RI 9602

REPORT OF INVESTIGATIONS/1995

Radar Positioning System Accuracy Test

UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

U.S. Department of the Interior
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By Walter K. Utt

UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES
Rhea Lydia Graham, Director

This report has been technically reviewed, but it has not been copy edited because of the closure of the agency.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter
in	inch
m	meter
m/s	meters per second
mph	miles per hour
pct	percent
s	second

OTHER ABBREVIATIONS USED IN THIS REPORT

NS	North to south
RMS	Root Mean Square
SEDM	Standard Error in the Difference of Means
SN	South to north

Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

RADAR POSITIONING SYSTEM ACCURACY TEST

By Walter K. Utt[1]

*****ABSTRACT**

The U.S. Bureau of Mines conducted research to develop an accurate, real-time, position monitoring and warning system for the vehicles used in surface mining. The product of this research will be technology to reduce accidents and injuries associated with the operation of surface mining haulage equipment. The position monitoring system should reduce accidents related to vehicle position and also increase the efficiency of haulage operations. This research was conducted in preparation for development of an accurate, real-time position monitoring and warning system, which notifies equipment operators when they deviate from a known safe course and are approaching a fixed hazard. A radar positioning system designed for marine applications was evaluated and a series of tests was run to determine the accuracy of the radar positioning system when used in a land vehicle. The radar position determination was compared to surveyed values. Both static and dynamic (moving vehicle) tests were conducted. The static test results were marginal and the dynamic test results were not accurate enough for the position monitoring and warning system. Although a promising technology, the system tested needs to be modified to meet the accuracy requirements of mobile mine equipment.

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***INTRODUCTION

Accidents involving powered haulage equipment are more severe than the average surface mining accident and are responsible for a disproportionate share of the total number of fatalities and lost workdays. In surface mines, which represent over 90 pct of the mined tonnage in the United States, powered haulage was the leading cause of fatal accidents. From 1989 to 1993, 114 miners lost their lives in surface haulage accidents. During this period, powered haulage accounted for 37 pct of the accidental deaths in surface mining and 21 pct of the total in the mining industry. Haul trucks were involved in two thirds of those accidents. About 25 pct of all surface mine mobile equipment accidents were related to vehicle position. The mine accident data were drawn from McAteer (*1*)[2]. Based upon safety concerns, haul trucks are the first priority for application of the vehicle position monitoring technology.

Injuries that occur during the operation of surface haulage equipment primarily result from acute impacts or large shock loadings, which may occur during routine loading and tramming operations, as well as from truck rollovers and collisions. Acute trauma injuries occur when an operator is subjected to a single, identifiable, and intense force loading. These injuries may occur during equipment operation on rough ground, contact with potholes or debris on roadways, and impacts during loading operations, as well as from rollovers and collisions. Truck rollover accidents are the most severe, often resulting in a fatality. They may result from overtravel at dumping locations or veering from the haulage road.

The purpose of this U.S. Bureau of Mines (USBM) research project was to develop technology to reduce accidents and injuries associated with the operation of surface mining haulage equipment. A vehicle position monitoring and warning system should reduce the accidents related to vehicle position and also increase the efficiency of the haulage operations. This research involved the development of an accurate, real-time position monitoring and warning system that notifies equipment operators when they deviate from a known safe course and are approaching a fixed hazard. The hazards at a surface mine site include road-edges, drop-offs, berms, highwalls, buildings, and other mobile equipment. In particular, this technology enhances the operator's control of the vehicle during low-light and inclement weather and during periods of fatigue, and prevents accidents that occur when the operator has been distracted or becomes inattentive to the task of equipment operation.

Although there has been some related research on positioning and control technology for application in underground mines (*2,3,4*), very little has yet been done for surface mining applications in the United States. However, a project to develop an autonomous truck, with automatic path navigation, has been underway in Japan for several years (*5*). and an autonomous haulage truck has been under development in the United States by a major equipment manufacturer. Some research at the USBM has been directed toward collision avoidance (*6,7*). USBM researchers hope to integrate an up-to-

[2]Italicized numbers in parentheses refer to items in the list of references at the end of this paper.

date collision avoidance system with the positioning system in the future. That should reduce the frequency of collisions with other mobile equipment. The USBM can facilitatea reduction in powered haulage accidents through the development of new enabling technologies and through a transfer of technology to industry.

SYSTEM CONSIDERATIONS

The system requirements for the vehicle position monitoring and warning system were formulated and refined during the course of the project. Observations of haul trucks on mine roads indicated that a margin of 2 to 3 m between a haul truck and the berm at the side of the road is typical. Consequently, it was decided that the system accuracy should be 1 m, maximum allowable RMS error in each axis, and that updates should occur within a time lag of 1 s. The maximum lateral deviation would be three times the RMS error (3 m).

A preliminary screening of 12 viable technical options resulted in the selection of two technologies which are promising candidates for the vehicle position monitoring and warning system: radar positioning (*8*) in combination with dead reckoning and the satellite-based Global Positioning System (GPS) (*9*) in combination with dead reckoning.

The term dead reckoning refers to the estimation of the next position of a vehicle based upon incremental change in position, which may be measured directly by an odometer or computed from measurements of velocity and the time interval. Prior work indicated that the dead reckoning technique could not be used alone due to the growth of the error with continuing movement. A position update from an accurate external source is required to correct the accumulated error. However, a radio or radar line of sight could be interrupted, so one could not rely on that for continuous operation. Consequently, a system in which dead reckoning is combined with a precise update from an external source is required and should be more robust and reliable. A combined system has been simulated by computer, as reported by Krakiwsky (*10*). The screening of the 12 viable concepts led to the further evaluation of radar positioning and the GPS for the precise position update.

The alternative Global Positioning System will be evaluated in a similar manner. The best approach will be selected for the development of an experimental version of the vehicle position monitoring and warning system.

RADAR POSITIONING

The use of radar positioning in combination with dead reckoning was one of the promising concepts which came out of the initial screening. The RADARFIX System of Radar Based Technologies, Inc, (RBT) was of particular interest since the patented system was advertised to be more accurate than other radar systems and it was contained entirely on the vehicle. It was the only radar or microwave system which did not use active transponders.

An agreement was negotiated with RBT to lease equipment and provide assistance in the initial installation and checkout of the RADARFIX system. The radar equipment was installed in a van and a series of tests was conducted in the fall of 1993.

***TEST CONFIGURATION

DESCRIPTION OF RADARFIX SYSTEM

Radar has been used to determine the position of harbor dredges in recent years. Triangulation from known landmarks on the shore is a common technique for determining the position of the dredge. When three or more landmarks are available, the position may be determined from the angle measurements by a technique surveyors call resection. A similar approach could be used to determine the position of the vehicles used in surface mining. However, the application to surface mining is a three dimensional position determination problem rather than the two dimensional problem associated with dredging. The radar position update could be used in conjunction with a dead-reckoning system to provide a more robust and reliable system for a land vehicle.

The RADARFIX system consists of an x-band civil marine radar system, an ATLAS 3200 with a wavelength of 3 cm, in conjunction with an interactive computer and a set of modern signal processing algorithms. The position determination process is conceptually an extension of triangulation to determine position from known landmarks. It does not use active transponders on the shore as other microwave systems do (*11*). Only passive landmarks are required, which makes the RADARFIX system both simpler and more economical to use. The RADARFIX system makes use of both range and angle measurements. The computer analyzes the radar signals; it recognizes certain echoes whose position coordinates have been previously recorded and deduces the vehicle's position very accurately.

It is difficult to derive constant and reliable results from fluctuating radar signals. The radar clutter and wavering echoes, which have troubled previous radar systems, have been addressed. Optimal filtering and continuous monitoring of the residual errors have been employed to cope with these problems. Methods have been developed and tested to offset the fading of signals; filter out multiple kinds of clutter, including signals from other similar radars; monitor the quality of image samples; and measure the connectivity of echoes.

Recent advances in radar image digitizing and computer processing have been incorporated. The position of the vehicle is over-determined both in terms of the number of landmarks and in terms of the samples for each landmark. Statistical processing algorithms, which have evolved from Kalman filtering, are employed to make the best estimate of position. The residual errors in the landmark positions are monitored continuously, which enables one to identify and delete a landmark that is inconsistent with the set and may even be degrading the accuracy. A weighted mean error parameter is used as an indicator of the quality of the vehicle position determination. The best set of landmarks may change with movement of the vehicle. The RADARFIX software includes a feature for automated management of the landmarks as the vehicle moves (*12*). The software is the property of Radar Based Technologies, Inc. and it is proprietary.

It is possible to obtain an accuracy on the order of 1 m at a point after the RADARFIX system has been calibrated and initialized at that point. However, if the vehicle moves 40 or 50 m, the new viewpoint in conjunction with the finite dimensions of the landmarks can introduce significant errors. There are two ways in which geometrical effects can affect the accuracy, the size and shape of a landmark may cause the location of the echo to change with a change in viewpoint, and the relative angular position of two or more natural landmarks may differ (parallax). The change in accuracy due to a change in viewpoint is a matter of importance in the application to mining vehicles. Consequently, the USBM has evaluated the effect of vehicle motion on the position determination.

TEST RANGE

A test range was established on the grounds of the Twin Cities Army Ammunition Plant in New Brighton, MN, through the cooperation of the U.S. Army. A test course was surveyed on a seldom used roadway. Five points along the center line of the road were surveyed, using the Minnesota state plane coordination system, so that the radar position measurements could be compared to the surveyed values. The course length was approximately 181 m. Some additional points were surveyed for use as sites for radar reflectors (artificial landmarks). A pair of corner reflectors were constructed for the radar test. Each edge of the radar corner reflector was 1 m in length. The dihedral angles were 90 degrees with an error less than 1 degree. The location of each radio and television tower in the neighborhood was obtained in the same state plane coordinate system so that they could be used as landmarks. A few water towers in the neighborhood were also located in the state plane coordinate system for use as landmarks. The radar test configuration is indicated in figure 1.

TEST VEHICLE CONFIGURATION

The test vehicle was a conventional 1-ton Chevrolet van modified to accommodate the radar and other test equipment. The data flow for the radar test is depicted in figure 2. The radar antenna was mounted on the top of the van as indicated in figure 3. The radar console, with the plan position indicator (PPI) display, was custom mounted on a desk inside the van (figure 4). An interactive computer was connected to the radar console. The RADARFIX software was installed in the interactive computer. A second computer was used to record test data. A photoelectric detector was used to determine when the van passed over an optical reflector on a surveyed point in the test course. The photodetector was located on the underside of the vehicle on the axis of the radar antenna. The switch signal from the photoelectric detector was used in the recording computer to designate the corresponding point in the stream of data from RADARFIX.

