Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-98/1378-2		
4. Title and Subtitle PROFILE EQUIPMENT EVALUATION		5. Report Date December 1997
		6. Performing Organization Code
7. Author(s) Emmanuel G. Fernando and Sut Ian Carolyn Leong		8. Performing Organization Report No. Research Report 1378-2
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. Study No. 0-1378
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Office P. O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Research: May 1996 - August 1997
		14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

Research Study Title: Development of Ride Quality Specifications Criteria for ACP Overlays

16. Abstract

The Texas Department of Transportation (TxDOT) is implementing smoothness specifications based on profilograph testing as part of its construction quality control/quality assurance (QC/QA) program. Most tests are presently conducted using automated, California-type profilographs in which the equipment is pushed over a prescribed wheelpath. It appears that smoothness specifications will continue to be based on the profilograph, at least for the short term. However, in view of advances in profiling technology, it becomes prudent to investigate other methods of measuring surface profile and develop smoothness specifications based on profilers that offer greater accuracy and higher production rates. Already, a number of districts have expressed concerns about the sensitivity of the profilograph to short wavelengths or high frequency ripples. This observation demonstrates the need for more accurate measurements of surface profile for the purpose of building pavements that offer excellent ride quality, lower road user costs, and longer service lives. In pursuit of its goal of providing smooth pavements, TxDOT initiated a research project with the Texas Transportation Institute (TTI) to develop a smoothness specification for asphalt concrete overlays based on the new generation of pavement profilers that offer greater accuracy in profile measurement relative to the profilographs presently used in construction projects. Among other things, this research project evaluated a number of profile measuring devices to establish the availability of equipment for implementing a new profile-based smoothness specification in Texas. This report presents the findings of the profile equipment evaluation.

17. Key Words	18. Distribution Statement
Smoothness Specification, Profile Measurement, Pavement Profilers, Surface Profile, Pavement Roughness, Roughness Statistics	No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	186	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

PROFILE EQUIPMENT EVALUATION

by

Emmanuel G. Fernando
Associate Research Engineer
Texas Transportation Institute

and

Sut Ian Carolyn Leong
Graduate Student
Department of Electrical Engineering
Texas A&M University

Research Report 1378-2
Research Study Number 0-1378
Research Study Title: Development of Ride Quality Specifications Criteria for ACP Overlays

Sponsored by the
Texas Department of Transportation
In Cooperation with
U.S. Department of Transportation
Federal Highway Administration

December 1997

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

IMPLEMENTATION STATEMENT

The Texas Department of Transportation (TxDOT) sponsored a research project to develop a smoothness specification for asphalt concrete overlays based on pavement profile. To establish the availability of equipment for developing and implementing such a specification, TTI researchers conducted a profile equipment evaluation. The results of this effort showed that devices are available for collecting accurate and repeatable profile data. More important, the availability of lightweight profilers makes it viable for highway agencies to develop and implement these specifications. To ensure that accurate, precise, uniform, and comparable profile measurements are obtained during construction, researchers recommend that TxDOT establish a facility for evaluating pavement profilers. The following recommendations are submitted:

1. The calibration facility should have at least two sections, one smooth and the other, medium-smooth. The profiles on these calibration sections should be measured on a regular basis with static methods such as the rod and level, Dipstick, or other suitable devices that provide true profiles and meet the resolution requirements of ASTM E 1364. For the purpose of establishing a reference to evaluate profile equipment, rod and level measurements should conform, as a minimum, to the requirements for a second order, Class II survey, established by the Federal Geodetic Control Committee (FGCC) and specified in Section 3.5 of the FGCC Standards and Specifications for Geodetic Control Networks (1993). Guidelines for field testing are also given by SHRP (1994).
2. Each calibration section should have a length equal to the test interval of 161 m used in the current profilograph specification. There should be sufficient lead-in to each section so that inertial profilers can reach the required operational speed, and the accelerometers can stabilize prior to the start of the section. A length equal to twice the cutoff wavelength is recommended based on findings from an analysis of the effect of the lead-in profile on the filtered profile determined for a given

wheelpath. The details of this analysis are documented in this report. The lead-in profiles should be measured on a regular basis just like the profiles of the calibration sections to evaluate the accuracy of measurements from a given inertial profiler. Sufficient distance must also be available beyond the end of a calibration section for an inertial profiler to slow down and come to a halt.

3. The evaluation of pavement profilers should be made not only on the basis of measured profiles but also on profile-based statistics that are determined as part of the intended profiler applications.

In addition to the above, TxDOT should establish a set of standard parameters for the operation of inertial profilers on paving projects where the smoothness specification is enforced. Researchers recommend adopting the same filter and cutoff wavelength presently implemented in TxDOT's profilers. This will provide for consistency between profile measurements made in conjunction with the smoothness specification, and those that are conducted as part of TxDOT's pavement condition surveys, sponsored research projects, field investigations, and other activities for which profiles are collected. In addition, researchers recommend a reporting interval of 150 mm or less and a resolution of 0.1 mm or finer for the reported elevations. Most inertial profilers already meet or exceed these proposed requirements.

For consistency in the evaluation of pavement smoothness from profile measurements, data collected using devices that measure and integrate differential elevations must also be filtered using the specified filter. To guard against mistracking, it is advisable that rod and level measurements be made at the beginning and end of a test segment to verify the profiles from these devices and to adjust the profiles as appropriate.

Finally, the evaluation of profile data taken on simulated bumps showed that filtering distorts the profile immediately after a bump, making it difficult to measure the bump height as the baseline is skewed. This points to the need for evaluating the applicability of a bump height criterion in a profile-based smoothness specification and investigating techniques to reduce or counteract the distortion caused by filtering of the bump profile. An alternative is to develop and use a smoothness statistic, calculated from pavement profile, that accounts for the effects of bumps based on criteria such as ride quality and pavement damage. Researchers are of the opinion that this approach is simpler and more meaningful since it ties the evaluation of the surface defect directly to the criteria used in the smoothness specification.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT), or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The engineer in charge of the project was Dr. Emmanuel G. Fernando, P.E. # 69614.

ACKNOWLEDGMENT

The work reported herein was conducted as part of a research study sponsored by the Texas Department of Transportation and the Federal Highway Administration. The support and guidance of the Project Director, Mr. Ken Fults, are gratefully acknowledged. Mr. Carl Bertrand of TxDOT's Pavements Section provided valuable advice in the evaluation of profile data from the profilers evaluated in this study, and arranged the profile measurements with TxDOT's profilers. A sincere note of appreciation is also extended to the following individuals who participated in the profile equipment evaluation:

1. Messrs. Harry Trigg III of Trigg Industries and Richard Wix of the Australian Road Research Board who gave freely of their time and resources to demonstrate the Walking Profiler;
2. Mr. Ken Law, of K. J. Law, Incorporated, who made available for evaluation in this study, the initial production version of the T6400 lightweight inertial profiler;
3. Dr. Roger Walker of the University of Texas at Arlington who developed the Construction Profiler for TxDOT and demonstrated the operation of another profiler based on a gyroscope that is still under development for TxDOT;
4. Mr. Leo de Frain of the Michigan DOT who demonstrated the Michigan LISA; and
5. Mr. Leon Woznow who provided the profile measurements from the CSC Digital Profilite.

Researchers are also grateful for the assistance provided by Dr. Roger Walker in the evaluation of profile data, specifically, in providing the computer program, DOTPRO, developed at the University of Texas at Arlington, to filter rod and level data using the filter implemented in TxDOT's profilers. The contribution of Mr. James Naismith is also acknowledged. Mr. Naismith is a registered land surveyor who supervised the rod and level measurements on the test sites established for the equipment evaluation. Finally, researchers extend their thanks to Mr. Tom Van de Walle and Ms. Kimberly Davis for the detailed and careful work they did in conducting the rod and level measurements.

TABLE OF CONTENTS

Page

LIST OF FIGURES

FIGURE Page

FIGURE | Page

FIGURE Page

FIGURE Page

FIGURE Page

FIGURE Page

FIGURE Page

LIST OF TABLES

TABLE Page

TABLE Page

SUMMARY

In pursuit of its goal of providing smooth pavements, TxDOT sponsored a research project with TTI to develop a smoothness specification for asphalt concrete overlays based on pavement profile. One of the tasks conducted in this research study is an evaluation of pavement profilers to establish the availability of equipment for implementing a profile-based smoothness specification in Texas. To accomplish this evaluation, researchers established a number of test sites on which profile measurements from seven different profilers were collected. In terms of the International Roughness Index (IRI), the smoothness of the test sites ranged from about 1.0 to 1.9 mm/m measured over a 161 m interval. Two of the profilers investigated estimate true profiles by measuring and integrating differential elevations. The other five profilers are based on the inertial profiling method. Three of these are lightweight versions of the conventional van-mounted inertial profiler.

To establish a reference for evaluating the repeatability and accuracy of the profiles from the devices investigated, researchers conducted rod and level measurements with a digital level that provided a resolution of 0.030 mm thereby satisfying the requirements for a Class I static level survey as specified in ASTM E 1364. These measurements were supervised by a registered land surveyor. Comparative evaluations were made between the profiles from each profiler, and corresponding rod and level measurements. Based on these comparisons, researchers conclude that devices are available for collecting profile data that are accurate and repeatable. More important, the availability of lightweight profilers allows highway agencies to use profile measurements as a basis for evaluating the quality of pavement smoothness on construction projects. The practical significance of this for pavement management is that it allows highway agencies to implement a consistent measure of pavement smoothness throughout the life-cycle of a given roadway. Based on the findings of the profile equipment evaluation, recommendations are made with respect to the application of profilers in the implementation of a smoothness specification based on pavement profile.

CHAPTER I
INTRODUCTION

The Texas Department of Transportation (TxDOT) is implementing smoothness specifications based on profilograph testing as part of its construction quality control/quality assurance (QC/QA) program. Most tests are presently conducted using automated, California-type profilographs (Figure 1) in which the equipment is pushed over a prescribed wheelpath. A profile of the surface is obtained from recorded vertical displacements of the measuring wheel relative to a 7.6 m reference plane established by the 12 support wheels of the instrument.

The profilograph has been in use for over 50 years. Its development dates back to 1940 when the first unit was built by Francis Hveem in California. Today, it is widely used by state highway agencies for QC/QA of surface smoothness on paving projects. As an instrument for measuring surface profile, the profilograph is relatively inexpensive, simple to operate and maintain, and provides a trace of the surface that users can easily understand. However, there have always been concerns about the accuracy of the measured profiles. Francis Hveem, in comparing profilograph traces with rod and level data, noted that the "*agreement appeared to be sufficiently close for all practical purposes but unanswered questions always persisted as to the exact shape of the bumps in the pavement*," (Scofield, 1993). Field tests conducted by TTI researchers showed that false depressions are introduced in the profilograph trace as the measuring wheel approaches, goes over, and leaves a given bump. Further, Kulakowski and Wambold (1989) have determined that the frequency response of the instrument is uniform only within the narrow range of wavelengths between 1.2 to 2.1 m. Outside this range, the frequency response oscillates, and profile components are either attenuated or amplified. Despite these known limitations in profile accuracy, the profilograph continues to be widely used by state highway agencies.

