ADF Indicator Speed	7 sec. maximum with indicator 175° off bearing and 70 μv/m to 0.5 v/m rf input signal level.
Audio Output	50 mw max across 500 ohm load Frequency response within 9 db variation from 350 Hz to 1400 Hz
Quadrantal Error Correction Capability	0 to 14.5 correction capability.
Image Rejection	80 db min., 200 kHz, 400 kHz 70 db min., 800 kHz 55 db min., 1600 kHz
Spurious Response	80 db min from 200 to 415 kHz.
Cross Modulation/Inter-Modulation	80 db min from 200 to 415 kHz.
Receiver Sensitivity	ADF mode not more than 100 μv/m for 6 db. Aural receiver mode not more than 70 μv/m for 6 db.
Receiver Selectivity	2.0 kHz min . 3 db bandwidth. 14 kHz max 80 db bandwidth
Items Required	KR 85 Receiver KI 225 or KI 225-01 Indicator Loop Antenna (King KA 42) with 12 ft. cable assembly (24 ft. Optional) Sense Antenna (H_E .25m) with 12 ft. of cable
Environmental Specifications	Temperature (Cat. D) -15° C to +55° C for continuous operation. Altitude tested up to 30,000 ft Humidity (Cat. A) 95% – 100% @ 50° C for 48 hours.
Lighting	Internal, blue-white
Mounting	Panel, rigid, in standard 6¼" x 2⅝" cutout.
Size	6.20" W (15.75 cm) x 2.60" H (6.66 cm) x 9.32" D (23.67 cm)
Weight	4.00 lbs. (1.81 kg) with rack & connectors, 3.53 lbs. (1.60 kg) without
Power Required	13.75v dc or 27.5v dc at 1.0 amp (ADF) or .8 amp (ANT)
TSO Compliance	TSO C41b, Category DACAAAX, Class A.

Heading Card	Manually rotatable
Power Required	.16 amp @ 13.75v or .08 amp @ 27.5v
Mounting	Panel, in standard 3" dia. cutout
Weight	1.6 lbs.
TSO Compliance	TSO C41b, Category DACAAAX, Class A

CHAPTER IV. POSITION DETERMINATION ALGORITHM

The algorithm used to reduce the ADF angle measurements to X-Y locations on a map is provided as the Appendix. The algorithm is designed for implementation in a computer. The solution is determinate, and does not utilize redundant data to improve accuracy. The latter feature would have been added if the quality of the test data had warranted such an effort.

The solution first determines the slant ranges to a minimum of three transmitters by simultaneously solving three equations expressing the law of cosines. Then the intersection of the three circles formed by those slant ranges around the transmitters are solved for intersections. These intersections are tested to remove the ambiguous solutions. The algorithm was tested with sample cases and with real data and was found to be adequate. Computation time on The Aerospace Corporation computer CDC 7600 was about 3 to 6 sec per point.

It is not immediately apparent why a simple graphical solution should be difficult. Figure 4-1 shows the locus of a constant angle difference between two points (transmitters). It is a circle passing through the two points, with a diameter equal to the baseline distance between transmitters divided by the sine of the angle difference. Producing those circles that represent the various angle differences is a difficult, time-consuming chore. Therefore, precomputed circles would have to be drawn on a map to represent the entire family of angle differences.