A portable generator was mounted at the rear of the van to provide electric power for the radar and the computers. A preliminary examination of the generator output revealed a voltage spike. Consequently, power conditioning was required, namely a SOLA transformer, which removed the spike.

EXPERIMENTAL ERROR

The errors from the experimental equipment, rather than the radar system under test, were due primarily to the survey and the location of the vehicle over the surveyed point. The photodetector on the underside of the vehicle was within 2.5 cm (1 in) of the axis of the radar antenna. Both static and dynamic tests were conducted. The vehicle was parked over an optical reflector for the static tests. For the dynamic tests, the vehicle was driven over the optical reflectors at speeds up to 13.4 m/s (30 mph). The optical reflectors used in the static tests were hexagonal, but approximated as circular for the purpose of estimating the error. The reflectors used in the static tests were 6 cm (2.4 in) in diameter. Wider, rectangular strip reflectors were used in the moving vehicle tests. The width of the reflector used in the moving vehicle tests was 47 cm (18.5 in). The surveyed points are estimated to be accurate to within 2.5 cm (1-in standard deviation in x or y) and that is conservatively high. The survey closure was excellent, about 1 in 50,000.

The experiment was set up so that the computational lag would not affect the comparison of the radar position measurements to the surveyed values. The computational lag of an operational system is expected to be in the range from 0.05 to 0.10 s. The effect of that lag in conjunction with the speed of the vehicle is indicated in figure 5. Although the travel during computation would have to be taken into account in a control loop, the radar position measurement was recorded above a reflector and that corresponds to the surveyed value even though there would be a delay in computing the value. The error in the estimate of the computational lag was expected to be less than 0.005 sec and preliminary data from the moving vehicle indicated that the effect on the vehicle travel would be negligible. The estimate of experimental error is summarized as follows:

Static

tangent to the path, standard deviation, xp = 3.6 cm (1.4 in)
lateral, standard deviation, yp = 3.6 cm (1.4 in)

Dynamic

tangent to the path, standard deviation, xp = 3.2 cm (1.3 in)
lateral, standard deviation, yp = 12.0 cm (4.7 in)

Since the experimental error was negligible in comparison to the estimated radar positioning system error (1 m), the measurements are satisfactory.

***DISCUSSION OF RESULTS

STATIC VEHICLE TEST

The static tests were conducted with the vehicle parked over an optical reflector. The coordinates of the point were then determined with the radar system. The average or mean value of each set of measurements was calculated. The random variation about the mean is represented by the standard deviation in each of the horizontal components, x positive to the east and y positive to the north. The state plane coordinates for southern Minnesota (the NAD83 version) were used in the survey. The radar system was initialized at one of the surveyed end points of the test course. The bias or offset is obtained by subtracting the surveyed value from the mean of the measurements. The root-mean-square (RMS) value contains both the random (standard deviation) and the bias contributions to the error. A set of measurements was taken at each of the five surveyed points along the course. The course was run in the direction from the south to the north (SN) and then from the north to the south (NS). The two sets of data could then be used to check the repeatability. One could also compare the two sets of bias values. If the two sets were consistent, it would indicate that one could remove the bias by calibration.

In the case of travel from SN along the test course, the static error in x is presented in figure 6. The RADARFIX system was initialized at the surveyed point at the south end of the course, point F. It was not re-initialized at the subsequent points, but the set of landmarks had been evaluated for each point in the course. The error is about 1 m except for point D where the RMS value jumps up to about 4 m (13.5 ft).

In the case of travel from NS, the static error in x is presented in figure 7. The RADARFIX system was initialized at the surveyed point at the north end of the course, point T3. The error was less than 1 m at point T3, but the RMS value increased to 2.0 m at point D and 2.5 m at point E. A comparison of the two groups of data shows significant differences from one surveyed point to the next (figures 6 and 7).

A similar comparison of the two groups of data can be made for the y component of position as well. In the SN case, the static error in y is presented in figure 8. The RMS value in y is lowest at the midpoint (D) and ranges from less than 1 m to about 4 m at point C. In the NS case, the static error in y is presented in figure 9. The RMS value ranges from less than 1 m to about 2 m. The results show significant variation from one survey point to the next.

The RMS variations in x for the SN case are compared to the NS case in figure 10. The RMS variations in y for the SN case are compared to the NS case in figure 11. The bias error in x is presented in figure 12. The bias of SN data is consistent in direction with NS data at points F,D, and T3, but not at points E and C. The bias error in y is presented in figure 13. If one were to calibrate in order to remove the apparent bias, there would still be a residual bias contribution to the RMS error.

The radar data for the static vehicle tests are presented in table 1. The errors for each surveyed point along the test track are presented in the tabulation. One can compare the data obtained when going from north to south with data obtained when going from south to north. A summary based upon all of the static data, a total of 651 samples, is presented in table 2.

Table 1.–Summary of RADAR test data for static vehicle, in meters

Survey point and item	Travel north to south X	Travel north to south Y	Travel south to north X	Travel south to north Y	All static data X	All static data Y
T3: (number of samples)	(85)	(85)	(72)	(72)	(157)	(157)
Survey	864051.31	332597.84	864051.31	332597.84	864051.31	332597.84
Av of measurement .	864050.9	332598.71	864050.15	332599.19	864050.56	332598.93
Standard deviation .	0.611	0.506	0.139	0.864	0.627	1.001
Bias	-0.407	0.871	-1.162	1.353	-0.754	1.090
RMS	0.734	1.007	1.170	1.605	0.980	1.480
C: (number of samples)	(36)	(36)	(70)	(70)	(106)	(106)
Survey	864078.12	332562.68	864078.12	332562.68	864078.12	332562.68
Av of measurement .	864078.53	332564.74	864077.55	332566.48	864077.88	332565.89
Standard deviation .	0.0295	0.0964	0.547	1.9	0.548	1.902
Bias	0.412	2.058	-0.571	3.801	-0.237	3.209
RMS	0.413	2.060	0.791	4.249	0.597	3.731
D: (number of samples)	(77)	(77)	(78)	(78)	(155)	(155)
Survey	864105.92	332526.31	864105.92	332526.31	864105.92	332526.31
Av of measurement .	864104.12	332526.43	864101.91	332526.54	864103.01	332526.49
Standard deviation .	0.319	0.156	1.259	0.692	1.299	0.709
Bias	-1.805	0.115	-4.009	0.234	-2.912	0.175
RMS	1.833	0.194	4.202	0.730	3.189	0.731
E: (number of samples)	(36)	(36)	(77)	(77)	(113)	(113)
Survey	864133.68	332490	864133.68	332490	864133.68	332490
Av of measurement .	864136.16	332488.05	864132.75	332491.57	864133.84	332490.45
Standard deviation .	0.471	0.369	0.326	0.855	0.573	0.931
Bias	2.481	-1.947	-0.929	1.568	0.156	0.449
RMS	2.525	1.982	0.985	1.786	0.594	1.034
F: (number of samples)	(39)	(39)	(81)	(81)	(120)	(120)
Survey	864161.49	332453.68	864161.49	332453.68	864161.49	332453.68
Av of measurement .	864160.9	332454.65	864160.36	332456.12	864160.54	332455.64
Standard deviation .	0.455	0.322	0.045	0.155	0.457	0.357
Bias	-0.587	0.971	-0.927	2.444	-0.954	1.962
RMS	0.743	1.023	0.928	2.449	1.058	1.995

RMS Root mean square.
X State plane coordinate for southern Minnesota, + east.
Y State plane coordinate for southern Minnesota, + north.

Table 2.–Summary of all static data from table 1, in meters

All survey points	All static data (total of 651 samples) X	All static data (total of 651 samples) Y
Weighted standard deviation of all samples . . .	0.798	1.057
Weighted average bias of all samples	-1.063	1.267
Root-mean-square error, includes systematic and random	1.329	1.650
99.7 pct ellipse, joint 2D distribution	2.612	3.242

The value at point D of the test course is based upon 78 data points as indicated in table 1. The probable cause of the greater value is the radar incidence angle in conjunction with the finite dimensions of the landmarks and the surroundings of the landmarks. A multipath effect could contribute to the position error. Scintillation could contribute to the angle error and also affect position.

The difference in the means for the two groups of data, the SN and NS data, was analyzed by a standard test. The standard error is computed and the "student t" test is applied to determine if the difference in the mean values is statistically significant. A difference of more than twice the standard error is usually regarded as significant. In nine of the ten comparisons presented in table 3, the difference of the means is significant. This is in agreement with the previous discussion and it means that we could not eliminate the bias error by a calibration run. The source of the error has not yet been isolated. It would not be due to the survey, since an error from that source would have appeared as a consistent bias. It may be a limitation in the precision of the radar positioning system.The radar positioning system is very accurate as the overall values in table 2 indicate. The overall RMS error in x is 1.33 m and the RMS error in y is 1.65 m. However, the bar graphs have shown occasional data sets of 70 or more data points which are off by 4.2 m. It is important to be aware of those possibilities when one is concerned with safety. The three sigma static error ellipse, which would encompass 99.7 pct of the cases, is presented as figure 14. The accuracy is good for radar, but marginal for our application.

Table 3.—Comparison of NS to SN static vehicle data, in meters

Survey point and item	Compare means, NS to SN	
	X	Y
T3:		
Difference of mean values, NS to SN	0.75	-0.48
Standard error of difference in means	0.683	0.1157
Student T, standard test of statistical significance .	10.986	-4.150
C:		
Difference of mean values, NS to SN	0.98	-1.74
Standard error of difference in means	0.0656	0.2277
Student T, standard test of statistical significance .	14.947	-7.643
D:		
Difference of mean values, NS to SN	2.21	-0.11
Standard error of difference in means	0.1471	0.0803
Student T, standard test of statistical significance .	15.022	-1.369
E:		
Difference of mean values, NS to SN	3.41	-3.52
Standard error of difference in means	0.0868	0.1152
Student T, standard test of statistical significance .	39.264	-30.550
F:		
Difference of mean values, NS to SN	0.54	-1.47
Standard error of difference in means	0.0730	0.0544
Student T, standard test of statistical significance .	7.394	-27.041

DYNAMIC VEHICLE TEST

The moving vehicle (dynamic) tests were conducted by driving along the course at a pre-selected speed. The road was paved and there were no bad potholes in the road. The RADARFIX system was initialized over an endpoint, then the van was backed up and driven forward over all five surveyed points. It was necessary to use a wider reflector strip than was used in the static test due to the difficulty of driving over a strip at the desired speed. Each reflector strip for the moving test was rectangular, with the wider dimension lateral to the direction of motion. The width was 47 cm (18.5 in) and the dimension in the direction of motion was 3.8 cm (1.5 in). Although an attempt was made to drive the course at a pre-selected speed, ranging from 0 to 13.4 m/s (30 mph), a perfectly constant speed could not be maintained. However, the RADARFIX system calculates a value of speed and those values were used in analyzing the data.