In Texas, it appears that smoothness specifications will continue to be based on the profilograph, a least for the short term. However, in view of advances in profiling technology,

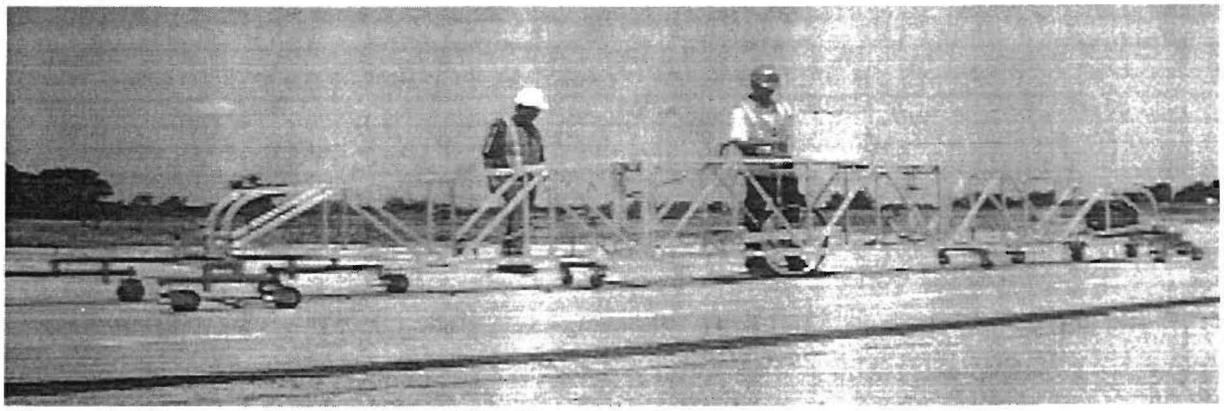

Figure 1. Picture of an Automated Profilograph.

it becomes prudent to investigate other methods of measuring surface profile and develop smoothness specifications based on profilers that offer greater accuracy and higher production rates. Already, a number of districts have expressed concerns about the sensitivity of the profilograph to short wavelengths or high frequency ripples. This observation demonstrates the need for more accurate measurements of surface profile for the purpose of building pavements that offer excellent ride quality, lower road user costs, and longer service lives.

In pursuit of its goal of providing smooth pavements, TxDOT initiated a research project with the Texas Transportation Institute (TTI) to develop a smoothness specification for asphalt concrete overlays based on the new generation of pavement profilers that offer greater accuracy in profile measurement relative to the profilographs presently used in construction projects. Among other things, this research project evaluated a number of profile measuring devices to establish the availability of equipment for implementing a new profile-based smoothness specification in Texas. The development of this smoothness specification is documented by Fernando (1998). This report presents the findings of the profile equipment evaluation.

TEST PROGRAM

To evaluate pavement profilers, researchers established a number of test sites on which profiles were measured. Table 1 shows the sites laid out for this investigation. Two of the

Table 1. Test Sites for Evaluating Profilers.

Site	Location	Length (m)	Wheelpath Profiled[1]	Direction of Measurement
Annex 1	Texas A&M Riverside Campus	175.6	Left	South
Annex 2	Texas A&M Riverside Campus	175.6	Left	South
SH47A	State Highway 47	336.5	Left and right	South
SH47B	State Highway 47	336.5	Left and right	North

[1]Relative to the direction of measurement.

sites, designated herein as Annex 1 and Annex 2, are located inside the Texas A&M Riverside campus and receive no vehicle traffic. Annex 1 is a rough site with an IRI of about 1.88 mm/m, while Annex 2 is medium-smooth with an IRI of about 1.51 mm/m. These statistics are averages of IRIs calculated for the left wheelpath of each site using profile data taken over a 0.161 km interval with TxDOT's Surface Profiler (SP). Figure 2 shows the test sites located inside the Texas A&M Riverside campus.

Another two sites were established on State Highway (SH) 47 adjacent to the Riverside campus (Figure 3). These sites, designated herein as SH47A and SH47B, are located within a new highway that was opened to traffic in August 1996. The sites are smooth and comprise four 0.161 km test sections on adjacent lanes of SH47. The average IRIs of the test sections computed from profile data taken on both wheelpaths with TxDOT's SP are 1.05 and 1.03 mm/m on SH47A, and 0.76 and 0.75 on SH47B.

Table 2 identifies the profilers evaluated in this research project along with the respective equipment developers. The approximate costs of the different profilers are also given based on information supplied by the developers. Table 3 shows the reporting interval, data resolution, and filter types for the data collected from the profile tests. To provide a reference for evaluating the data, rod and level measurements were also conducted on the left wheelpaths of Annex 1, Annex 2, and SH47A over a distance of 175.6 m. The number of repeat rod and level measurements made were four for Annex 1 and SH47A, and five for

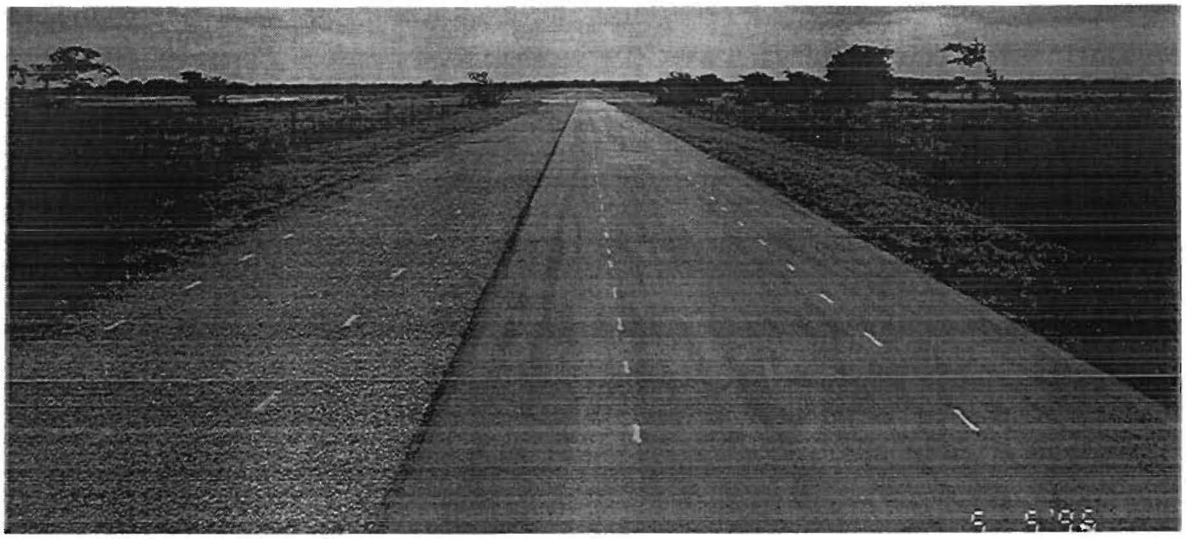

Figure 2. Sites Annex 1 (left) and Annex 2 (right) Located Inside the Riverside Campus.

Figure 3. Sites SH47A (left) and SH47B (right) Located on Adjacent Lanes of SH47.

Table 2. Profilers Investigated in the Research Project.

Profiler	Description	Developer	Contact	Cost (US$)[1]
Digital Profilite Model 300 (CSC)	Rolling profiler, pushed by operator	Leon Woznow	CSC Profilair, British Columbia, Canada (604) 988-7293	31,400 + notebook PC
Walking Profiler (WPR)	Rolling profiler, pushed by operator	ARRB[2] Transport Research	Trigg Industries, California (213) 845-9390	17,000 including notebook PC
Lightweight Inertial Surface Analyzer (LISA)	Tractor-mounted inertial profiler	Michigan DOT	Leo DeFrain, Michigan DOT (517) 322-5715	45,000 + trailer
Lightweight Profilometer T6400	Tractor-mounted inertial profiler	K. J. Law Engineers	K. J. Law Engineers, Michigan (800) 521-5245	50,000 including trailer
Construction Profiler (CPR)[3]	Golf-cart mounted inertial profiler	TxDOT	Carl Bertrand, TxDOT (512) 465-3686	35,000 + labor
Laser Rut/Profiler (LRP)[4]	Van-mounted inertial profiler	TxDOT	Carl Bertrand, TxDOT (512) 465-3686	75,000 + labor
Surface Profiler (SP)	Van-mounted inertial profiler	TxDOT[5]	Carl Bertrand, TxDOT (512) 465-3675	75,000 + labor

[1]Contact equipment developer for latest pricing.
[2]Australian Road Research Board.
[3]TxDOT profilers are currently built by the department for its internal use only.
[4]Includes sensors for measuring rut depths.
[5]Initially developed by K. J. Law and later modified by TxDOT.

Table 3. Features of Profilers Tested.

Profiler	Wheelpaths profiled per run	Reporting interval (mm)	Resolution of elev. data (mm)	Output profile	Speed of operation (km/h)
CSC	one	254	0.010	Unfiltered or true profile	0.25 to 1.50
WPR	one	241	0.005	Unfiltered or true profile	0.80 max
LISA	one	76	0.025	Filtered using 3rd order Butterworth; 0.6 to 33 m wavelengths	13 to 19
T6400	one	150	0.025	Filtered using 3rd order Butterworth; 33 m cutoff wavelength	24
CPR	one	54	0.025	Filtered using 4th order IIR[1]; 33 m cutoff wavelength	16 to 22.5
LRP	two	266	0.025	Filtered using 4th order IIR; 33 m cutoff wavelength	highway speed
SP	two	143	0.025	Filtered using 4th order IIR; 33 m cutoff wavelength	highway speed

[1]Infinite Impulse Response filter is second order Butterworth that is cascaded.

Annex 2. Rod and level data were taken at 152.4 mm intervals with a digital level that provided a resolution of 0.030 mm thereby satisfying the requirements for a Class 1 static level survey as specified in ASTM E 1364. The rod and level surveys were supervised by a registered land surveyor.

All tests were conducted on delineated wheelpaths and along the prescribed directions given in Table 1. Two to five profile measurements were made on a given site by operators from the equipment developers. For measurements collected with the inertial profilers, plywood strips were placed at selected offsets from the start and end of a test site to locate these points on the measured profiles. In this way, researchers were able to line up all the measured data on a given site. Profile tests were conducted in May, June, and July of 1996 for all profilers with the exception of the K. J. Law T6400 which was not available for testing until October 1996. By that time, SH47 was already opened to traffic. Because of traffic control constraints, no measurements were made on SH47B with the T6400 profiler.

Figures 4 to 10 illustrate the different devices evaluated in the study. It is noted that researchers also looked at a prototype of a gyroscope-based device under development in another TxDOT project. However, problems arose with the gyroscope unit during the tests that indicated the need for additional study. Consequently, no further evaluations were conducted. The profile data collected are analyzed in the next chapter.

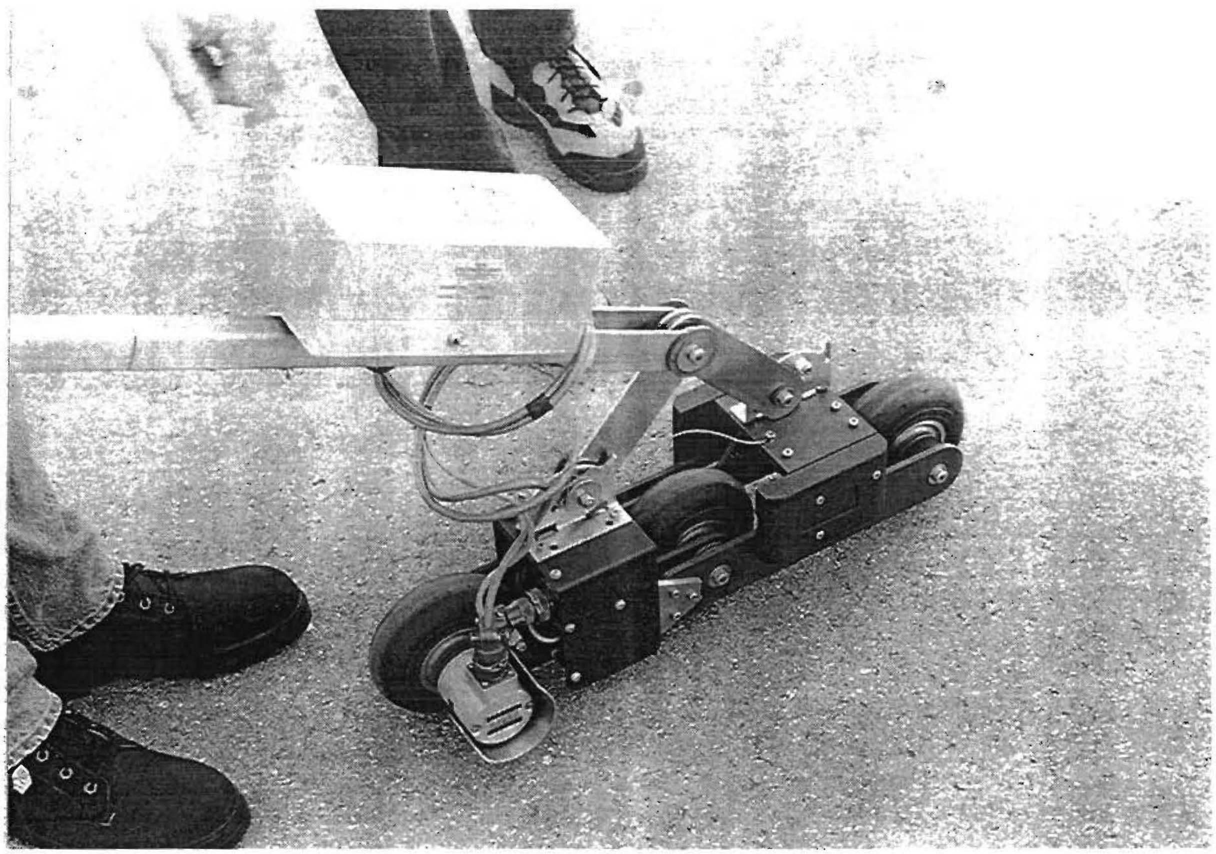

Figure 4. The Digital Profilite 300 Manufactured by CSC Profilair.