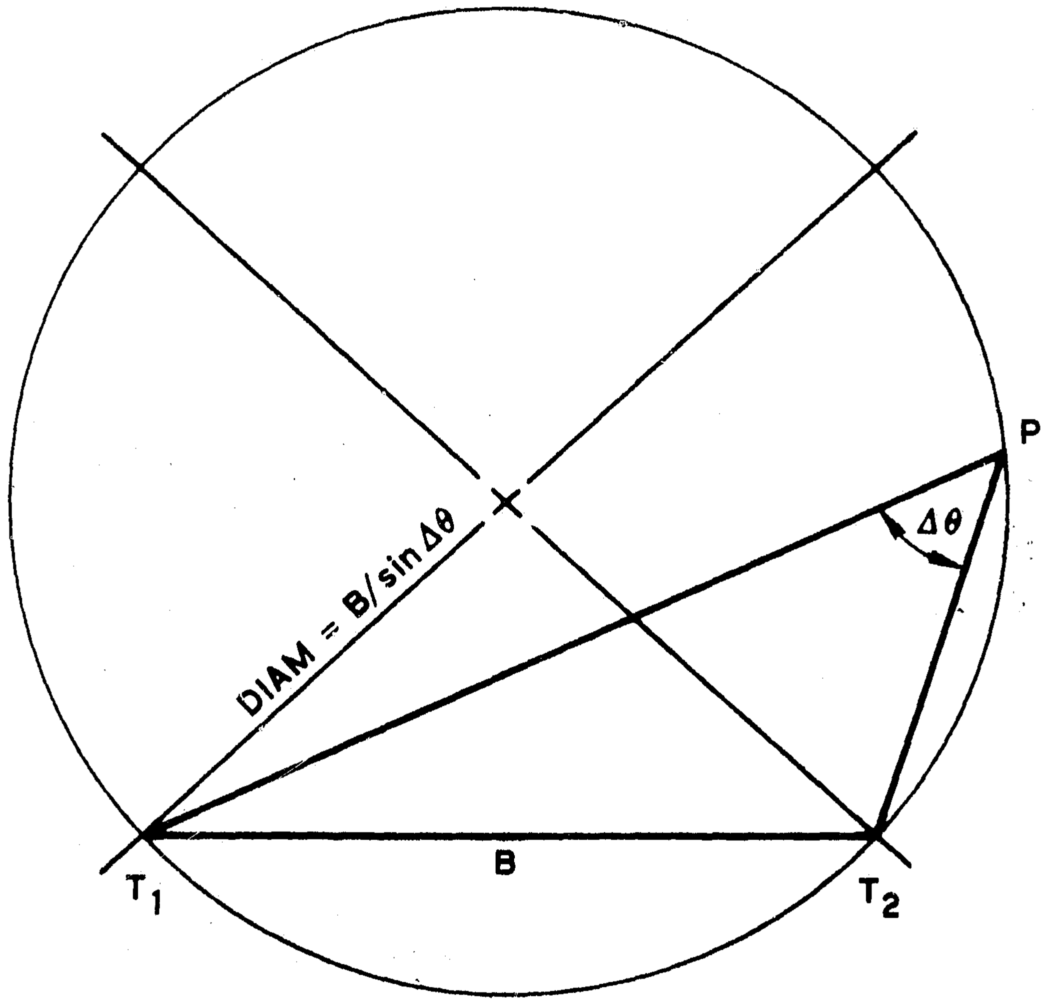

Fig. 4-1. Locus of a Constant Angle Difference Between Two Transmitters

No attempt was made to evaluate the geometric dilution of precision (GDOP) for this geometry. To the best of our knowledge, no such analysis has been published. However, for the simpler case of absolute bearing intersections, the minimum dilution (perpendicular intersections) case yields errors that are directly proportional to the product of the angle error times the range. For this "best" case, angle errors of a tenth radian (~6 deg) produce X-Y errors of a 0.1 mile per mile of range from the transmitter. Thus, at 10 miles range, the "best" position error would be about 1 mile. For those cases where the intersection is not perpendicular, the error associated with a 6-deg error can easily exceed, by a large factor, the value for the "best" case.

CHAPTER V. TEST RESULTS

Data was taken from three types of experiments. The first experiment was to evaluate the quadrantal error, using many transmitters; the second, to measure the bearing angle variances at many locations from many transmitters; and the last, to define the variation of the indications as the vehicle moved in a definite path with respect to one transmitter.

A. Quadrantal Error and Reading Error

This error, which is defined as the error caused by the presence of the vehicle, was measured using nine AM transmitters. Measurements were made at 12 points of a compass rose that was accurately drawn using an optical transit. The location chosen for the tests was clear of tall buildings, long wires, and other suspect reradiators.

Table 5-1 presents the measured data for the case with the sense antenna on the front bumper; Table 5-2 presents the data for the case of the sense antenna on the roof, which was the final configuration.