The dynamic test was conducted by driving the course from SN and then from NS. The data were analyzed and compared in the same manner as for the static case. The standard deviation, the bias, and the RMS value were determined for each of the surveyed points. The data for each surveyed point are presented in table 4. The errors for the dynamic case are about twice as large as those for the static case.

The effect of speed on the magnitude of the error was an important concern. The offset or bias in x for the SN case is presented as a function of vehicle speed in figure 15. It looks like a scatter diagram with no apparent trend. The bias in y for the SN case is presented in figure 16. There is no apparent trend with speed. However, the random noise contribution to the error, as indicated by the overall standard deviations in table 5, increased significantly from the static case as shown in table 2. The NS data looks very similar to the SN data. The magnitude of the bias did not change with speed. The increased random noise may be the result of vibrations adversely affecting the radar system.

In the case of travel from SN, the dynamic error in x is presented in figure 17. The RADARFIX system was initialized at the surveyed point at the south end of the course, point F. It was not re-initialized at the subsequent points, but the set of landmarks had been evaluated for each point in the course. The RMS error in x ranges from 2 to 4 m. The dynamic error in y is presented in figure 18. The RMS error in y also ranges from 2 to 4 m. One can see that the random error is a large part of the RMS.

In the case of travel from NS, the dynamic error in x is presented in figure 19. The RADARFIX system was initialized at the surveyed point at the north end of the course, point T3. The RMS error in x ranges from 1.8 to 3.2 m. The dynamic error in y is presented in figure 20. The RMS error in y ranges from 0.9 to 3.6 m.

The RMS error in x for the SN case is compared to the NS case for the moving vehicle in figure 21. The magnitudes are comparable, ranging from 2 to 4 m. The RMS data in y for the SN case is compared to the NS case in figure 22. The RMS value ranges from 0.9 to 4 m.

The radar positioning system is accurate as the overall values in table 5 indicate. The overall RMS error in x is 3.58 m compared to 1.33 m in the static case. The overall RMS error in y is 3.05 m compared to 1.65 m in the static case. The three sigma dynamic error ellipse, which would encompass 99.7 pct of the cases, is presented in figure 23. The accuracy is not as good in the dynamic case as it was in the static case.

If vibration is the cause of the increased error in the dynamic case, it may be possible to reduce the effect in a re-design. The marine radar was used because it was readily available for the test. Since the tracking accuracy is dependent on the wavelength raised to the fourth power (*13*), a shorter wavelength may be used. If radar positioning were to be used in a land vehicle, a more appropriate radar system would be used with a shorter carrier wavelength and a more compact antenna.

Table 4.–Summary of RADAR test data for moving vehicle, in meters

Survey point and item	Travel north to south		Travel south to north		All dynamic data	
	X	Y	X	Y	X	Y
T3: (number of samples)	(15)	(15)	(18)	(18)	(33)	(33)
Survey	864051.31	332597.84	864051.31	332597.84	864051.31	332597.84
Av of measurement .	864049.1	332600.6	864048.8	332597.9	864048.94	332599.13
Standard deviation .	1.8617	2.4296	3.101	2.737	3.617	3.660
Bias	-2.194	2.757	-2.463	0.0328	-2.374	1.287
RMS	2.877	3.675	3.960	2.737	4.326	3.880
C: (number of samples)	(14)	(14)	(19)	(19)	(33)	(33)
Survey	864078.12	332562.68	864078.12	332562.68	864078.12	332562.68
Av of measurement .	864078.6	332564.4	864074.8	332566.7	864076.41	332563.42
Standard deviation .	3.212	2.17	1.566	2.386	3.573	3.225
Bias	0.481	1.769	-3.333	0.0026	-1.708	0.741
RMS	3.248	2.800	3.683	2.386	3.961	3.309
D: (number of samples)	(12)	(12)	(19)	(19)	(31)	(31)
Survey	864105.92	332526.31	864105.92	332526.31	864105.92	332526.31
Av of measurement .	864105.9	332527.5	864102.8	332525.5	864104	332526.27
Standard deviation .	1.845	1.591	1.812	2.632	2.586	3.076
Bias	-0.0167	1.957	-3.097	-0.808	-1.920	-0.036
RMS	1.845	2.522	3.588	2.753	3.221	3.076
E: (number of samples)	(13)	(13)	(19)	(19)	(32)	(32)
Survey	864133.68	332490	864133.68	332490	864133.68	332490
Av of measurement .	864132.6	332491	864132.7	332487.4	864132.66	332488.86
Standard deviation .	1.507	1.437	3.412	3.009	3.730	3.335
Bias	-1.092	0.955	-0.968	-2.616	-1.021	-1.138
RMS	1.861	1.725	3.547	3.987	3.867	3.523
F: (number of samples)	(15)	(15)	(20)	(20)	(35)	(35)
Survey	864161.49	332453.68	864161.49	332453.68	864161.49	332453.68
Av of measurement .	864161	332453.8	864160.2	332450.7	864160.54	332452.03
Standard deviation .	1.745	0.875	1.818	1.67	2.520	1.885
Bias	-0.539	0.102	-1.273	-3.013	-0.947	-1.651
RMS	1.826	0.881	2.219	3.445	2.692	2.506

RMS Root mean square.
X State plane coordinate for southern Minnesota, + east.
Y State plane coordinate for southern Minnesota, + north.

Table 5.—Summary of all dynamic data from table 4, in meters

All survey points	All dynamic data (total of 651 samples)	
	X	Y
Weighted standard deviation of all samples . . .	3.206	3.044
Weighted average bias of all samples	-1.585	-0.173
Root-mean-square error, includes systematic and random	3.576	3.049
99.7 pct ellipse, joint 2D distribution	7.029	5.993

***CONCLUSIONS

The radar accuracy test data from the test range were analyzed. The error ellipse for the static vehicle shows that 99.7 pct of the time the error would be less than 3.24 m. That is good for radar, but marginal for our application. The error ellipse is about twice as large for the dynamic vehicle and that is not satisfactory for our application. Although the RADARFIX system is an accurate radar positioning system, the increase in the error for the moving vehicle would have to be eliminated before one could apply the RADARFIX system to the vehicle position monitoring and warning system.

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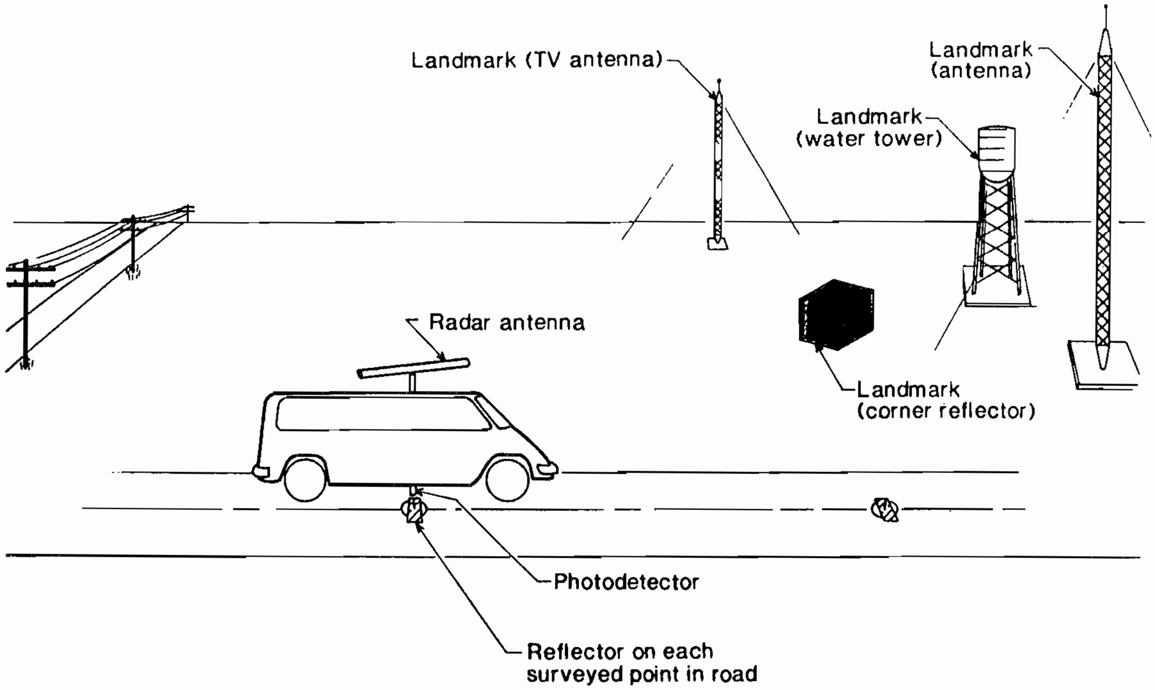