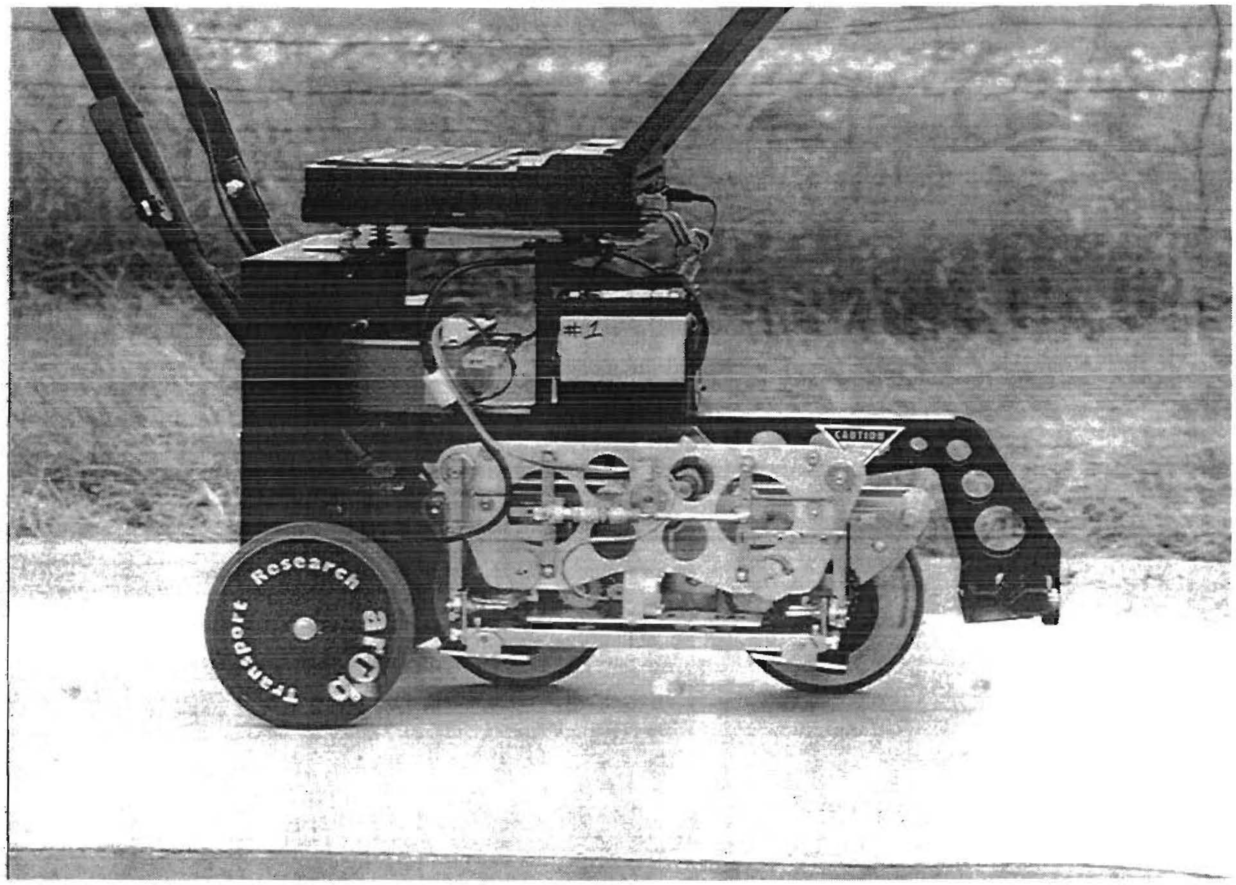

Figure 5. The Walking Profiler Developed by ARRB Transport Research Limited.

Figure 6. The Michigan LISA.

Figure 7. The K. J. Law Lightweight Profilometer Model T6400.

Figure 8. The Construction Profiler Developed by TxDOT.

Figure 9. The Laser Rut/Profiler Developed by TxDOT.

Figure 10. The TxDOT Surface Profiler.

CHAPTER II
ANALYSIS OF PROFILE DATA

Researchers compared the profiles collected to the rod and level data to assess the different profilers. In particular, the repeatability of the measured elevations was compared to the repeatability of corresponding rod and level data. Additionally, the International Roughness Index (IRI) was computed for each profile. Comparisons were then made between the computed IRIs from the different profilers and corresponding IRIs from the rod and level surveys. In addition, the accuracy of the test data from the different profilers was evaluated by comparing the data with the corresponding rod and level profiles. The results from the comparisons are presented in this chapter. It is emphasized that the results reported should not be regarded as indicative of current performance. Since design changes may have occurred from the time of the equipment evaluation, individuals or agencies should look at their needs, contact the respective vendor(s) and conduct tests of their own before making decisions on profiling equipment. The intent of the evaluation was not to certify equipment but to establish the availability of devices for measuring surface profile to implement a profile-based smoothness specification.

REPEATABILITY OF PROFILES

The original profiles from the tests conducted are presented in Appendix A. For any given equipment, the profiles from repeat measurements at a particular site are shown in a corresponding figure. Prior to the analysis, researchers initially lined up the repeat measurements relative to the start of a given site. For the LISA, T6400, and CPR profilers, the start of a site was located in the profile data using markers inserted in the data by placing a plywood strip 1.83 m prior to the beginning station of a given site. This strip appeared as a spike which served as a reference in locating the start of the site in the profile data. For the TxDOT LRP and SP profilers, measurements were triggered automatically using reflective aluminum strips that were placed on the surface 1.83 m before the start of a site. The profiles from these devices are thus already lined up and the only thing done was to locate the starting point of the site in the profile data. Measurements with the CSC and WPR profilers, as well as with the rod and level, started at the beginning of each site.

To evaluate repeatability, the standard deviation of the measured elevations from repeat measurements was calculated at each reporting location. The average of the computed standard deviations was then used as measure of the repeatability of the given equipment. Researchers then compared the averages determined to corresponding statistics computed from rod and level data. Profiles from rod and level measurements are shown in Figures A1 to A3 of Appendix A.

Table 4 summarizes the average standard deviations from the analysis of profile repeatability. The lower this statistic, the better the repeatability of the measured elevations from a given device. To gauge the repeatability of the measured profiles, the average standard deviations are compared to corresponding statistics calculated from rod and level data in Figures 11 to 14. The statistics associated with the CSC and WPR are compared with corresponding statistics from rod and level data in Figure 11, while Figures 12, 13, and 14 provide similar comparisons for the LISA, T6400, and TxDOT's profilers, respectively. Note that different scales have been used in these figures to accentuate differences between the average standard deviations determined for a given profiler, and corresponding statistics determined from rod and level data. It is observed that the statistics vary between profilers. The statistics plotted in Figures 11 to 14 are also summarized in Table 5. Note that rod and level data were collected on the left wheelpaths of Annex 1, Annex 2, and SH47A for a distance of 175.6 m. Thus, the average standard deviations given in Table 5 were computed at the same intervals over which rod and level data were collected.

In evaluating the repeatability of inertial profilers investigated in this study, the rod and level data were initially filtered according to the method used for a given inertial profiler. Recall that rod and level data were collected on the left wheelpaths of Annex 1, Annex 2, and SH47A over a distance of 175.6 m. These profiles were used to evaluate the data from the different profilers. Since inertial profilers need a lead-in to reach the required operational speed and to stabilize the accelerometers prior to the start of a given site, rod and level

Table 4. Averages (in mm) of the Standard Deviations of Original Profiles.

Profiler	Annex 1		Annex 2		SH47A		SH47B	
	LWP	RWP	LWP	RWP	LWP	RWP	LWP	RWP
CSC	8.1339		9.6013		3.9057	18.2339	4.5993	3.8005
WPR	0.7729		1.6123		1.2311	5.6855	0.3658	2.3991
LISA	1.4962		1.0068		0.8027	0.6709	1.0474	0.7246
K. J. Law	3.4940		5.1029		1.7704	0.8960		
CPR	0.8263		0.9357		0.9358	0.6630	1.1165	0.6552
LRP	1.1474	1.2580	0.6873	0.8067	0.4368	0.4581	0.3571	0.4172
SP	0.5071	0.5734	0.3316	0.3280	0.3183	0.2823	0.3196	0.3082

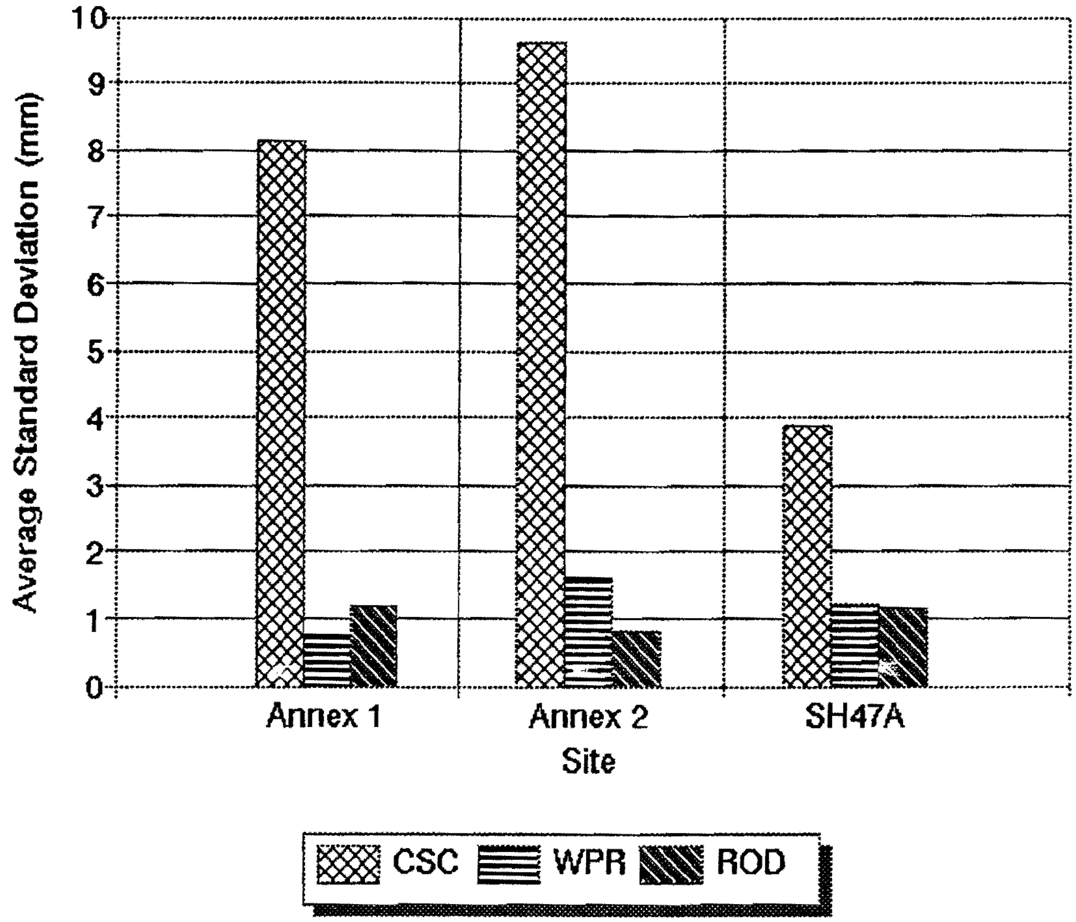

Figure 11. Average Standard Deviations of Profiles from CSC and WPR Compared to Rod & Level.