All raw data points represent an average of at least 3 readings of the indicator. The indicator was always set to read zero at the zero point of the rose. By treating the entire ensemble of data, the standard deviation for both antenna configurations is seen to be 2.1 deg for one case and 2.6 deg for the case used in later testing. Since the true bearing is unknown in an operational case, this error is an uncorrectable error of that magnitude. This value, when root square summed (RSS'd) with the reading error standard deviation, represents a minimum value of standard deviation for the case of

Table 5-1. Quadrantal Error — Sense Antenna in Front

		Truck Axis, deg											
Station	KHz	0	22.5	45	67.5	90	112.5	135	157.5	180	225	270	315
KLAC	570	0	+1.5	+4.0	+3.5	0	+1.2	+1.0	+1.2	-1.3	+2.7	+2.0	+3.0
KFI	640	0	+0.7	+2.2	+2.3	-1.5	+2.3	+1.2	-1.3	-1.5	-0.5	+1.2	+1.5
KMPC	710	0	+3.5	+0.7	+1.2	+1.0	+1.5	+1.3	+2.2	+1.7	+3.4	+1.7	+1.0
KABC	790	0	+2.5	+1.0	+0.8	-0.3	+0.2	+0.7	+1.2	+0.7	+3.0	+1.7	+1.7
KHJ	930	0	+3.5	+0.3	+0.5	-1.0	-0.5	0	+2.2	+1.2	+2.0	+1.0	+1.7
KNX	1070	0	+1.4	+0.6	+3.8	+0.6	+1.1	+0.6	-0.9	-2.1	-2.7	-2.7	-0.7
KIIS	1230	0			+0.8	+0.7	-0.2					-4.7	-4.3
KGER	1390	0	-1.2	-2.0	+0.5	+2.7	+0.5	-3.7	-5.5	-4.3	-2.0	-2.7	-1.7
KPOL	1540	0	-1.9	-2.4	-2.2	-4.4	-4.2	-3.7	-2.5	-3.0	0	-2.7	-0.7

Mean = +0.13 deg
Standard deviation = 2.1 deg

Table 5-2. Quadrantal Error — Sense Antenna on Roof

		Truck Axis, deg											
Station	KHz	0	22.5	45	67.5	90	112.5	135	157.5	180	225	270	315
KLAC	570	0	+0.2	-3.0	-2.5	+1.0	-1.5	0	+4.2	+3.3	+1.5	-2.0	+1.5
KFI	640	0	+1.8	-2.3	-2.8	-1.0	-0.8	-0.3	+4.5	+2.4	-1.3	-1.3	-1.3
KMPC	710	0	+2.5	-3.7	-1.5	+0.6	-0.2	-0.7	+0.5	-1.7	-5.7	-2.7	-2.7
KABC	790	0	+1.2	-2.0	-0.5	+1.0	+0.8	+0.3	+3.2	0	-4.0	-1.0	-1.0
KHJ	930	0	+1.5		+0.5	+1.3	+0.5	0	+2.2	-1.0	-5.0	-1.0	-3.6
KNX	1070	0	+5.5			-5.7	-4.5	-3.0	-0.5	-0.3	-5.0	-2.3	-5.0
KIIS	1230	0	-0.5			-8.0	-2.5	-0.5	-6.5	0	-4.7	-6.3	-1.0
KGER	1390	0	-3.5		-5.3	-1.5	-1.5	-1.0	+4.2	+2.0	-7.3	-3.0	-5.0
KPOL	1540	0	-1.8		+0.5	-3.7	+3.2	+0.7	+0.2	-0.3	-5.3	-1.3	-3.6

Mean = 1.04 deg
Standard deviation = 2.6 deg.

zero propagational error. The standard deviation of the reading error is estimated to be about 0.6 deg from many readings. This value, RSS'd with the 2.6 deg, seen as the quadrantal error for the tested configuration, is 2.7 deg.

B. Bearing Angle Measurements

The angle of arrival encountered by the ADF represents the actual radio wave front as modified by the environment. In the tests using a stationary truck at various locations, the wave fronts from different transmitter sites were not affected in the same manner, since they traversed different propogational paths. Thus, it was impossible to determine a priori, or by comparisons of the measured data, whether or not the wave front had in fact been influenced by the surroundings.

In order to measure the effect of the surroundings, a set of 5 readings was taken at each location for each of 17 transmitters. These readings were averaged for each transmitter to minimize the random reading error. The average readings were differenced from the computed bearings to compute a mean bias in the readings. Then the variance around that mean bias was used to indicate the errors introduced by the environment. The value of the mean bias about which the variance was computed was dependent on the heading at which the truck was parked. If it was pointed north along the meridian, then the theoretical bias would be zero, since the local meridian was the reference for the true bearing calculation.