Figure 1. Radar test configuration

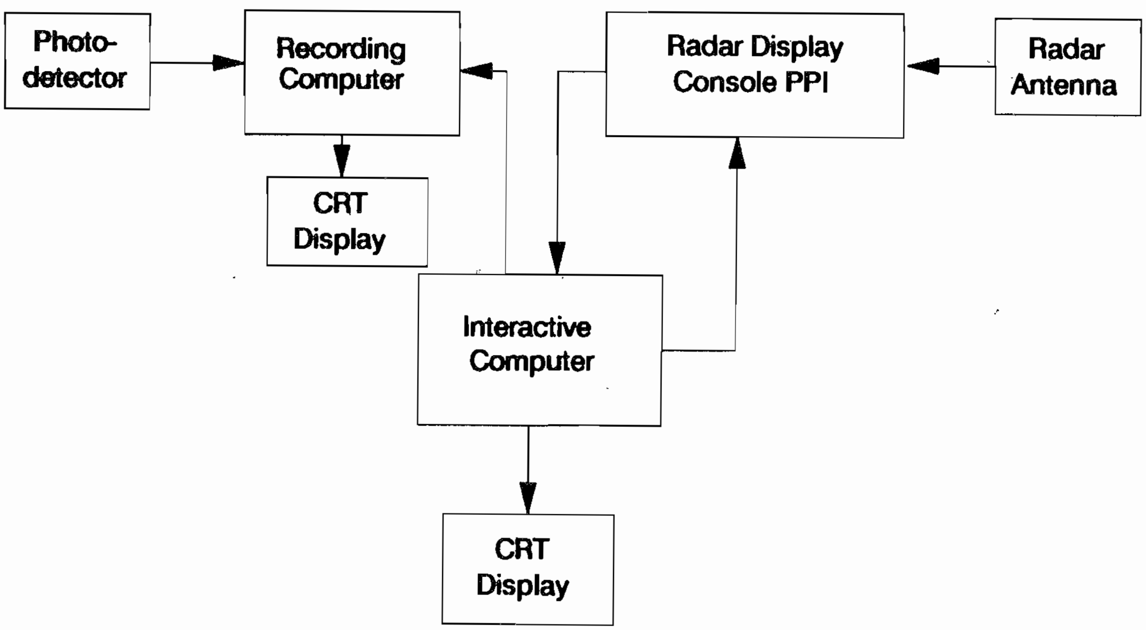

Figure 2. Data flow for radar test

Figure 3. Van at test range

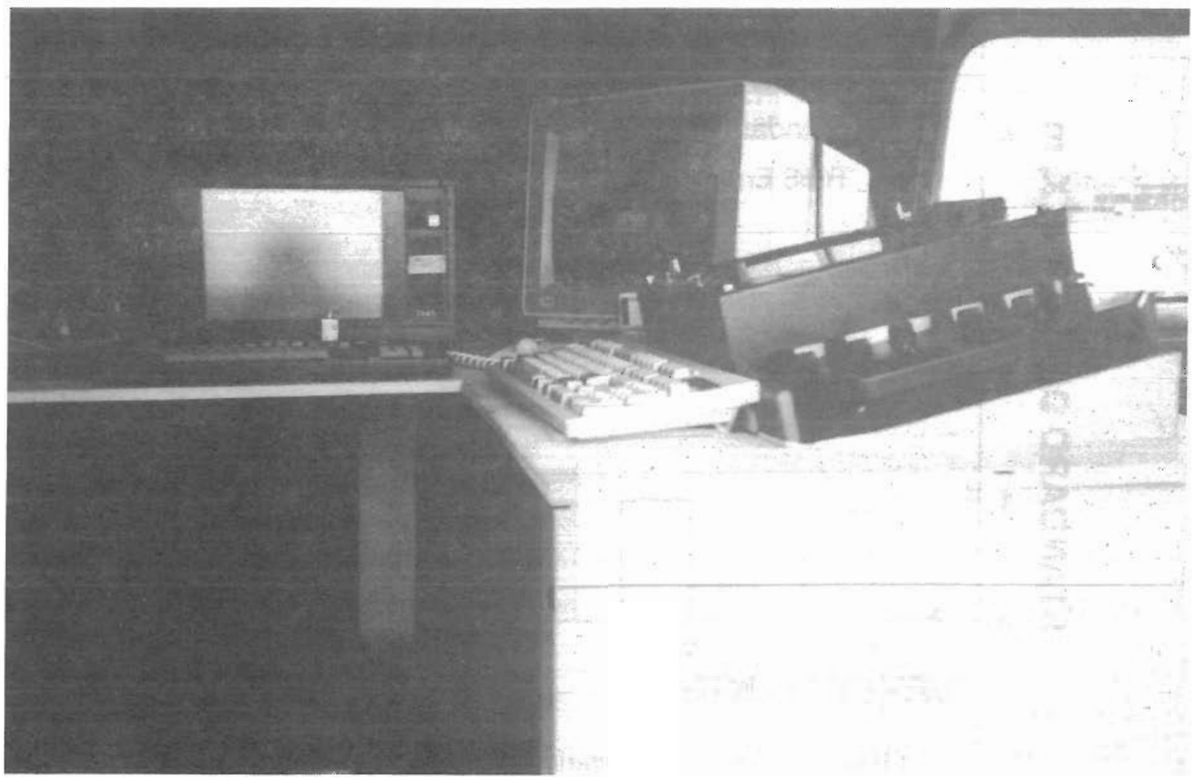

Figure 4. Equipment in van

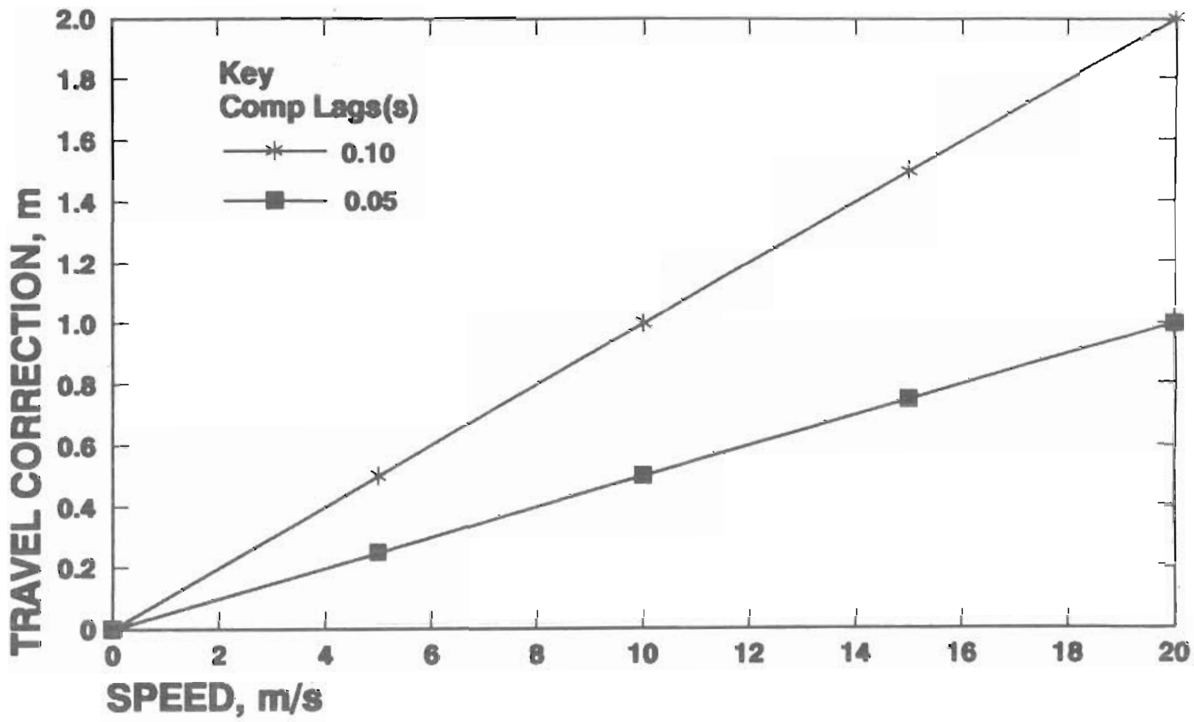

Figure 5. Travel vs. speed

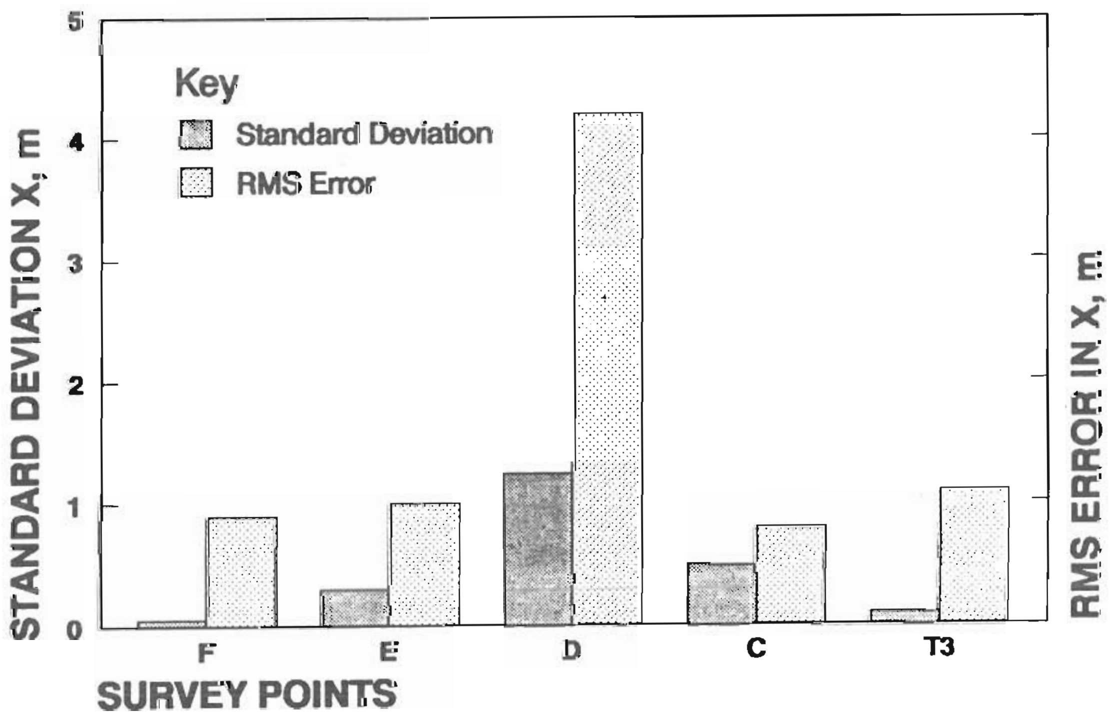

Figure 6. Errors in x, static vehicle, SN, initialized at F

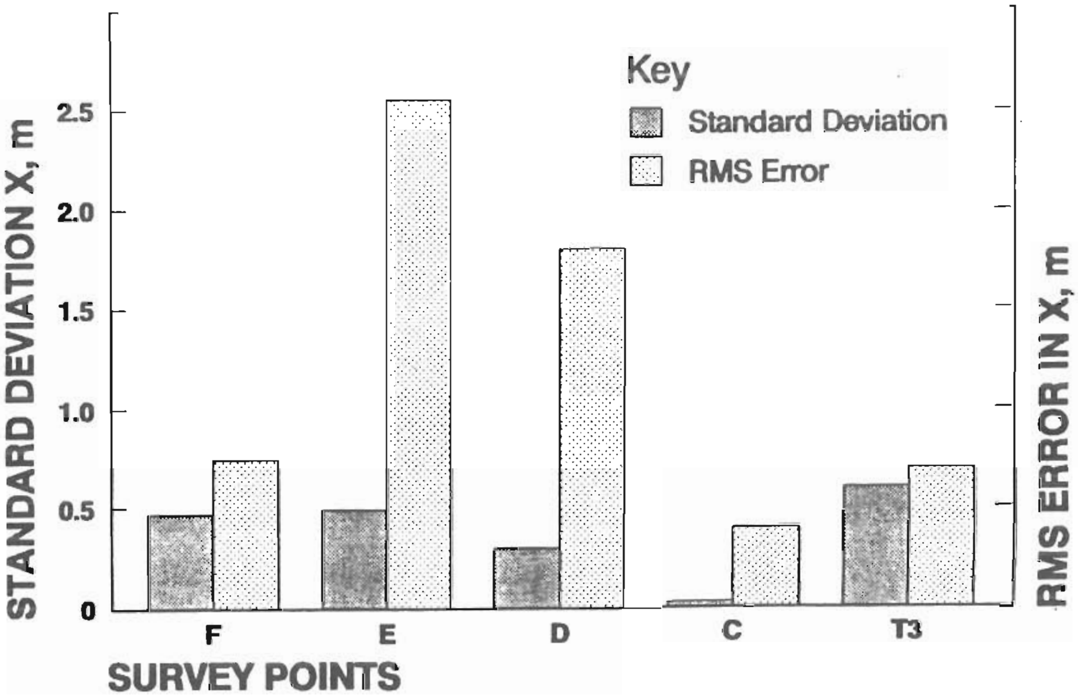