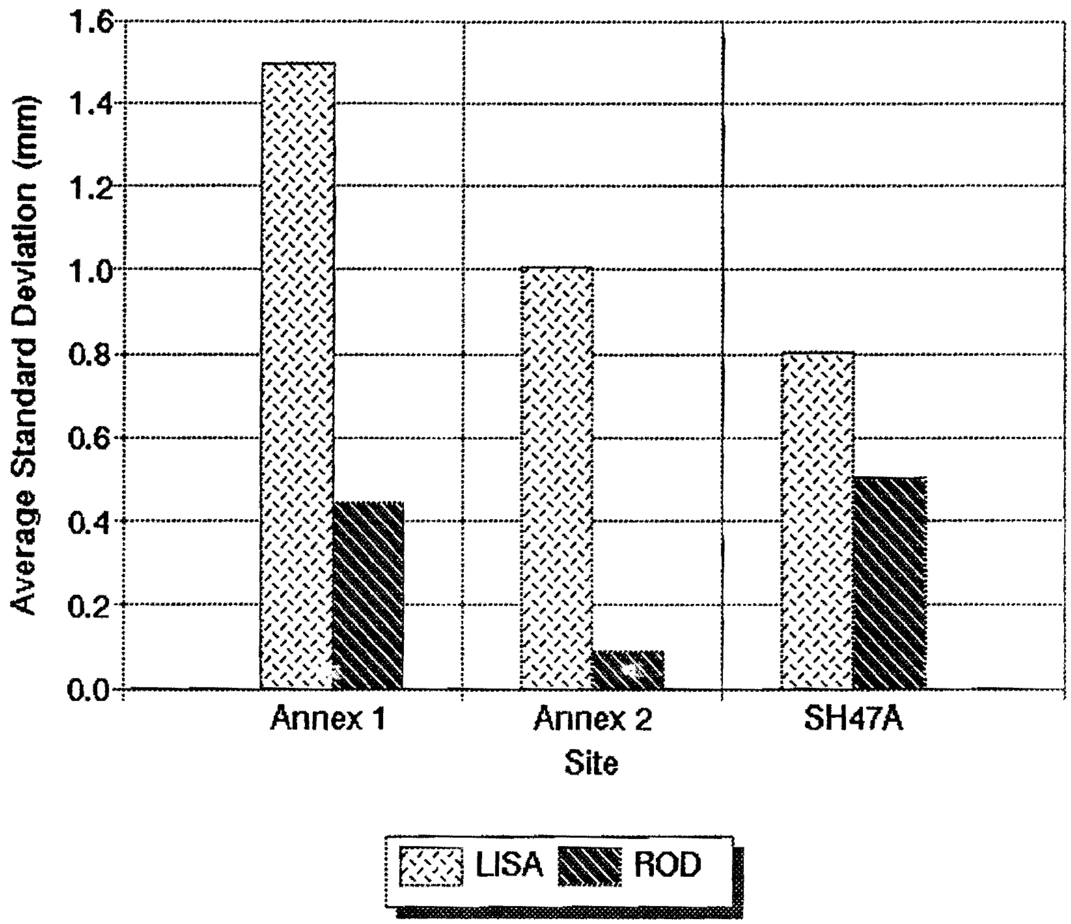

Figure 12. Average Standard Deviations of Profiles from LISA Compared to Rod & Level.

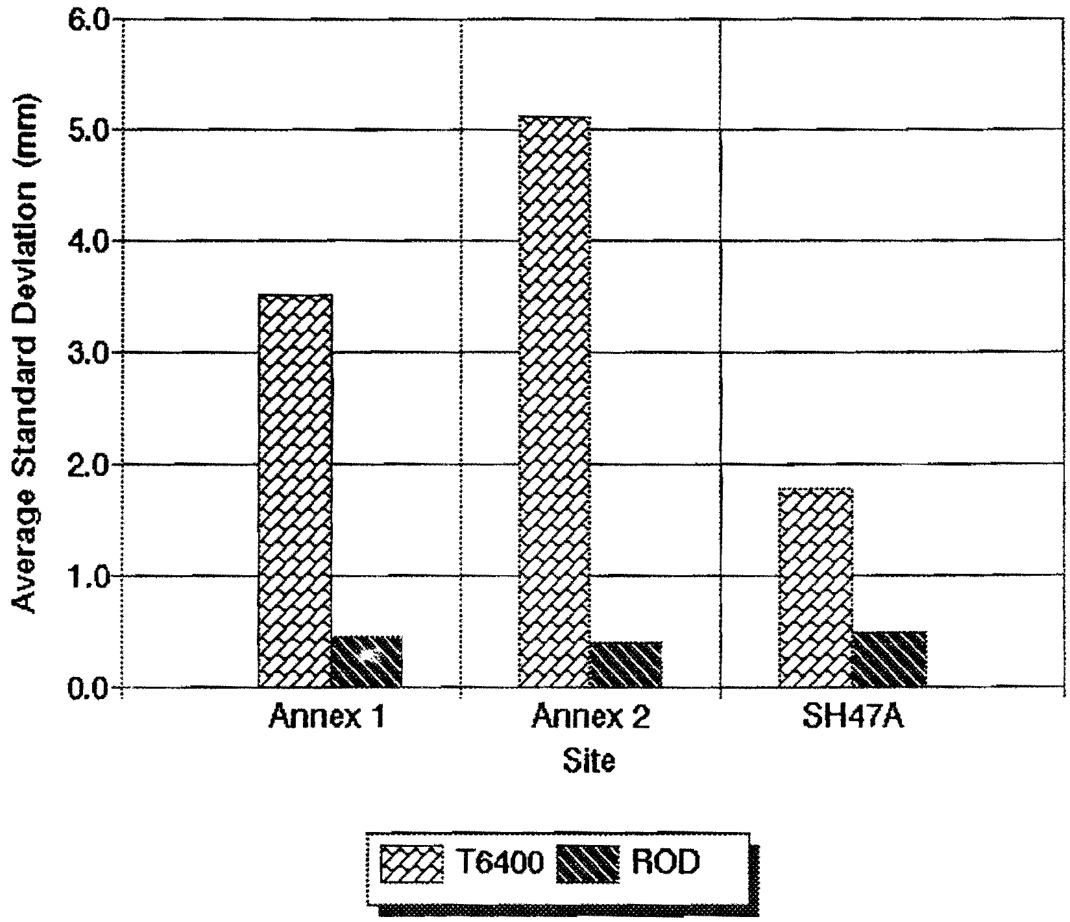

Figure 13. Average Standard Deviations of Profiles from T6400 Compared to Rod & Level.

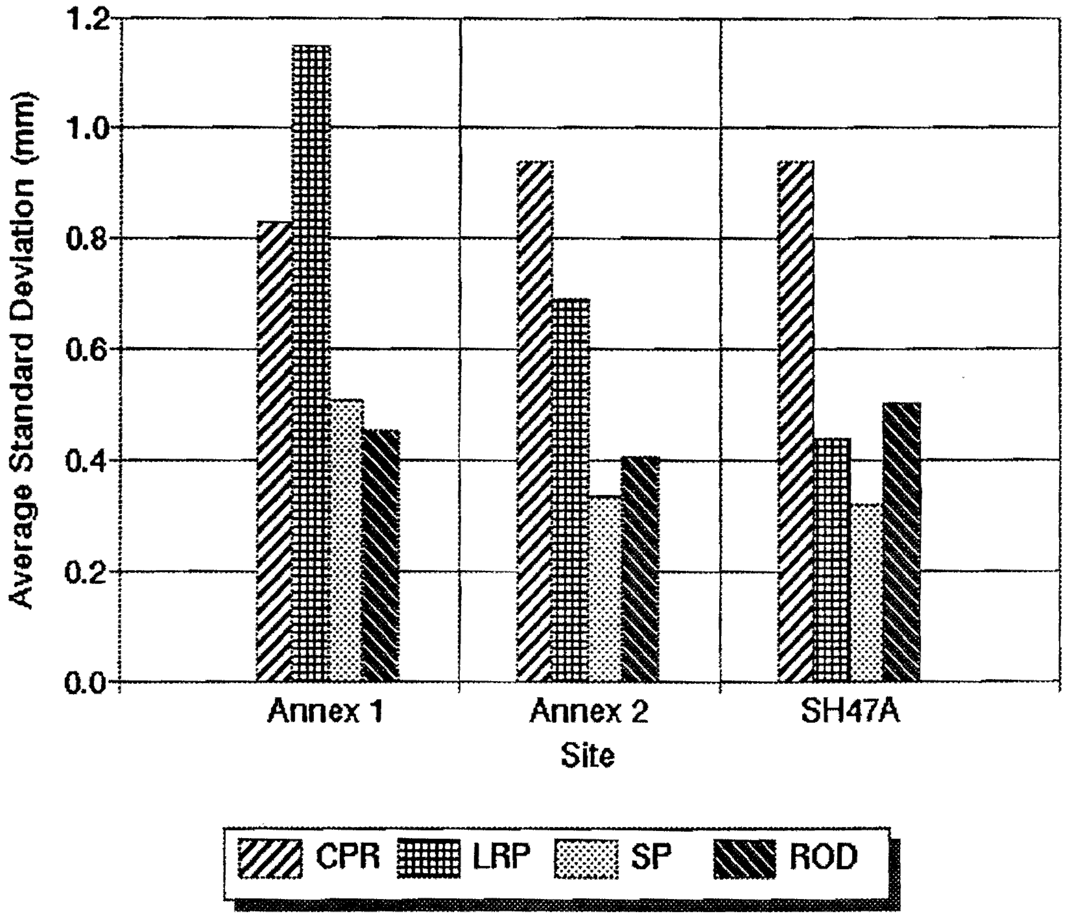

Figure 14. Average Standard Deviations of Profiles from CPR, LRP, and SP Compared to Rod & Level.

Table 5. Averages of the Standard Deviations of Original Profiles vs Rod and Level Data.

Profiler	Site	Average Standard Deviation (mm)	
		Profiler	Rod and Level[1]
CSC	Annex 1	8.1339	1.1668
	Annex 2	9.6013	0.7979
	SH47A	3.9057	1.1332
WPR	Annex 1	0.7729	1.1668
	Annex 2	1.6123	0.7979
	SH47A	1.2311	1.1332
LISA	Annex 1	1.4962	0.3601
	Annex 2	1.0068	0.3028
	SH47A	0.8027	0.4097
K. J. Law	Annex 1	3.4940	0.3826
	Annex 2	5.1029	0.3477
	SH47A	1.7704	0.4361
CPR	Annex 1	0.8263	0.3998
	Annex 2	0.9357	0.3676
	SH47A	0.9358	0.4552
LRP	Annex 1	1.1474	0.3995
	Annex 2	0.6873	0.3648
	SH47A	0.4368	0.4518
SP	Annex 1	0.5071	0.3995
	Annex 2	0.3316	0.3648
	SH47A	0.3183	0.4518

[1] Data taken on left wheelpaths of Annex 1, Annex 2, and SH47A over a 175.6 m interval.

profiles were reflected to simulate the lead-in during filtering. This was done because no rod and level data were collected prior to the beginning of each test site.

An attempt was made to evaluate the significance of the lead-in using the rod and level data collected at the different sites. In this evaluation, a selected interval of the profile for a given site was removed to simulate the absence of lead-in data. Researchers then filtered the modified profile and compared the results with those obtained when the filter is applied to the original data. Appendix B presents the results from this evaluation. With respect to repeatability of the filtered profiles based on the original and modified data, the averages of the standard deviations of repeat measurements were found to be very similar. This finding indicates that reflecting the rod and level profiles to simulate the lead-in during filtering is acceptable with respect to evaluating the repeatability of repeat measurements from a given inertial profiler. This is logical since repeatability is a function of the variability in repeat measurements.