The stations used are tabulated in Table 5-3 with the geodetic locations as listed on their FCC license. Also listed are the X-Y coordinates in a grid used on the U.S. Geological maps that were the basis for the

Table 5-3. Locations of AM Broadcast Transmitters

Station	Freq, KHz	Longitude	Latitude	X	Y
KLAC	570	118° 11' 36.0"	34° 4' 11.0"	389,588	3,770,699
KFI	640	118° 0' 48.1"	33° 52' 47.6"	406,337	3,749,650
KMPC	710	118° 24' 24.0"	34° 10' 24.0"	369,736	3,782,187
KABC	790	118° 22' 20.0"	34° 1' 40.0"	372,941	3,766,048
KIEV	870	118° 13' 36.0"	34° 8' 14.0"	386,486	3,778,183
KHJ	930	118° 22' 18.0"	34° 2' 26.0"	372,993	3,767,465
KGBS	1020	118° 11' 10.0"	33° 55' 0.0"	390,261	3,753,728
KNX	1070	118° 20' 56.0"	33° 51' 35.0"	375,112	3,747,414
KRLA	1110	118° 3' 10.0"	34° 2' 13.0"	402,669	3,767,064
KGFJ	1230	118° 16' 35.0"	34° 2' 5.0"	381,859	3,766,818
KGIL	1260	118° 27' 15.0"	34° 14' 58.0"	365,315	3,790,626
KFAC	1330	118° 20' 42.4"	34° 1' 10.0"	375,464	3,765,124
KGER	1390	118° 11' 10.0"	33° 53' 20.0"	390,261	3,750,648
KALI	1430	118° 4' 54.0"	34° 7' 9.5"	399,980	3,776,196
KTYM	1460	118° 21' 52.0"	34° 0' 24.0"	373,665	3,763,707
KWIZ	1480	117° 54' 36.0"	33° 45' 6.4"	415,955	3,735,445
KDAY	1580	118° 15' 24.0"	34° 5' 8.0"	383,694	3,772,454

coordinate conversion from street location to X-Y location. In Table 5-4 the various test sites at which data were taken are listed by street location and X-Y location.

Table 5-5 summarizes the entire set of data. The differences between measured angles and the mean biases, as computed from true bearings, are given; the resulting variances and standard deviations for each location are also given. In some cases, two sets of data were taken with different truck bearings. The differences seen between these sets are always less than the standard deviation of data for that site.

In Table 5-6 the data are further summarized to indicate the measured standard deviations with the accompanying environment. The listing is in order of decreasing errors. As might have been expected, the poorest results were obtained in the downtown area of Los Angeles. The lowest errors due to surroundings were in the flat inland areas that were not in the vicinity of high buildings, or were in the uncluttered marina areas. Even in the better areas, it can be seen that the standard deviations vary from approximately 4 to 8 deg. In the downtown areas with high-rise buildings, or in the light industrial areas, the standard deviations vary from 20 to over 90 deg. At these levels, the ADF location method can be considered unusable. As shown in the previous section, errors greater than a tenth radian make the system unuseable at ranges as short as 1 to 2 miles from the transmitter.

C. Observations Over Radial and Tangential Paths

Several tests were made by driving the truck directly to and from several radio stations. Ranges from the station varied from approximately 20 miles to less than 1 mile.

Table 5-4. Locations of ADF Test Sites

Site No.	Location	Description	X	Y
1	Bldg #219, LAAFS	Open, flat	372,350	3,753,900
2	4696 Colorado	Light industry	382,350	3,778,300
3	5500 Ferguson	Truck depot	391,650	3,763,250
4	Adams and Fairfax	Commercial	373,500	3,766,410
5	Marina del Rey	Seacoast	366,500	3,759,700
6	Grand and Venice	High-rise area	383,400	3,766,850
7	Portofino	Seacoast	371,180	3,745,600
8	4334 E. Washington	Light industry	391,000	3,763,400
9	Union Station	Railroad area	386,150	3,768,900
10	Aerospace A-2 Lot	Open, flat	372,550	3,753,300
11	Beach Blvd and Artesia	Open, flat, business	407,650	3,748,350
12	6th and Olive	Downtown, high-rise	384,420	3,768,100
13	Crest and Hawthorne	Hilly residential	371,070	3,736,350
14	Marineland	Seacoast, base of hill	370,450	3,733,800
15	12th and Hill	Downtown, high-rise	383,650	3,767,020
16	San Fernando Plaza	Valley, commercial	370,680	3,785,000
17	San Fernando Mission	Rural, foot of hills	365,540	3,793,000