Figure 7. Errors in x, static vehicle, NS, initialized at T3

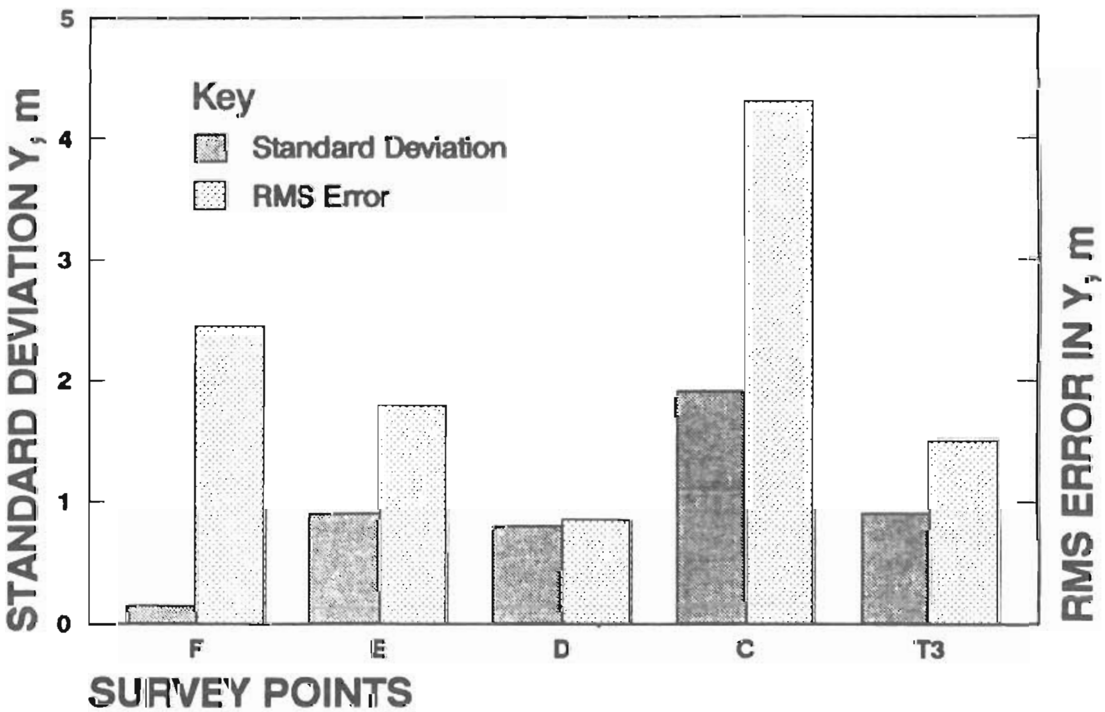

Figure 8. Errors in y, static vehicle, SN, initialized at F

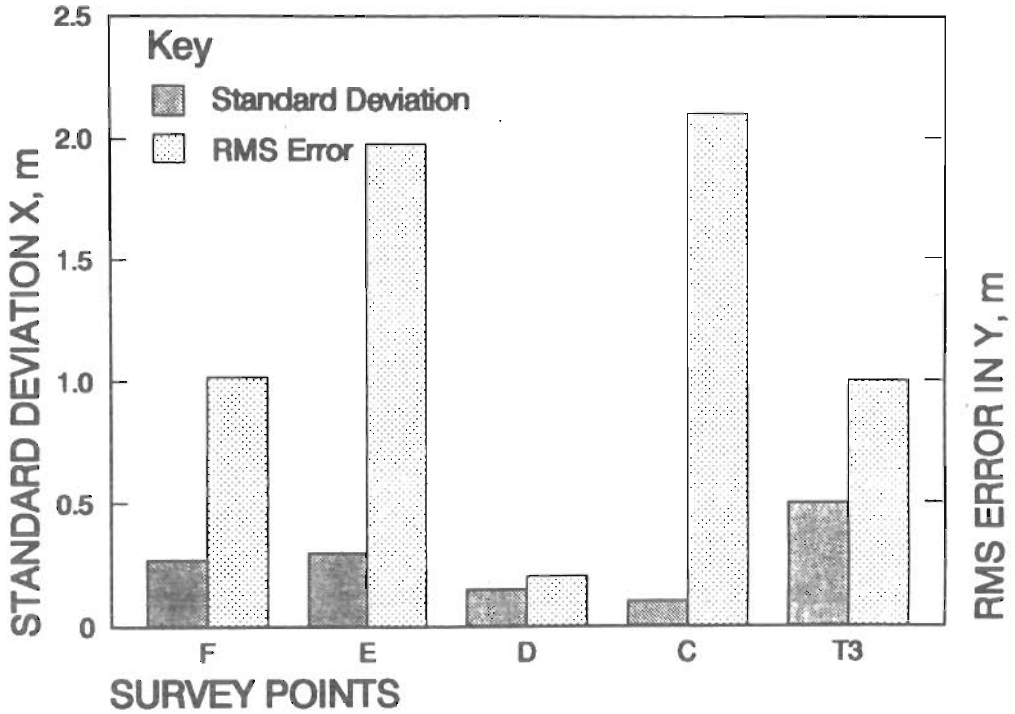

Figure 9. Errors in y, static vehicle, NS, initialized at T3

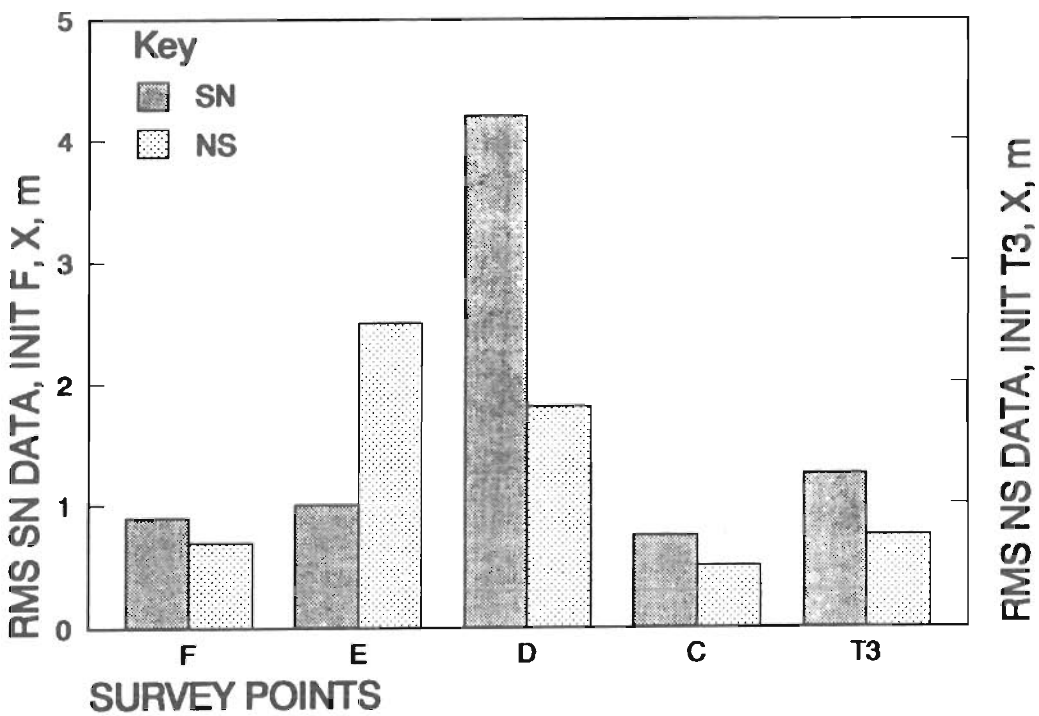

Figure 10. RMS error in x, static vehicle, SN compared to NS

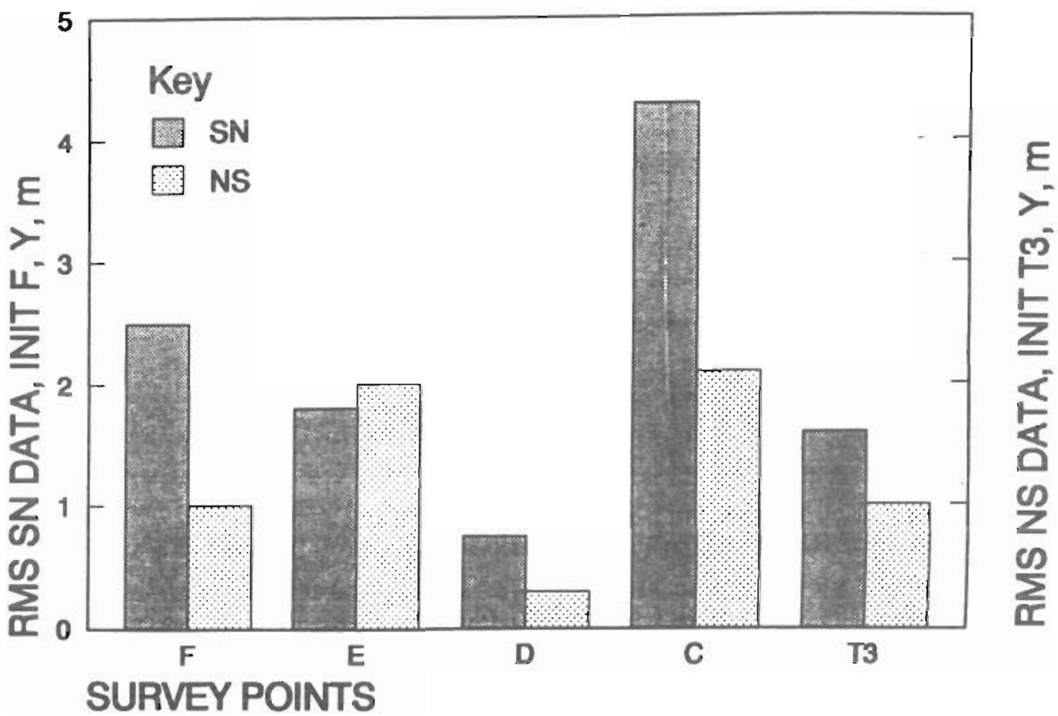