Table 5 presents the average standard deviations based on filtering the original rod and level data measured at the different sites. Note that the statistics computed from the rod and level profiles vary because of differences in filters among the profilers tested as given in Table 3. To evaluate the repeatability of the CSC and WPR profilers relative to the rod and level data, no filtering of the rod and level data was necessary since the profiles from the CSC and WPR are unfiltered.

By comparing the average standard deviations of measured elevations with the corresponding statistics from the rod and level data, the repeatability of the different profilers may be assessed. The results from the analysis prompt the following observations:

1. Of the two devices that measure and integrate differential elevations to estimate the true surface profile, the Walking Profiler showed better repeatability relative to the rod and level data than the CSC profiler. This is evident when one compares the profiles measured with the CSC (Figures A4 to A9 in Appendix A) with the profiles from the Walking Profiler (Figures A10 to A15). It is observed from Table 5 that, on Annex 1, the average standard deviation of repeat measurements from the Walking Profiler is lower than the

corresponding statistic computed from rod and level data. On Annex 2, the average standard deviation is about twice that of the rod and level, while on SH47A, the computed statistics are quite comparable.

2. Among the lightweight profilers, the data from the T6400 were not as repeatable as the profiles from the Michigan LISA and TxDOT's Construction Profiler. Figures A16 to A19 illustrate the repeat measurements from the T6400. As may be observed, the repeatability of the profiles from this device is not good on the rough site (Annex 1). On the medium-smooth site (Annex 2), the profiles show good repeatability for the first 60 m. Thereafter, the repeatability drops. The repeatability demonstrated by the T6400 is best on the smooth site (SH47A). These results indicate that the equipment is best used for measuring profiles only on new pavement construction or resurfacing projects which is what the developer recommends. Relative to the T6400, the LISA and the Construction Profiler demonstrated better repeatability for all the sites tested, as may be observed from Figures A20 to A25 for the LISA, and Figures A26 to A31 for the Construction Profiler.

3. Among the inertial profilers evaluated, the van-mounted profilers demonstrated the best repeatability as may be observed from Table 5. In particular, the average standard deviations of repeat measurements from the Texas Surface Profiler are very good relative to corresponding statistics computed from the rod and level data. On Annex 1, the average standard deviations associated with the Surface Profiler and the rod and level are very comparable. On Annex 2 and SH47A, the average standard deviations from the Surface Profiler are lower than the corresponding statistics from the rod and level. The original profiles from the Texas Surface Profiler are shown in Figures A32 to A39 while those from the Laser/Rut Profiler are shown in Figures A40 to A47.

Since the reporting interval differed between profilers as shown in Table 3, the profiles were also synchronized with respect to the rod and level to determine if the computed standard deviations are influenced in any way by the reporting interval. Through a process of interpolation and/or decimation, the profiles from all devices were synchronized such that the reporting interval is 152.4 mm, the distance between rod and level measurements. Table 6 shows the average standard deviations computed from the synchronized profiles. These statistics are compared with the corresponding values determined from the original profiles in Figure 15. The excellent agreement between the average standard deviations computed from original and synchronized profiles indicates that the repeatability is unaffected by differences in reporting interval between profilers so that the observations given previously still apply. Table 7 compares the average standard deviations computed from the synchronized profiles with the corresponding statistics from rod and level data.

INTERNATIONAL ROUGHNESS INDICES (IRIs) COMPUTED FROM PROFILES

The International Roughness Index (IRI) is a profile-based statistic that was initially established in a study sponsored by the World Bank (Sayers, Gillespie, and Queiroz, 1986; Sayers, Gillespie, and Paterson, 1986). Since its initial development, the IRI has gained worldwide acceptance as a statistic for measuring pavement smoothness. In the U.S., states are currently required to report the IRIs for highways included in the Highway Performance Monitoring System (HPMS) data base.

The calculation of IRIs from pavement profiles is discussed by Sayers (1995) and is included in an appendix to ASTM E 1364. In the IRI algorithm, the response of a quarter car model (Figure 16) to a measured pavement profile is simulated. This involves the solution of a set of first-order ordinary differential equations given by (Sayers, 1995):

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}h_{ps} \tag{1}$$

where the **x**, **A**, and **B** arrays are defined as follows:

$$\boldsymbol{x} = \left[\, z_s,\ \dot{z}_s,\ z_u,\ \dot{z}_u \,\right]^T \tag{2}$$

Table 6. Averages (in mm) of the Standard Deviations of Synchronized Profiles.

Profiler	Annex 1		Annex 2		SH47A		SH47B	
	LWP	RWP	LWP	RWP	LWP	RWP	LWP	RWP
CSC	8.1428		9.6096		3.9008	18.2421	4.6012	3.8023
WPR	0.7693		1.6094		1.2315	5.6814	0.3651	2.3074
LISA	1.4960		1.0069		0.8026	0.6710	1.0478	0.7247
K. J. Law	3.4925		5.1004		1.7693	0.8954		
CPR	0.7865		0.9293		0.9353	0.6577	1.1126	0.6482
LRP	1.1284	1.2201	0.6831	0.8005	0.4311	0.4504	0.3479	0.4109
SP	0.4649	0.5283	0.3077	0.3121	0.2996	0.2684	0.2964	0.2975

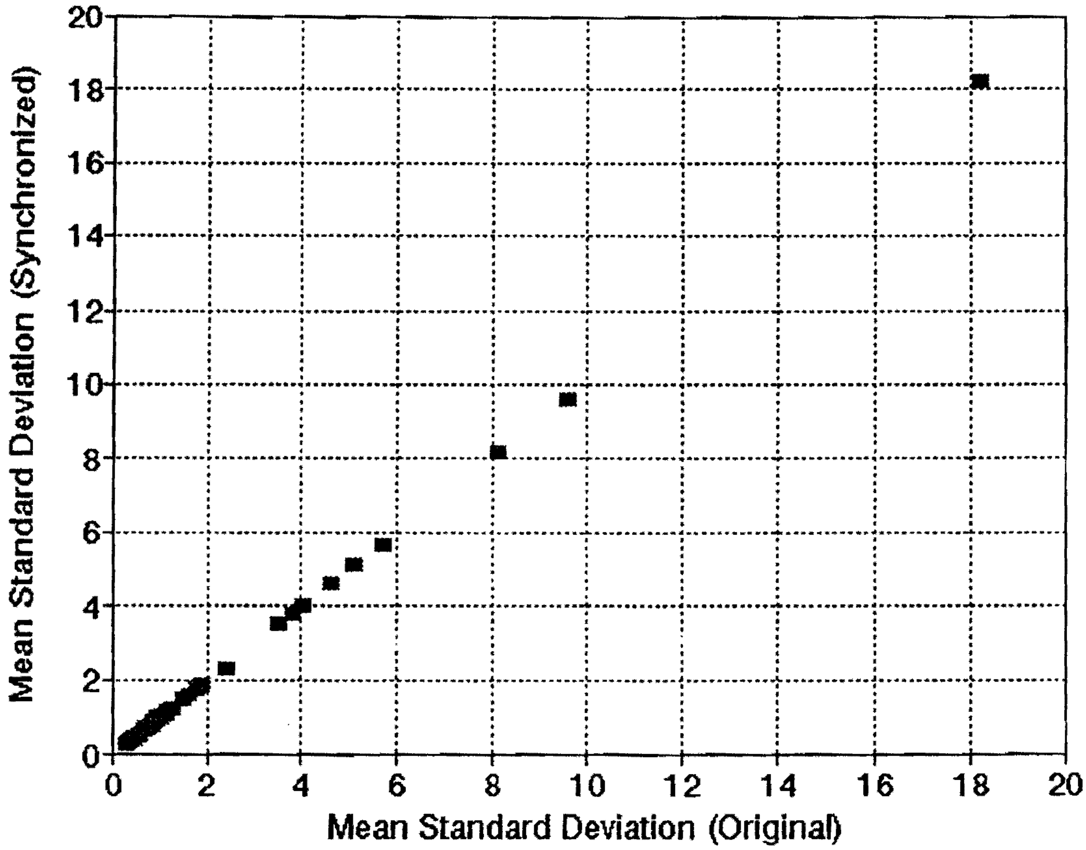

Figure 15. Average Standard Deviations from Original Profiles Compared to Corresponding Statistics from Synchronized Profiles.

Table 7. Averages of the Standard Deviations of Synchronized Profiles vs Rod & Level Data.

Profiler	Site	Average Standard Deviation (mm)	
		Profiler	Rod and Level[1]
CSC	Annex 1	8.1428	1.1906
	Annex 2	9.6100	0.8185
	SH47A	3.9008	1.1528
WPR	Annex 1	0.7693	1.1906
	Annex 2	1.6094	0.8185
	SH47A	1.2315	1.1528
LISA	Annex 1	1.4960	0.4445
	Annex 2	1.0069	0.0916
	SH47A	0.8026	0.5017
K. J. Law	Annex 1	3.4925	0.4346
	Annex 2	5.1004	0.3877
	SH47A	1.7693	0.4808
CPR	Annex 1	0.7865	0.4514
	Annex 2	0.9293	0.4049
	SH47A	0.9353	0.4998
LRP	Annex 1	1.1284	0.4514
	Annex 2	0.6831	0.4049
	SH47A	0.4311	0.4998
SP	Annex 1	0.4649	0.4514
	Annex 2	0.3077	0.4049
	SH47A	0.2996	0.4998

[1] Data taken on left wheelpaths of Annex 1, Annex 2, and SH47A sites over a 176 m interval.

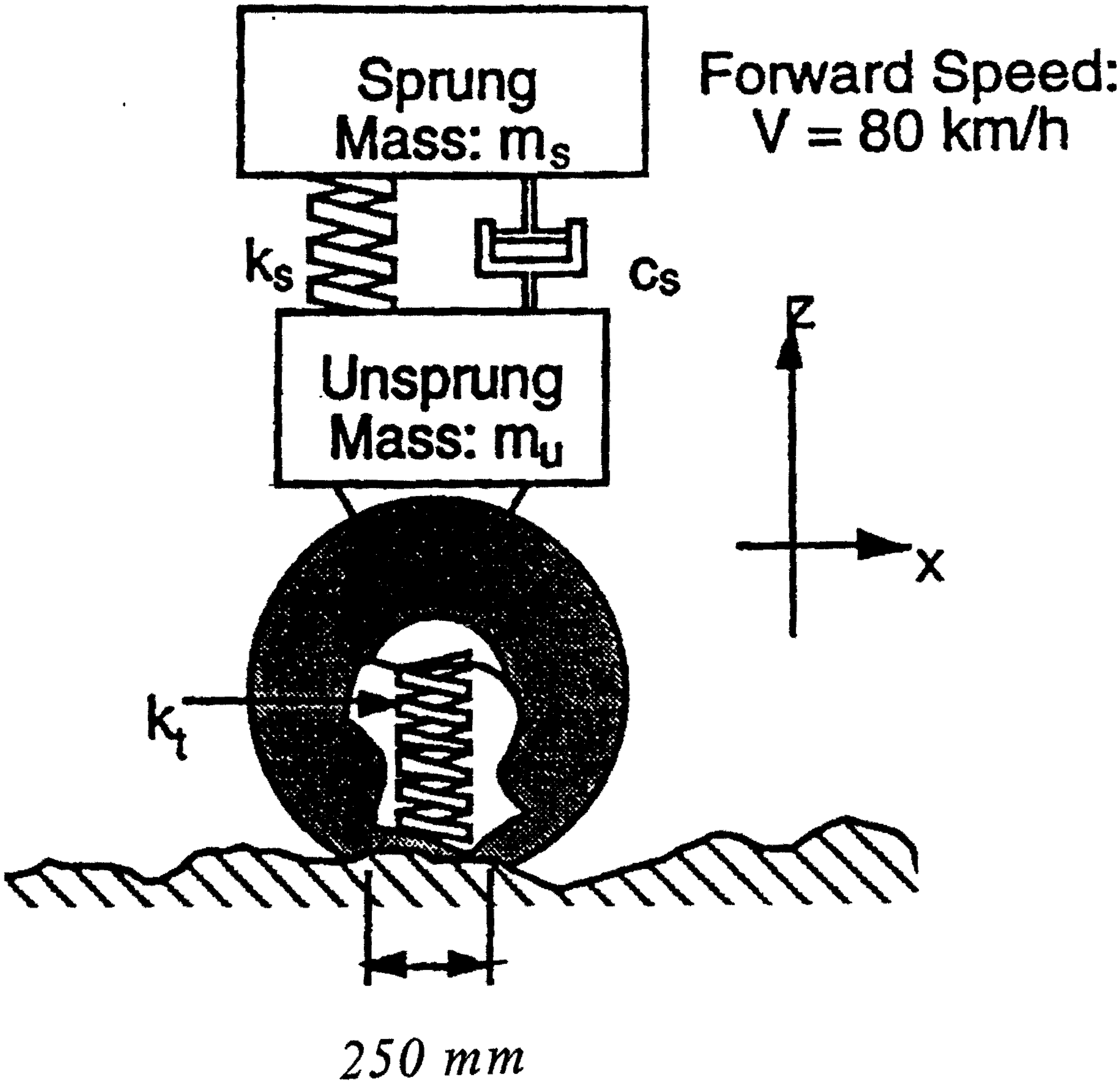

Figure 16. The Quarter Car Model (Sayers, 1995).