Table 5-5. ADF Data Summary

Test Site	Site Nos. 1	1	2	3	4	5	5	6	7	8	9	10	10	11	12	13	14	15	16	17
KLAC	-4.7	-3.3	25.6	-6.1		9.1	7.0		-0.6	16.5		-1.9	-2.8	-4.3	85.6	-0.5	11.4	-51.4	-2.7	-5.7
KFI	1.2	1.6	-0.5	-3.0	-39.4	1.1	1.5	-10.7	10.4	6.0	-24.5	5.3	4.4	8.2	0.2	6.5	-28.4	9.6	10.7	3.4
KMPC	-5.0	-3.4	4.1	4.4	44.2	6.0	6.3	36.0	-6.3	38.1	-6.7	5.3	6.0	-7.4	-115.6	-4.3	13.4	53.8	-11.2	-0.3
KABC	-5.6	-0.7	-25.1	4.7	9.1	-2.4	-4.1	11.9	-1.1	17.6	11.7	-0.9	0	-9.2	87.1	-6.0	5.8	-16.4	2.2	7.5
KIEV	-4.4		-2.9	5.3		-0.8	-3.1	12.2	-1.9	-5.3	-14.0	5.6	7.1	-2.4	-125.1	-3.5	21.1	68.9	22.5	12.4
KHJ	6.9	7.2	33.0	2.7	-30.5	-9.5	-10.6	36.0	0.7		4.7	0.5	1.0	-8.1		-6.5	21.3	-35.5	1.5	9.2
KGBS	1.9	-1.4	5.0	2.7	5.6	-7.5	-5.4	-7.2	4.8		15.9	-3.9	-4.2	-6.0	-77.0	4.0		-85.2	-3.1	-3.9
KNX	1.3	6.7	9.8	-7.4	-0.7	-9.2	-4.6	-0.3	-6.3	48.3	28.1	5.4	5.3	-9.6	83.9	1.4	1.1	-12.1	3.5	.6
KRLA	1.4		-14.4	-3.5	23.1	-9.9	-1.0	15.4	-5.7		-5.2	2.1	4.8	0.3	21.8	12.2	-5.7	6.5	5.9	-10.0
KGFJ	-2.7	-4.6		13.2	14.1	3.6	3.0	19.6	-7.5		-9.8	-0.9	-7.7	3.4	-104.6	4.1	12.1	4.8	8.0	3.4
KGIL	-9.0	-4.8	-11.3	5.5	7.9	-1.8	-0.9	10.4	-1.5	-36.4	-0.9	1.9	1.2	5.4		1.9	11.8	68.8	9.0	-1.9
KFAC	1.1	-3.0	3.4	7.4	-5.6	1.0	-0.6	35.3	-13.6	-52.8	26.4	-8.3	-7.8	7.7	-119.4	-10.1	5.7	9.2	-1.5	-12.3
KGER	3.4	3.8	15.8	-3.5	5.4	-1.1	0.4	14.1	9.0		13.6	-1.0	-1.5	1.1	108.4	3.5	-12.4	-0.2	9.3	-5.4
KALI	1.9	4.1	-6.7	1.2	20.9	2.2	1.9	69.2	5.8	-10.2	14.7	7.0	7.5	0.4	-48.4	-0.8	-2.1	52.7	-9.7	6.9
KTYM	9.4	-1.9	7.8	-3.5	26.4	2.4	3.5	19.7	0.9	-40.1	21.7	-14.3	-16.1	3.7	-120.0	-6.0	16.7	-36.0	1.4	-3.1
KWIZ	13.4	-2.6	46.9	0.2	-14.5	16.7	10.6	-41.2		-36.9	7.8	4.5	3.2	12.2		6.3	-19.1	-92.5	2.0	14.7
KDAY	-11.1	2.9	17.8	-22.0	4.5	0.6	-3.2	12.6	-12.3	10.0	17.9	-4.5	-1.2	7.0	-119.0	-2.7	-6.7	54.1	-1.3	-15.1
n	17	15	16	17	15	17	17	16	16	12	16	17	17	17	14	17	16	17	17	17
σ^2	38.2	15.15	358.7	56.9	451.4	44.9	25.3	766	47.4	976	257	30.0	37.4	43.4	8944	31.6	203	2338	6724	67.7
σ	6.2	3.9	18.9	7.5	21.2	6.7	5.0	27.7	6.9	31.2	16.0	5.5	61	6.6	94.5	5.6	14.2	48.4	8.2	8.2