Figure 11. RMS error in y, static vehicle, SN compared to NS

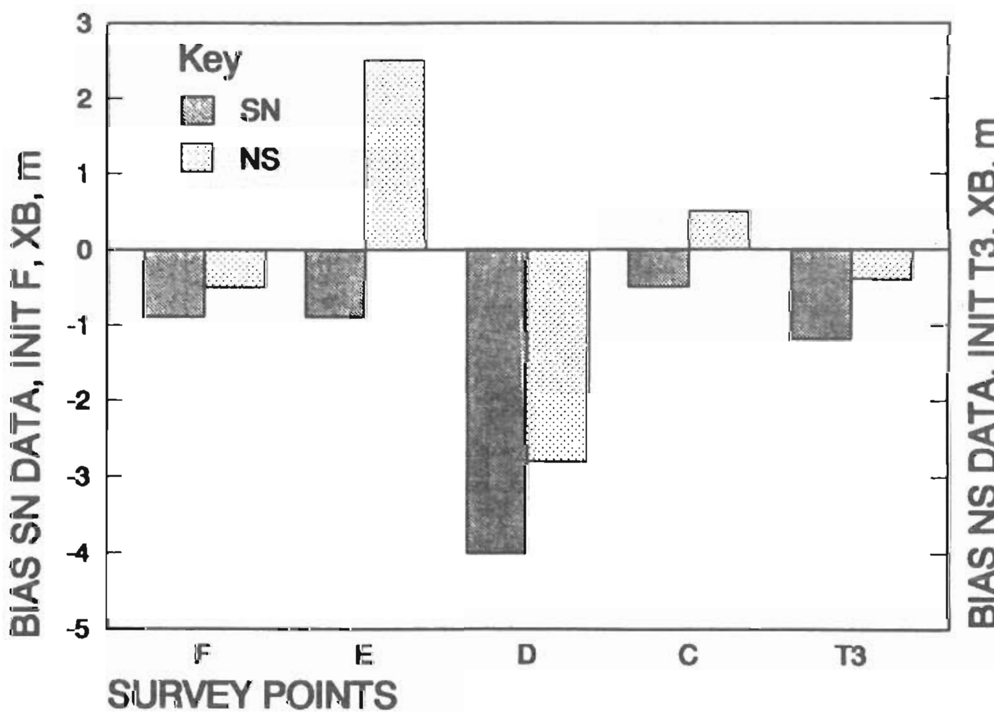

Figure 12. Bias error in x, static vehicle, SN compared to NS

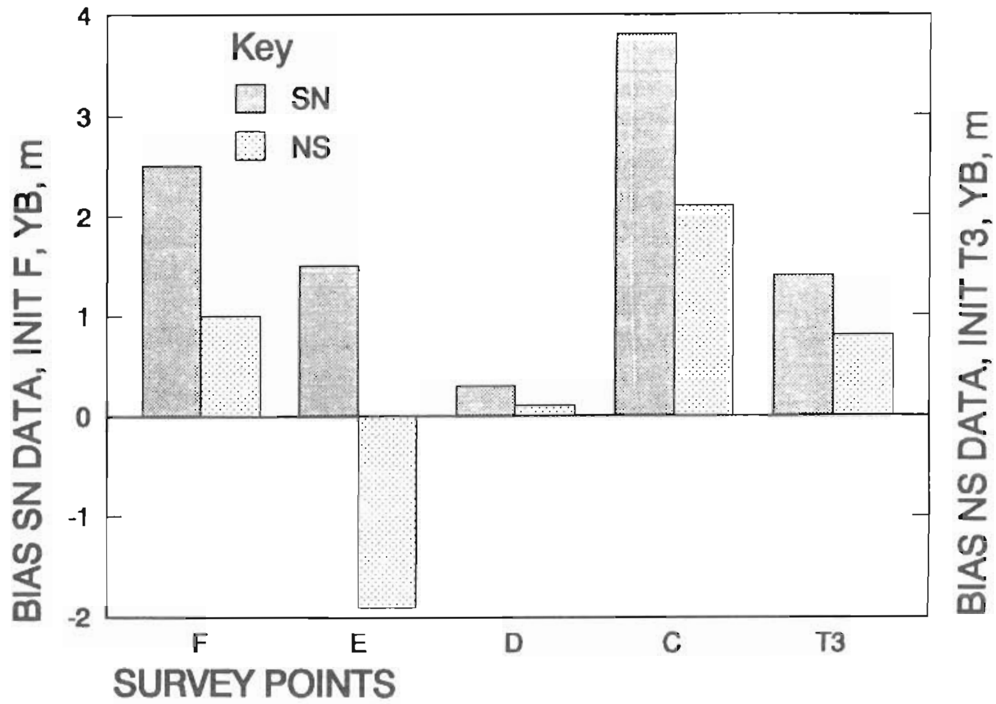

Figure 13. Bias error in y, static vehicle, SN compared to NS

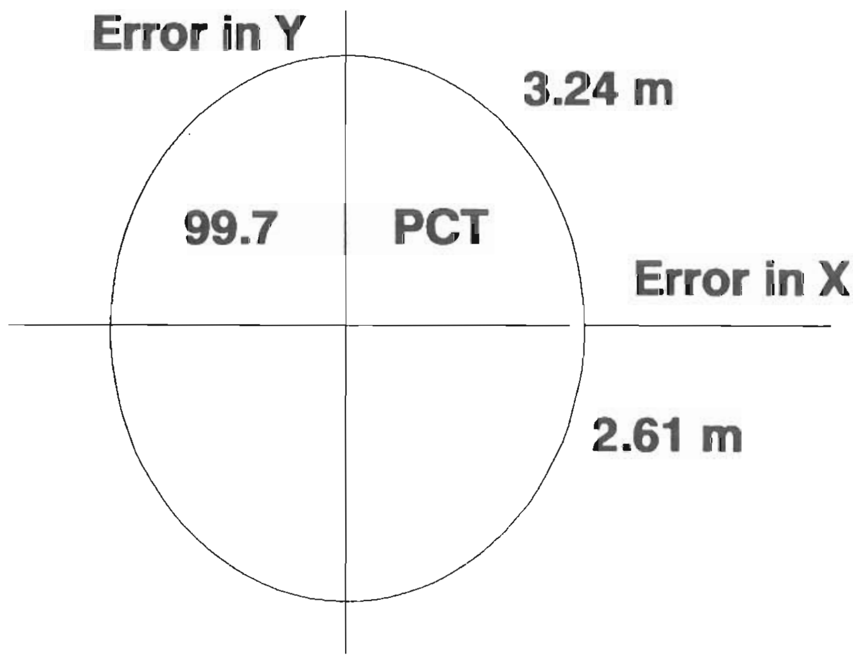

Figure 14. Radar error ellipse, static

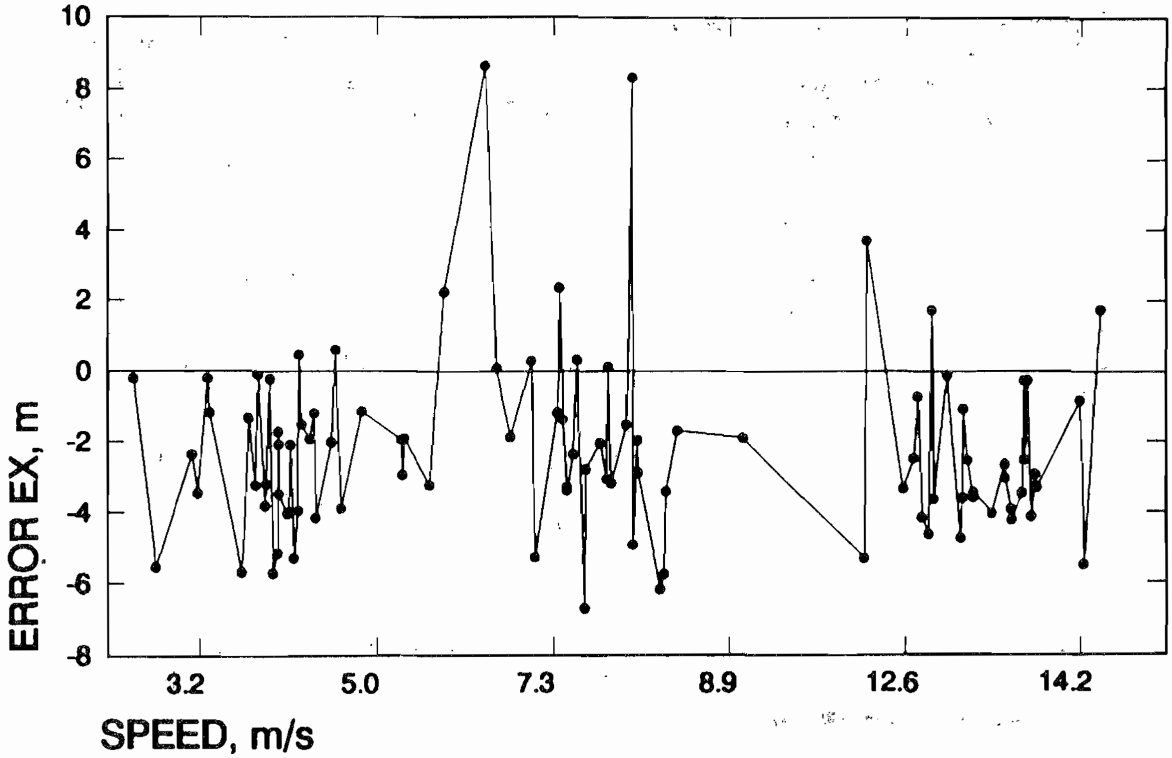

Figure 15. Error in x vs. speed, SN