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -k_2 & -c & k_2 & c \\ 0 & 0 & 1 & 0 \\ \frac{k_2}{\mu} & \frac{c}{\mu} & -\frac{k_1 + k_2}{\mu} & -\frac{c}{\mu} \end{bmatrix} \tag{3}$$

$$B = \left[0,\ 0,\ 0,\ \frac{k_1}{\mu} \right]^T \tag{4}$$

and

h_{ps} = smoothed profile using a moving average filter with a base length of 250 mm

z_s = height of the sprung mass, m_s, in the quarter car model (Figure 16)

z_u = height of unsprung mass, m_u

In Eqs. (1) and (2), a dot over a given symbol denotes a time derivative. The coefficients in arrays, A and B, are normalized parameters of the quarter car model defined as:

$$c = \frac{c_s}{m_s} = 6.0 \ per \ \sec \tag{5}$$

$$k_1 = \frac{k_t}{m_s} = 653 \ per \ \sec^2 \tag{6}$$

$$k_2 = \frac{k_s}{m_s} = 63.3 \ per \ \sec^2 \tag{7}$$

$$\mu = \frac{m_u}{m_s} = 0.15 \qquad (8)$$

The IRI is an accumulation of the simulated motion between the sprung and unsprung masses in the quarter car model normalized by the length, L, of the profile (Sayers, 1995):

$$IRI = \frac{1}{L} \int_0^{L/V} |\dot{z}_s - \dot{z}_u| \, dt \qquad (9)$$

In the algorithm proposed by Sayers (1995), the set of differential equations given in Eq. (1) is redefined so that the input is the smoothed profile slope in lieu of the smoothed profile elevation. The IRI is then computed as the average of the absolute differences in filtered slope variables, s_s and s_u, determined from the quarter car simulation and associated with the sprung and unsprung masses, respectively. Thus,

$$IRI = \frac{1}{n} \sum_{i=1}^{n} |s_{s,\,i} - s_{u,\,i}| \qquad (10)$$

Appendix C presents tables of the computed IRIs from the profile measurements made on the test sections established in this study. The IRIs were calculated over a 0.16 km interval. Researchers compared the computed IRIs to corresponding values determined from the rod and level data. In this way, the profilers were also evaluated on the basis of a statistic that quantifies the surface smoothness of the test sections surveyed.

Since the reporting interval varied between profilers, researchers first established the influence of this variable on the computed IRIs. This was accomplished by comparing the IRIs from the original profiles with the corresponding IRIs determined from the synchronized profiles, i.e., those profiles with elevations calculated at 152.4 mm intervals corresponding to the distance between rod and level measurements. Figure 17 compares the statistics

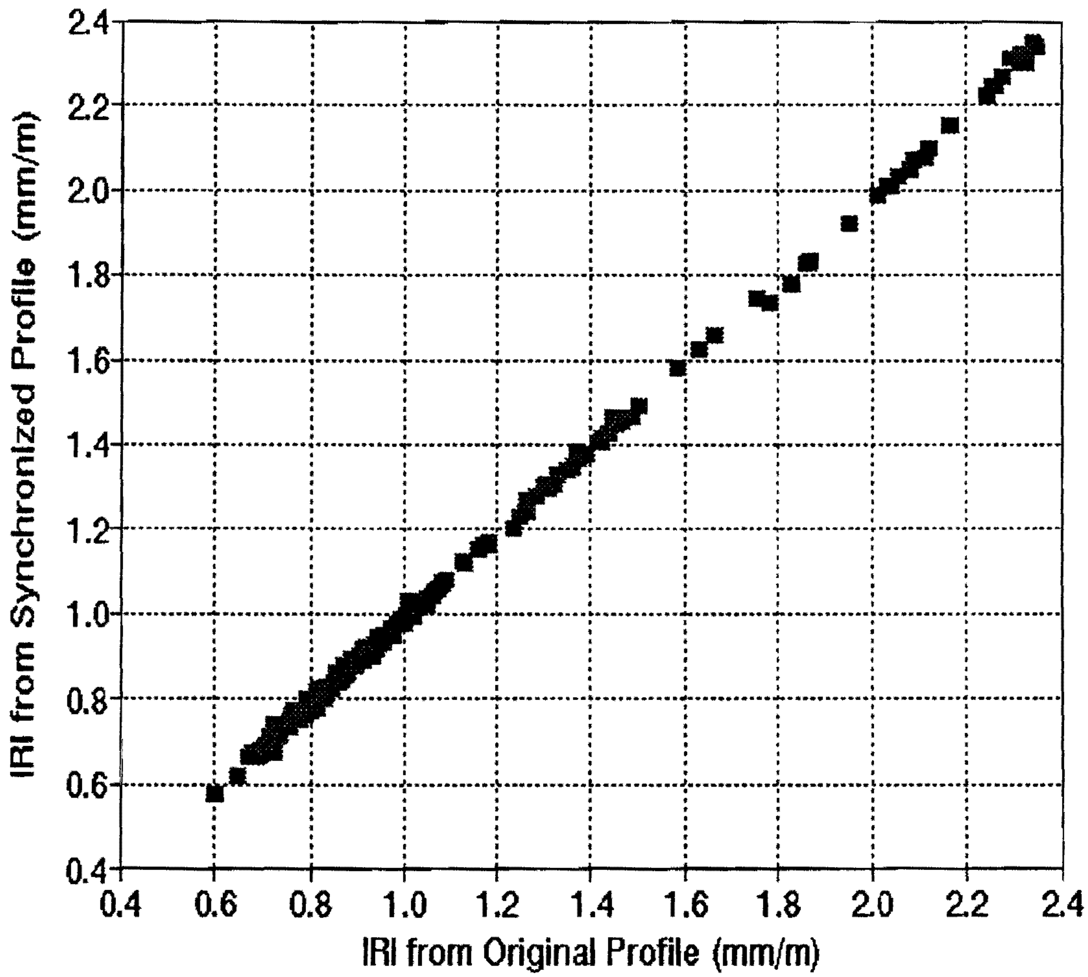

Figure 17. Comparison of IRIs from Original Profiles with IRIs from Synchronized Profiles.

determined from this evaluation. As may be observed, there is excellent agreement between the IRIs computed from original and synchronized profiles. The coefficient of determination, R^2, of the linear relationship between the statistics shown is 0.999 with a standard error of the estimate of 0.011 mm/m. In view of the high correlation between the IRIs from original and synchronized profiles, the comparisons given in the following are based on the IRIs from the original profiles.

Comparison of Computed IRIs

Figures 18 to 24 compare the IRIs from the different profilers with the corresponding IRIs from the rod and level. In evaluating the inertial profilers, researchers initially filtered the rod and level data according to the method used for a given profiler. In this process, the rod and level profiles were reflected to simulate the lead-in during filtering. Based on the results presented in Appendix B, this was found to be acceptable for evaluating the profilers on the basis of computed IRIs. The IRIs determined from the filtered data were thus compared to the corresponding IRIs from a given profiler. With respect to the CSC Digital Profilite and the Walking Profiler, the IRI algorithm was applied directly to the profiles from these devices and from the rod and level since all three methods provide unfiltered or true profiles.

Table 8 compares the average IRIs for the different test sections. To establish the accuracy of the profiler IRIs relative to the rod and level, the discrepancies between corresponding average IRIs are also given. The average of these discrepancies as well as any consistent trend in the discrepancies will indicate any bias in the computed IRIs from a given profiler. Negative values of the average discrepancy indicate a tendency to underestimate the rod and level IRIs. Conversely, positive values indicate a tendency to overestimate so that the closer the average discrepancy is to zero, the lesser the bias associated with a given profiler. The average discrepancies associated with the profilers are given in Table 8. In addition, the average of the absolute discrepancies is shown to gauge the overall accuracy of the profiler IRIs relative to the rod and level. The comparison of computed IRIs prompt the following observations:

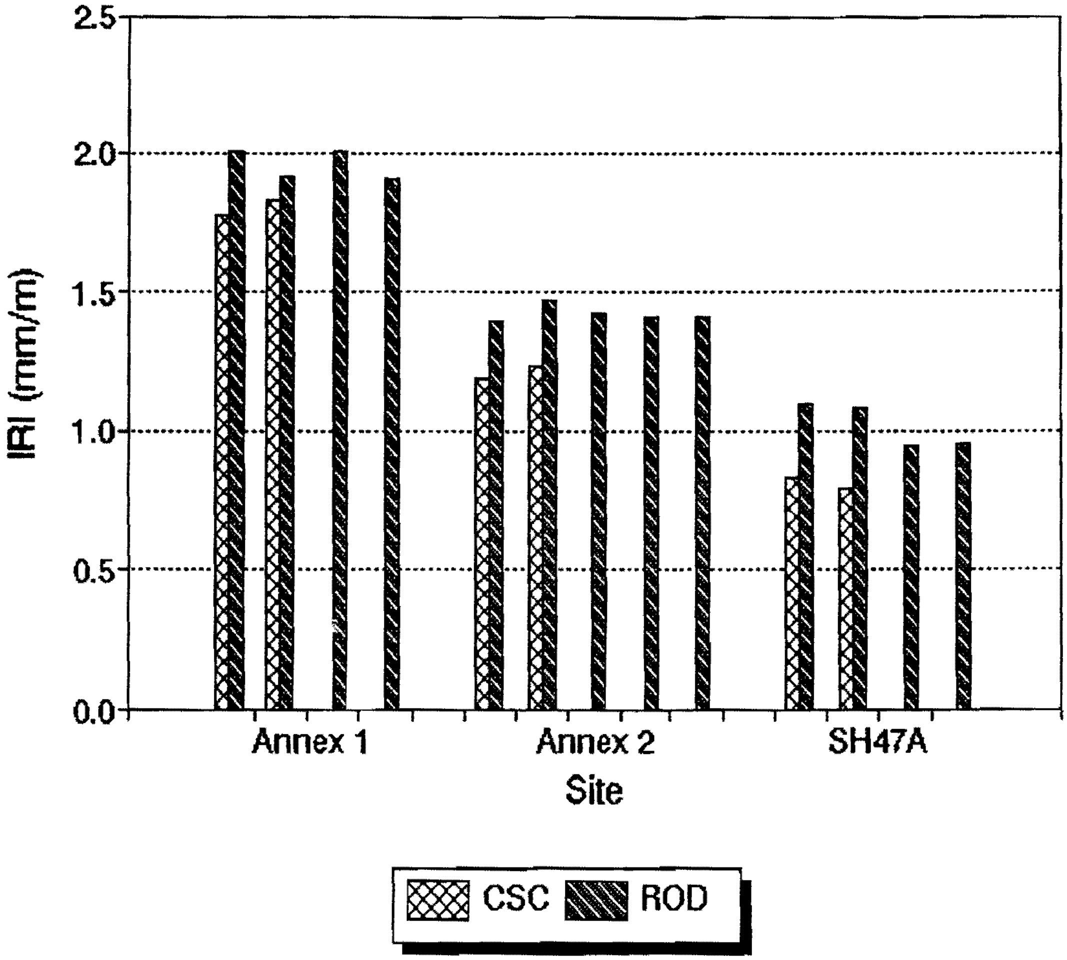

Figure 18. Comparison of IRIs from CSC and Rod & Level Profiles.