NOTES: All data values in units of degrees.
Data valves are average differences between readings and mean bias value.
See Table 5-4 for description of test sites.

Table 5-6. Summary of Test Data

Site No.	Standard Deviation (deg)	Site Description
12	94.5	Central downtown, high-rise area
15	48.4	Central downtown, high-rise area
8	31.2	Light industry, high noise area
6	27.7	Downtown, large buildings
4	21.2	Heavy business and traffic area
2	18.9	Light industrial
9	16.0	Railroad terminal area
14	14.2	Seacoast, rural, over hill
17	8.2	Residential, foot of mountains
16	8.2	Business area, center of valley
3	7.5	Truck depot, light industry
7	6.9	Seacoast, low buildings
5	6.7	Seacoast, low buildings
11	6.6	Open, flat, small business
1	6.2	Open, flat, low buildings
10	6.1	Open, flat, low buildings
13	5.6	Hilltop, residential
10[a]	5.5	Open, flat, low buildings
5[a]	5.0	Seacoast, low buildings
1[a]	3.9	Open, flat, low buildings

[a]Second data set with different truck heading.

The results in all cases were similar. Along the run, numerous short term (100- to 500-ft) major variations from the correct reading would occur. Peak-to-peak values of these variations invariably exceeded 180 deg. In some cases, there were longer term disturbances that lasted for more than 1 mile and produced errors in the 10- to 30-deg range.

Sometimes, the cause of the anomaly would be evident, such as a singular tall building or major intersection of power transmission lines; but, at other times, the cause of the disturbance was not readily apparent. Measurements made during two tangential runs yielded essentially the same results.

The results of these tests indicate that a homing system using an ADF is feasible. The percentage of the time that the indication was within 5 deg of the true bearing during the test runs exceeded 50%. This leads to the conclusion that the ADF technique is applicable to a police vehicle homing system.

CHAPTER VI. CONCLUSIONS

From the results of testing performed on the ADF in the Los Angeles area it is concluded:

- The angle of arrival measurement technique, as tested, is not a useful method to locate a highjacked truck.
- The errors experienced by the ADF on the downtown areas casts some doubt as to the viability of any angle or phase measurements of radio signals taken in that environment.
- The results of these tests indicate that a homing system using an ADF is feasible.
- Not all angle of arrival measurement schemes are indicted by the results of these tests. A moving transmitter located by stationary receivers sited carefully in a benign area may be a useful technique to achieve some level of accuracy.
- It is planned as part of the FY 74 program to test other radio type location systems in the same test areas used for the ADF, to compile a comparative data bank.

CHAPTER VII. PLANS FOR FY 74

- It is planned to utilize the data base and test data established during this investigation to form the basis of evaluation of selected electronic location schemes. It is important for comparative results to utilize the identical test area and vehicle.
- There are no plans to continue testing of the truck installed ADF, as the results of the test program conclusively demonstrate the inadequacy of this technique.

APPENDIX. ADF POSITION SOLUTION

1. Introduction

One of the methods proposed by The Aerospace Corporation to locate trucks that have been hijacked is to measure bearings from the trucks to various commercial AM broadcast band transmitters. The measurement of three bearings provides the minimum data to compute a location in two coordinates. (Three measurements are required since an unknown bias exists in the measurements.) The solution given here assumes a flat earth and does not exploit any redundant measurements, if made, to reduce random errors or to estimate systematic errors.