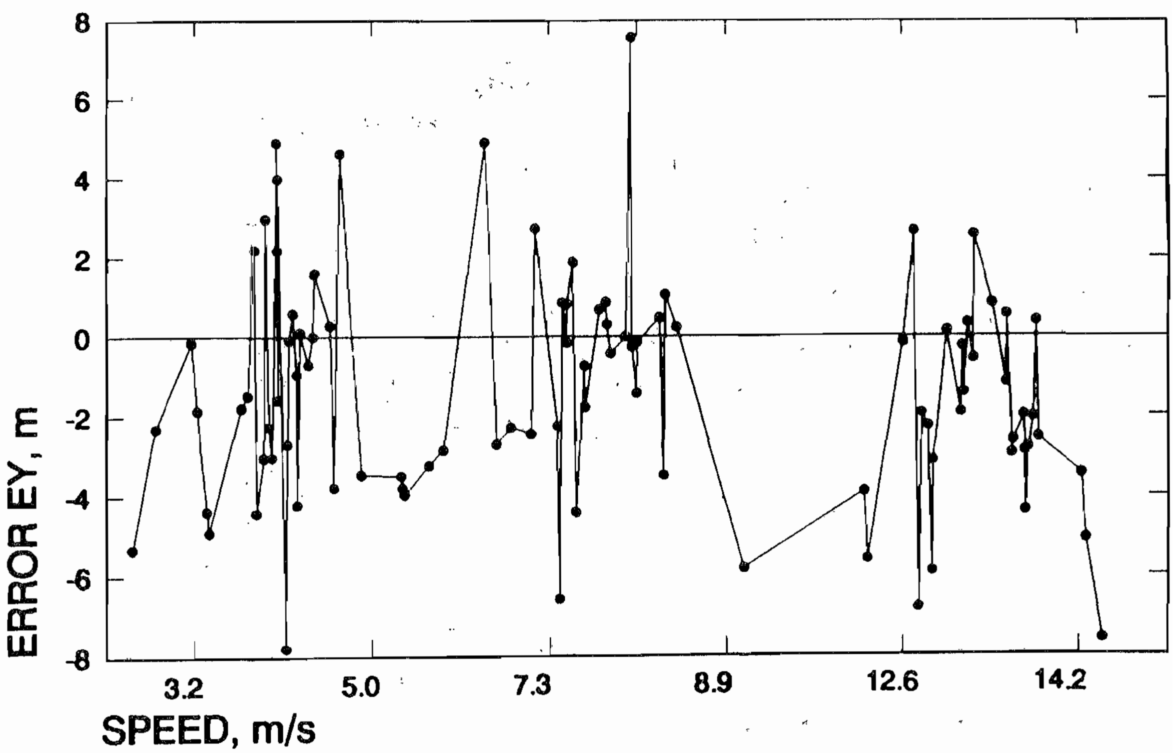

Figure 16. Error in y vs. speed, SN

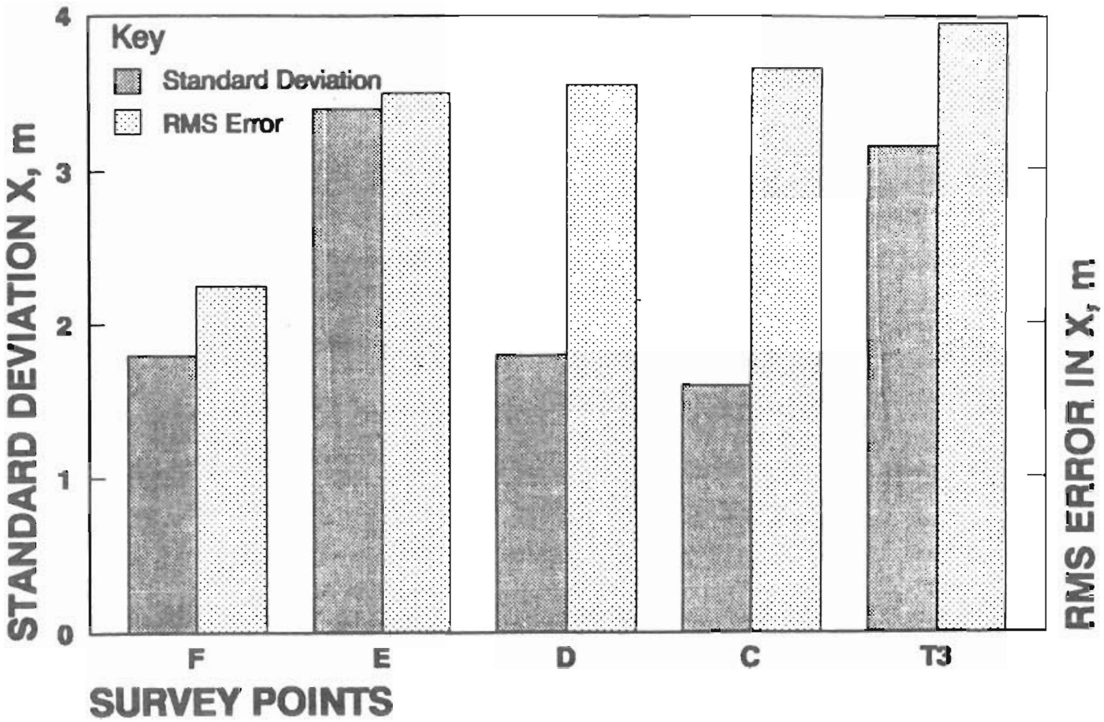

Figure 17. Errors in x, moving vehicle, SN, initialized at F

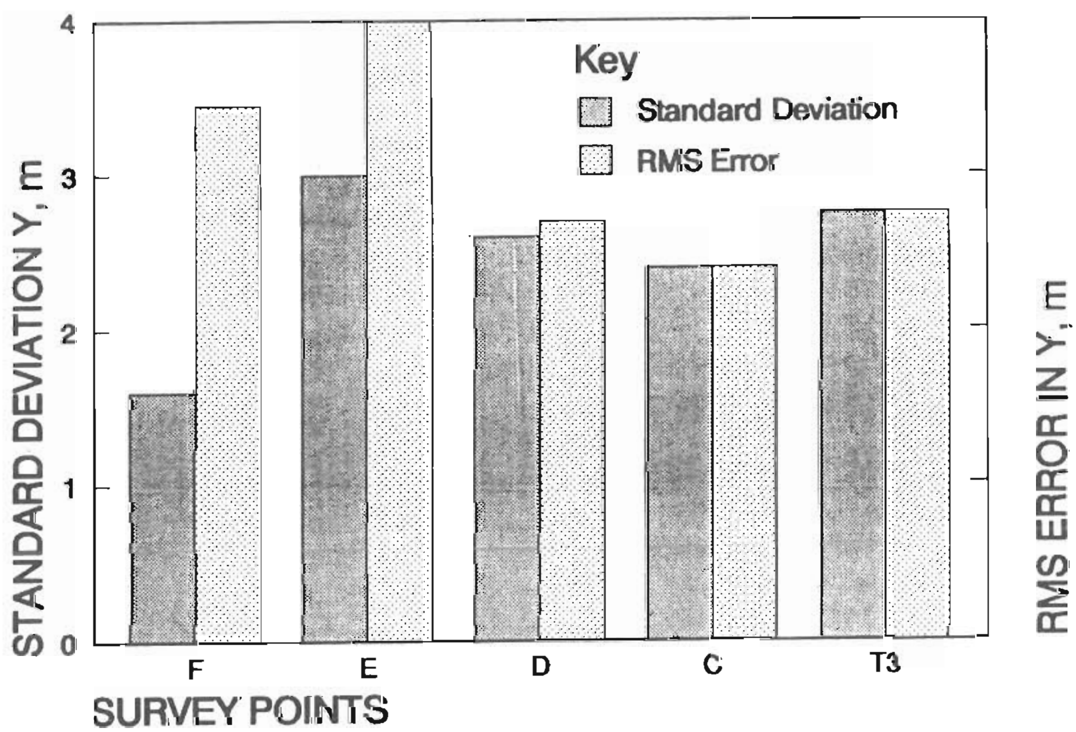

Figure 18. RMS error in y, moving vehicle, SN, initialized at F

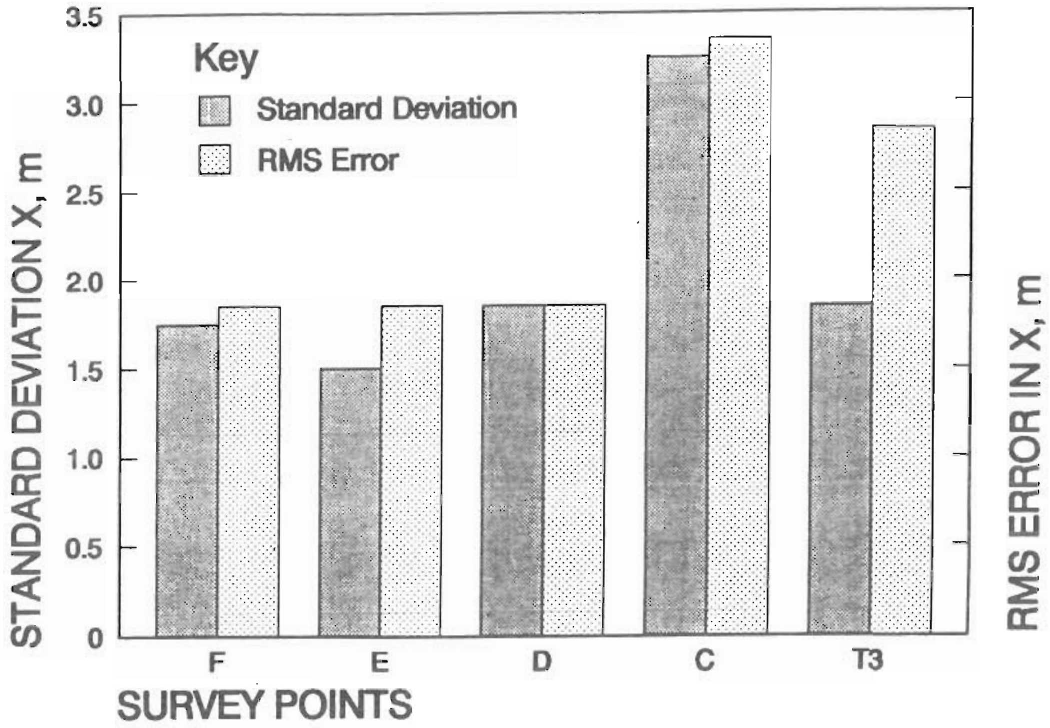

Figure 19. Errors in x, moving vehicle, NS, initialized at T3

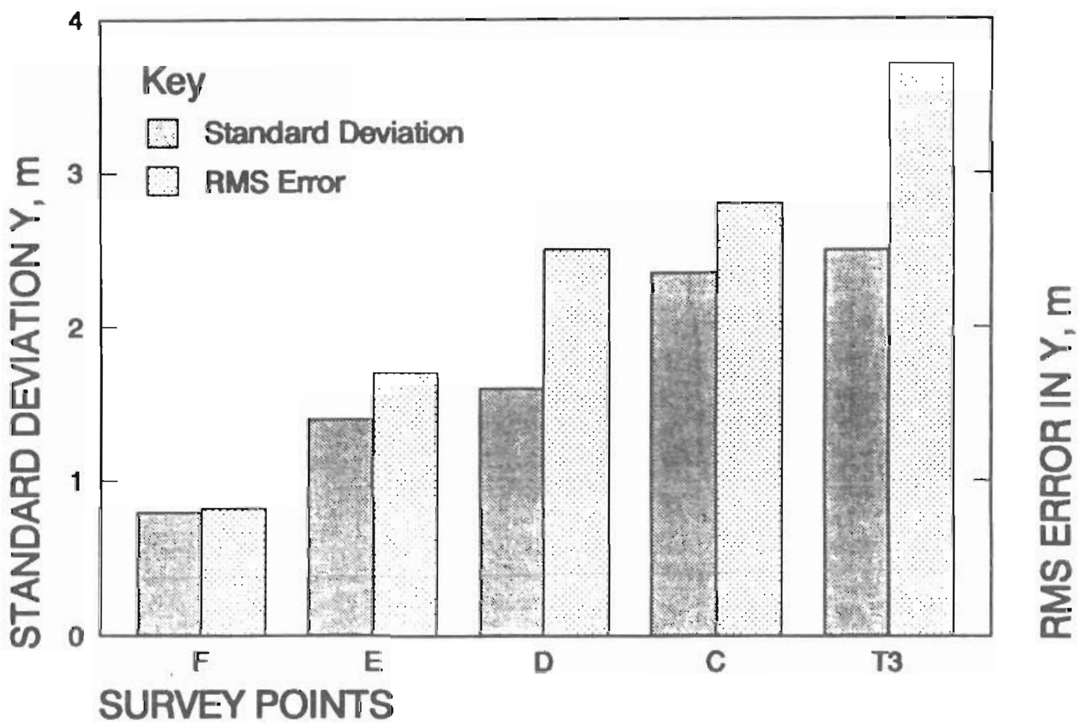