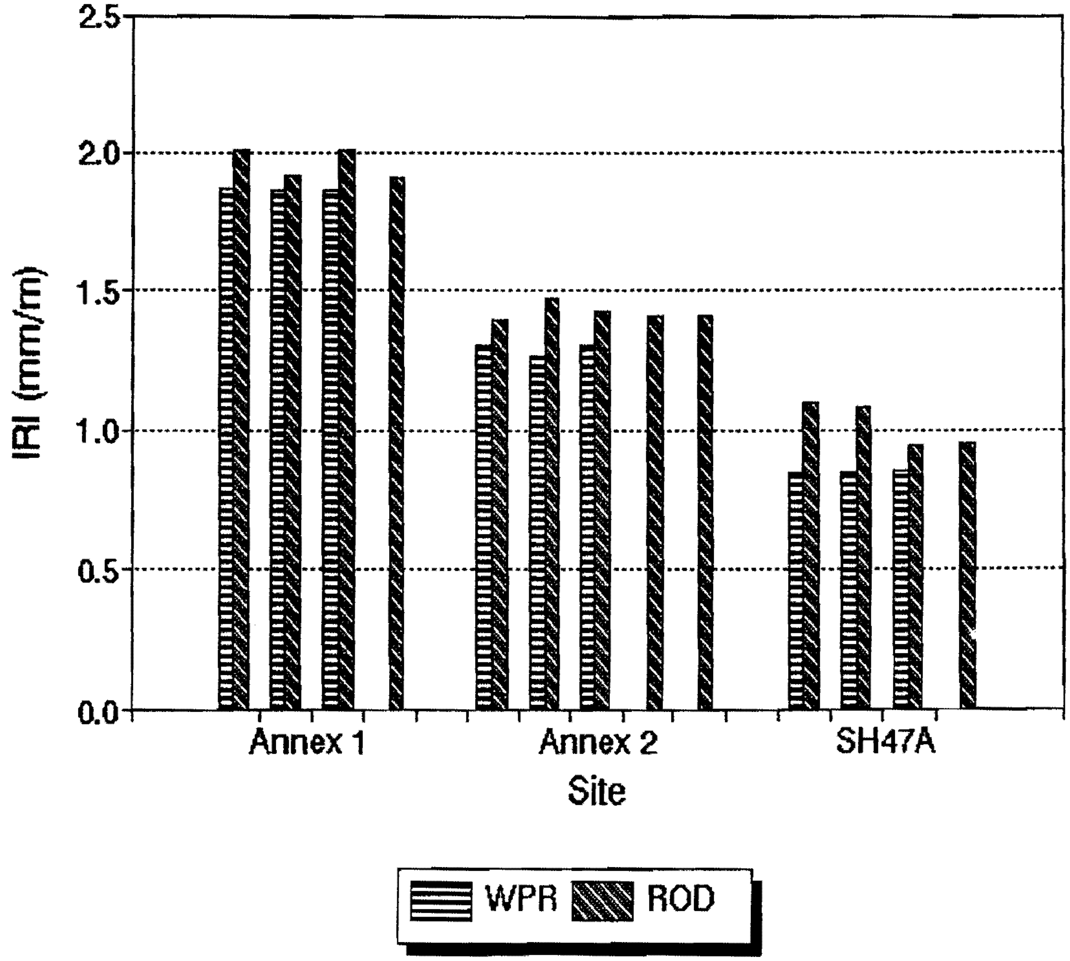

Figure 19. Comparison of IRIs from WPR and Rod & Level Profiles.

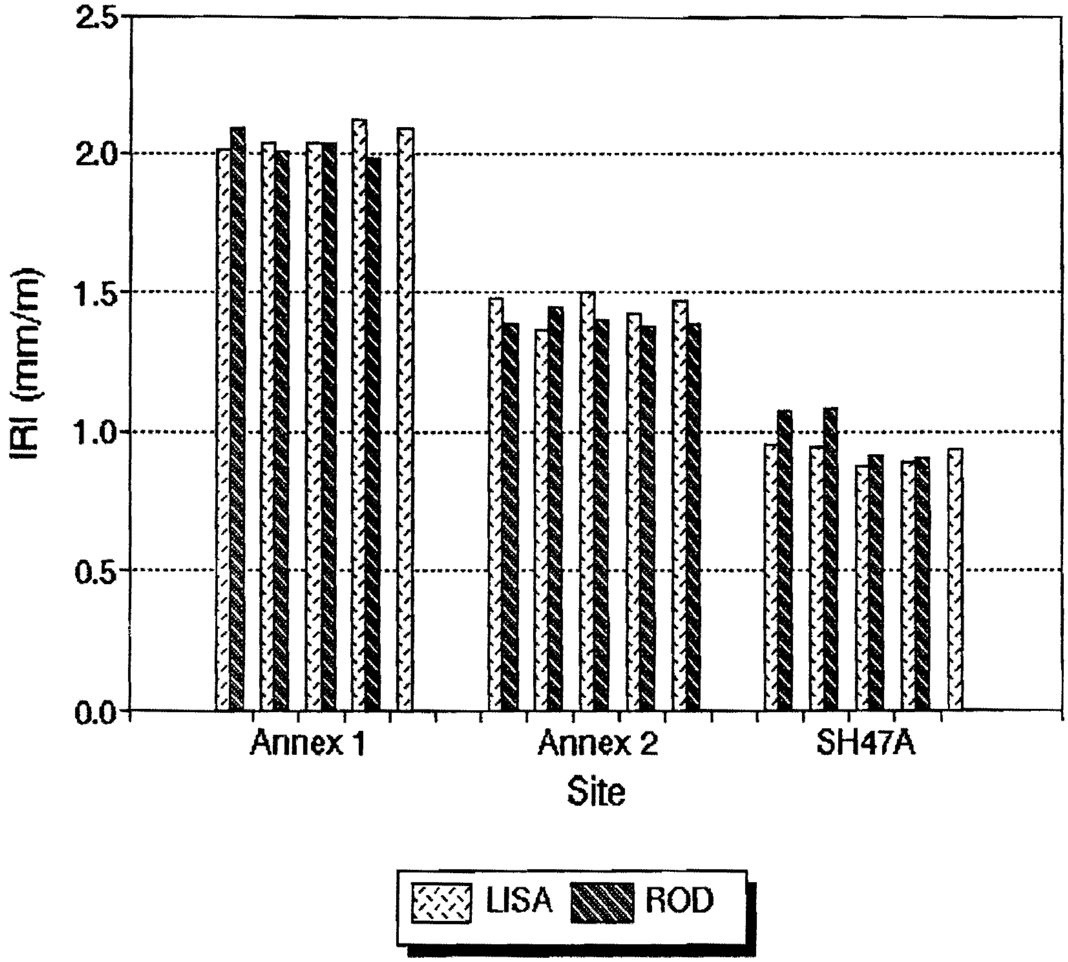

Figure 20. Comparison of IRIs from LISA and Rod & Level Profiles.

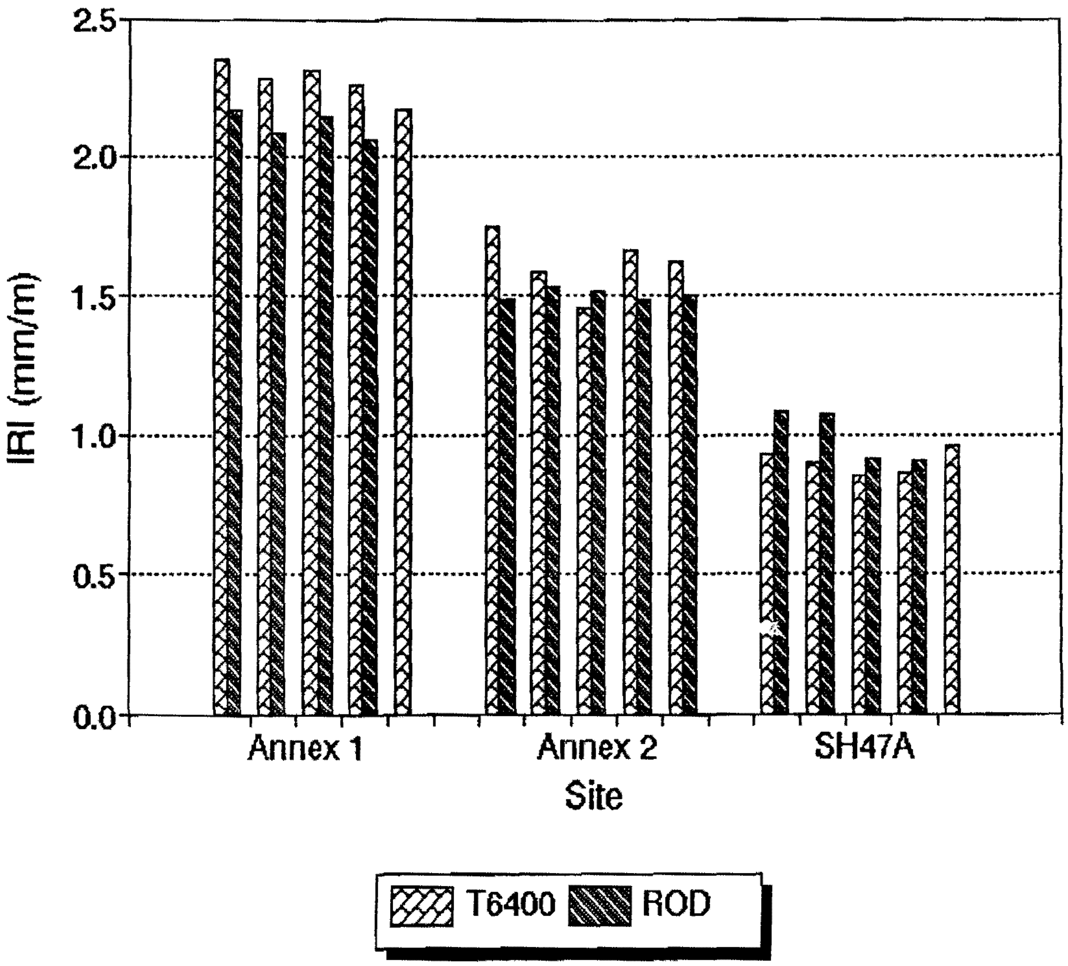

Figure 21. Comparison of IRIs from T6400 and Rod & Level Profiles.