2. Coordinate System

The coordinate system will be an X-Y plane corresponding to the reference 1 U.S. Department of Interior 1/24,000 scale polyconic charts. The grid used corresponds to the 1-km Universal Transverse Mercator grid ticks on those charts. (The Y axis is generally parallel to a meridian and the X axis is generally parallel to a line of constant latitude.)

3. Location Algorithm

To simplify the solution, we employed an iterative algorithm to solve the intersection of two lines of position generated by the angles measured between stations. The position is determined by first determining the radial distance from each station to the truck, and then solving for the intersection of the circles which are the loci of those radii. The intersection ambiguities that occur are resolved by comparing solutions from two pairs. The geometry is shown in Fig. A-1. Using the law of cosines,

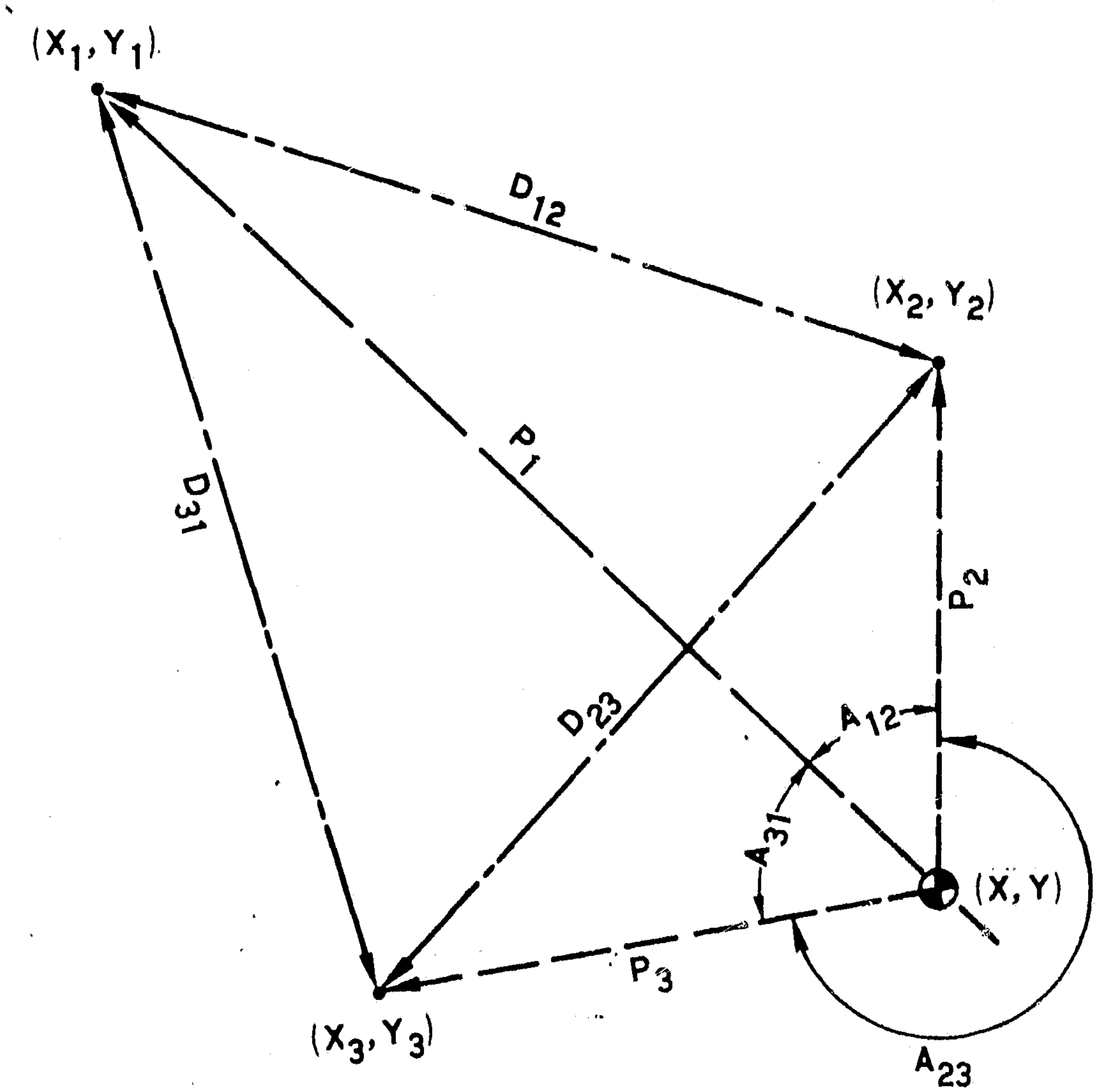

Fig. A-1. Geometry of the Intersection of Two Lines of Position

$$D_{12}^2 - p_1^2 - p_2^2 + 2p_1p_2 \cos A_{12} = 0 \quad (1a)$$

$$D_{23}^2 - p_2^2 - p_3^3 + 2p_2p_3 \cos A_{23} = 0 \quad (1b)$$

$$D_{31}^2 - p_3^2 - p_1^2 + 2p_3p_1 \cos A_{31} = 0 \quad (1c)$$

where

$$D_{12}^2 = (X_2 - X_1)^2 + (Y_2 - Y_1)^2$$

$$D_{23}^2 = (X_3 - X_2)^2 + (Y_3 - Y_2)^2$$

$$D_{31}^2 = (X_1 - X_3)^2 + (Y_1 - Y_3)^2$$

$$A_{12} = (A_2 - A_1)$$

$$A_{23} = (A_3 - A_2)$$

$$A_{31} = (A_1 - A_3)$$

Equations (1) are solved by a Newton-Raphson technique as follows: Initial values of $p_1 = D_{12}/2$, $p_2 = D_{23}/2$ and $p_3 = D_{31}/2$ are inserted in Eqs. (1), and the differences from zero (l_{12}, l_{23}, l_{31}) are evaluated. From the set of linear error equations

$$l_{12} = 2(p_1 - p_2 \cos A_{12}) \Delta p_1 + 2(p_2 - p_1 \cos A_{12}) \Delta p_2 \quad (2a)$$