Figure 20. Errors in y, moving vehicle, NS, initialized at T3

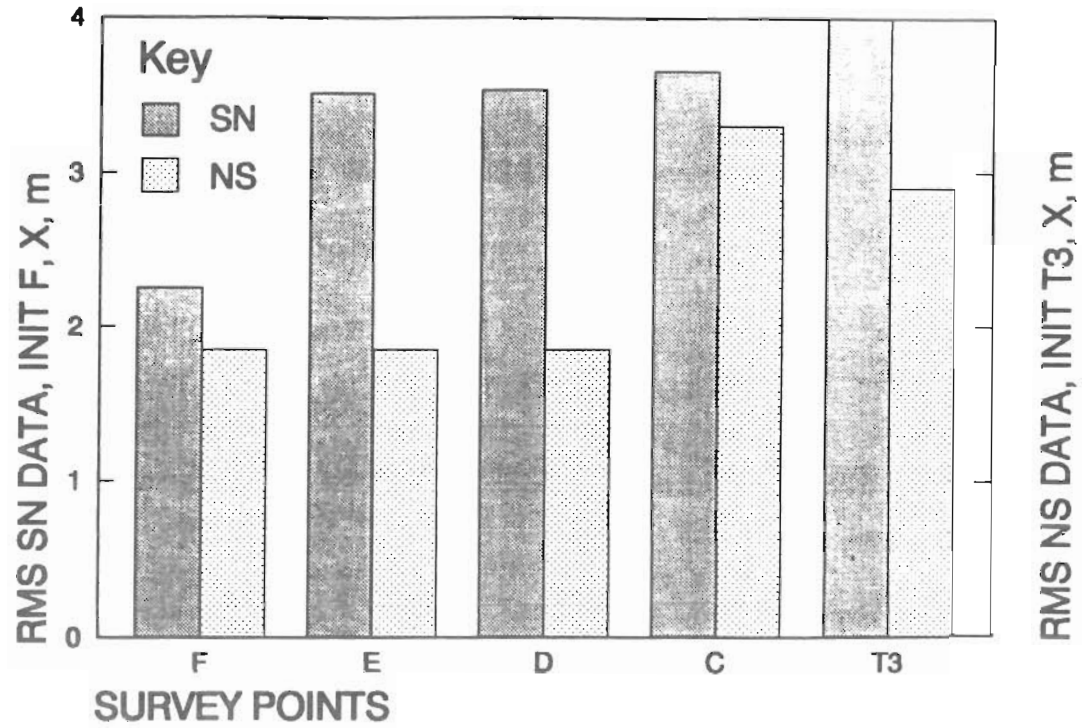

Figure 21. RMS error in x, moving vehicle, SN compared to NS

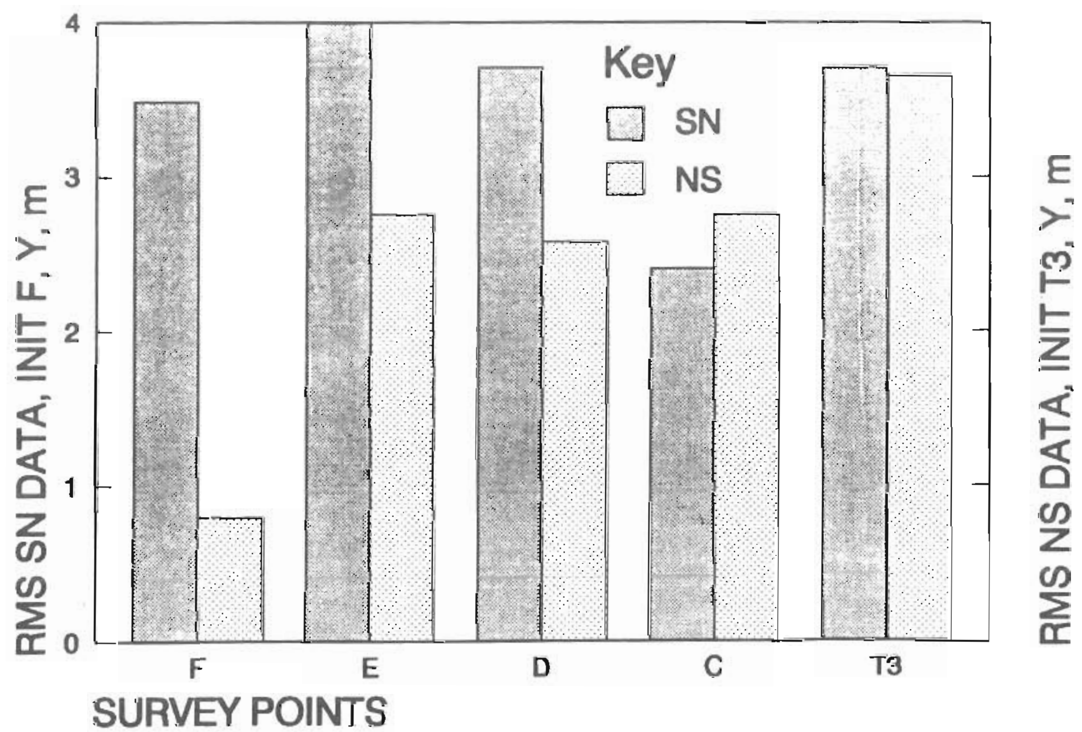

Figure 22. RMS error in y, moving vehicle, SN compared to NS

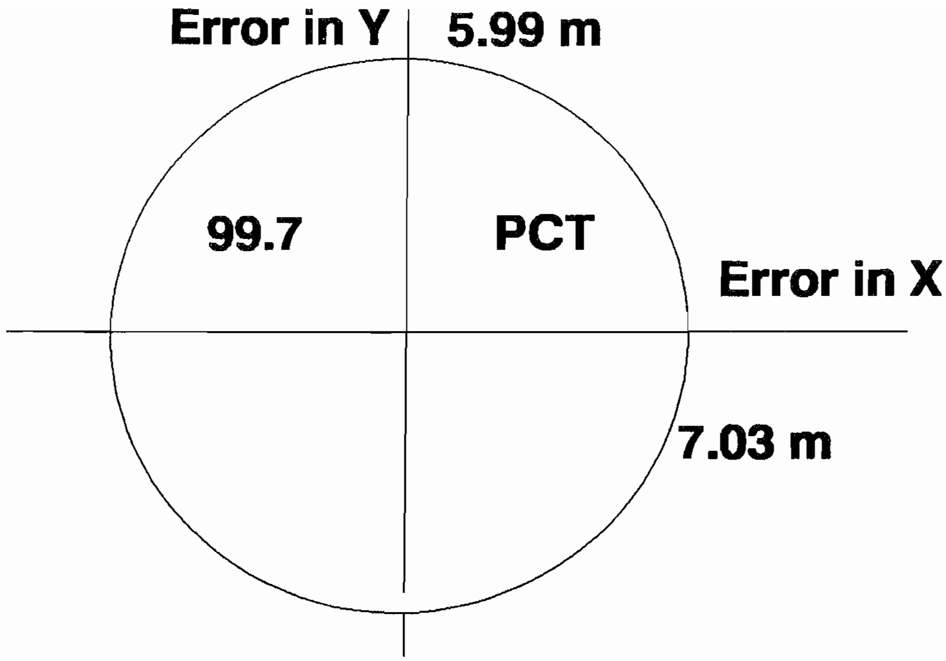

Figure 23. Radar error ellipse, moving

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