$$l_{23} = 2(p_2 - p_3 \cos A_{23}) \Delta p_2 + 2(p_3 - p_2 \cos A_{23}) \Delta p_3 \quad (2b)$$

$$l_{31} = 2(p_1 - p_3 \cos A_{31}) \Delta p_1 + 2(p_3 - p_1 \cos A_{31}) \Delta p_3 \quad (2c)$$

$$p_i^{n+1} = p_i^n - \Delta p_i^n \quad (3)$$

the values of Δp_1, Δp_2, and Δp_3 are computed. The (nth + 1) trial value of each radius is the nth value corrected by the computed error. This loop of error determination and correction is iterated until Δp_n is less than 1 m, or the least significant digit in the X-Y grid.

Using the final value of p_1, p_2, and p_3 we can write

$$(X - X_1)^2 + (Y - Y_1)^2 - p_1^2 = 0 \tag{4a}$$

$$(X - X_2)^2 + (Y - Y_2)^2 - p_2^2 = 0 \tag{4b}$$

$$(X - X_3)^2 + (Y - Y_3)^2 - p_3^2 = 0 \tag{4c}$$

Taking the pair (4a) and (4b), we again use the iterative technique. An initial value of X is taken as $(X_1 + X_2)/2$, and $Y = (Y_1 + Y_2)/2$. The errors l_1 and l_2 are computed and used in the linear pair

$$2\,(X - X_1)\,\Delta X + 2\,(Y - Y_1)\,\Delta Y = l_1 \tag{5a}$$

$$2\,(X - X_2)\,\Delta X + 2\,(Y - Y_2)\,\Delta Y = l_2 \tag{5b}$$

from which values of ΔX, ΔY are computed.

The (nth + 1) trial values are then:

$$X^{n+1} = X^n - \Delta X^n \tag{6a}$$

$$Y^{n+1} = Y^n - \Delta Y^n \tag{6b}$$

This loop is iterated until ΔX, ΔY are reduced to 1 m, or less. Then the entire procedure is repeated with pairs (4b) and (4c), except that the initial values of X and Y tested are the final values determined with pairs (4a) and

(4b). If the final values of the latter pair agree, within 10 m, with those of the first pair, the computation is complete. If not, the final values from pair (4b) and (4c) are used as initial values of the pair (4c) and (4a). When two consecutive final values agree to within 10 m, the solution is complete.

END