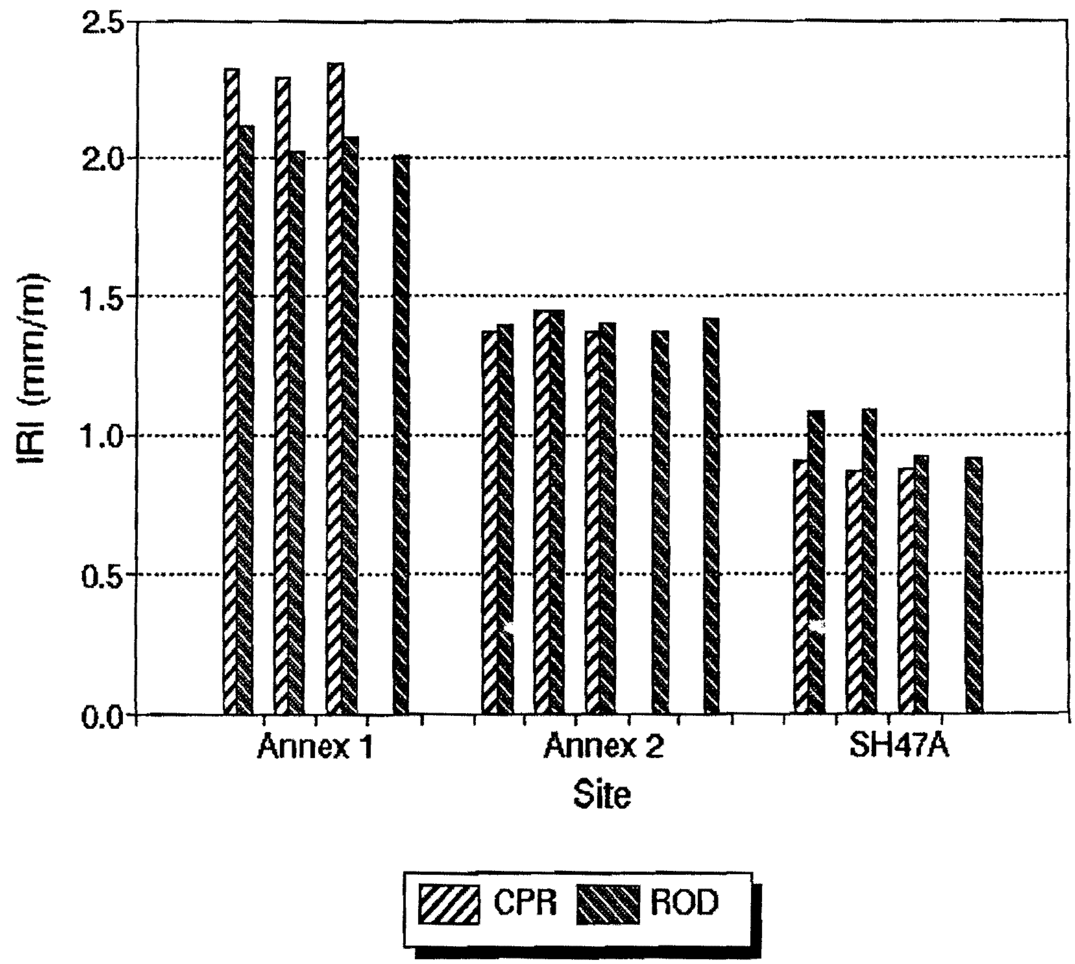

Figure 22. Comparison of IRIs from CPR and Rod & Level Profiles.

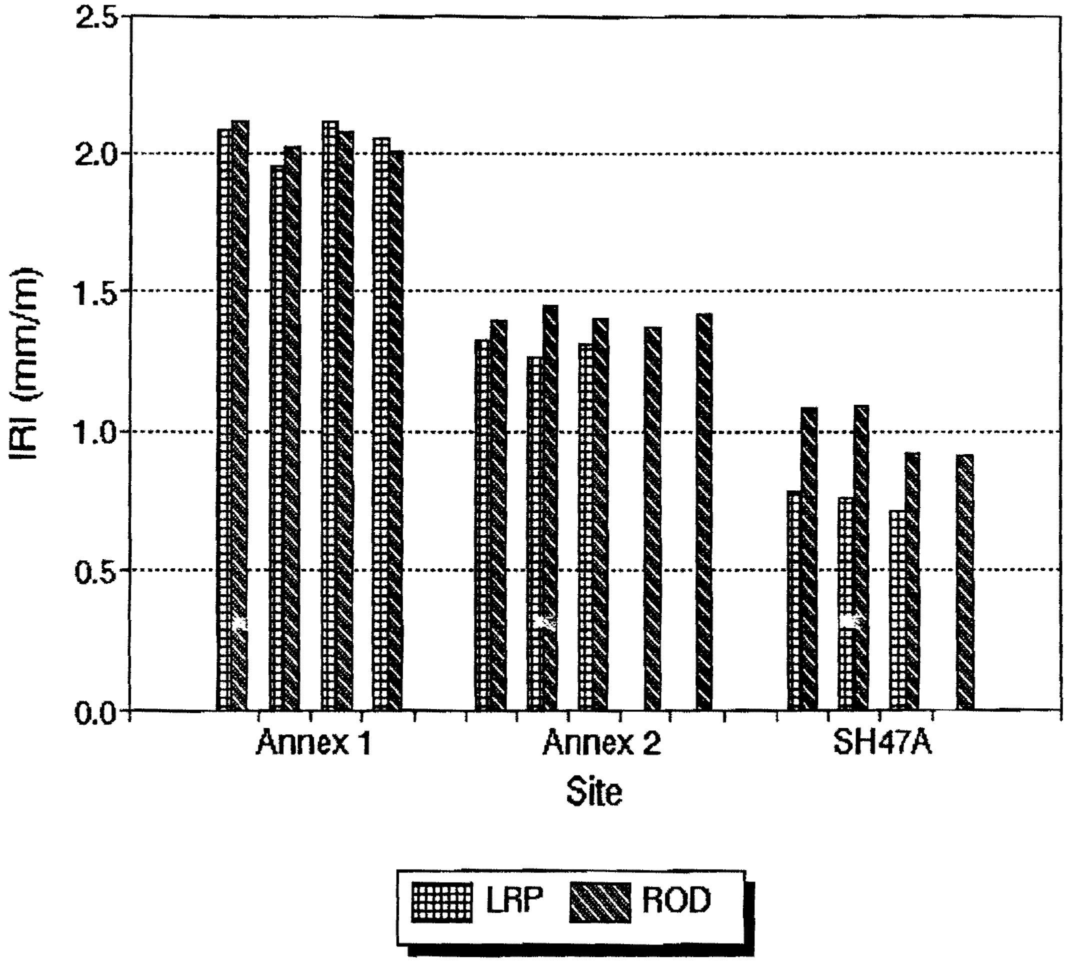

Figure 23. Comparison of IRIs from LRP and Rod & Level Profiles.

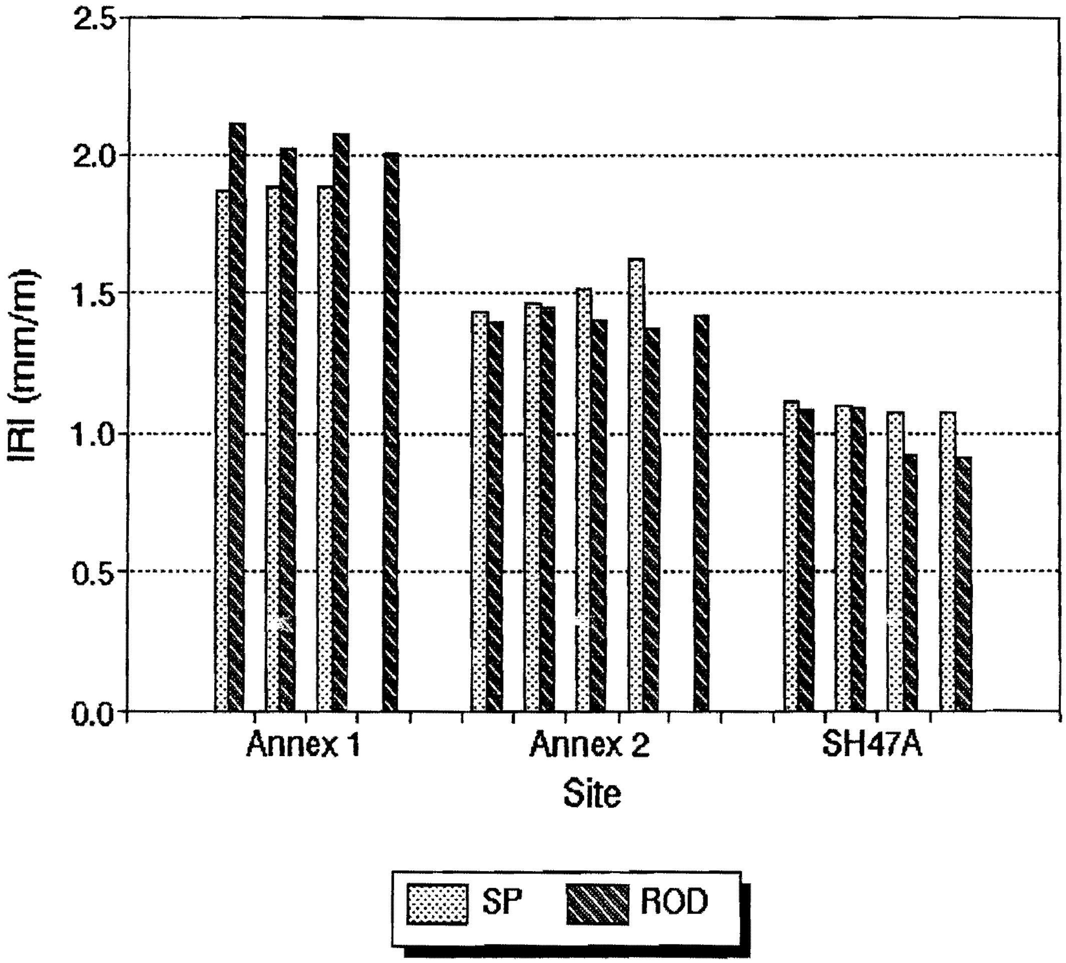

Figure 24. Comparison of IRIs from Surface Profiler and Rod & Level Profiles.

Table 8. Discrepancies in Computed IRIs from a Given Profiler and from the Rod & Level.

Profiler	Site	Average IRI (mm/m)		Discrepancy (mm/m)	Average Discrepancy (mm/m)	Average Absolute Discrepancy (mm/m)
		Profiler	Rod & Level			
CSC	Annex 1	1.804	1.957	-0.153	-0.191	0.191
	Annex 2	1.210	1.421	-0.211		
	SH47A	0.812	1.021	-0.209		
WPR	Annex 1	1.862	1.957	-0.095	-0.132	0.132
	Annex 2	1.290	1.421	-0.131		
	SH47A	0.850	1.021	-0.171		
LISA	Annex 1	2.060	2.027	0.032	0.001	0.051
	Annex 2	1.448	1.402	0.045		
	SH47A	0.921	0.996	-0.075		
T6400	Annex 1	2.273	2.112	0.161	0.059	0.122
	Annex 2	1.617	1.506	0.111		
	SH47A	0.900	0.996	-0.096		
CPR	Annex 1	2.317	2.054	0.263	0.046	0.129
	Annex 2	1.397	1.406	-0.009		
	SH47A	0.886	1.003	-0.117		
LRP	Annex 1	2.051	2.054	-0.003	-0.120	0.120
	Annex 2	1.298	1.406	-0.108		
	SH47A	0.755	1.003	-0.248		
SP	Annex 1	1.879	2.054	-0.176	0.006	0.122
	Annex 2	1.510	1.406	0.103		
	SH47A	1.091	1.003	0.088		

1. The average IRIs from the CSC and WPR underestimate the corresponding statistics from the rod and level. This is reflected not only in the data presented in Table 8 but also in Figures 18 and 19 which show that the IRIs from replicate runs of the CSC and WPR are consistently lower than the rod and level IRIs. Of the two devices, the Walking Profiler showed less bias and better accuracy than the CSC Digital Profilite. The magnitude of the average discrepancy and the average absolute discrepancy associated with the Walking Profiler are lower than those associated with the CSC profiler.
2. Among the lightweight profilers, the average discrepancy between IRIs is closest to zero for the LISA indicating that it showed the least bias relative to the rod and level IRIs. In addition, the average absolute discrepancy is smallest for the LISA indicating greater accuracy in the computed IRIs compared to the T6400 and the Construction Profiler (CPR) which showed about the same level of bias and accuracy.
3. Of the van-mounted inertial profilers, the LRP exhibited a tendency to underestimate the rod and level IRIs as indicated in the negative discrepancies between IRIs for this profiler. The data in Table 8 and Figure 23 show that the rod and level IRIs are particularly underestimated for the smooth section (SH47A). The Surface Profiler (SP) showed significantly less bias compared to the LRP. Its average discrepancy of 0.006 mm/m is closer to zero than the corresponding average of -0.120 mm/m for the LRP. However, the averages of the absolute discrepancies for the two profilers are very comparable indicating similar levels of accuracy in the computed IRIs from the two devices.

In addition to the above comparisons, researchers evaluated the correlation between the computed IRIs from a given profiler and the corresponding IRIs from the rod and level. This was accomplished using the IRIs computed from replicate profile measurements that are illustrated in Figures 18 to 24. If the IRIs from a given profiler are highly correlated with the IRIs from the rod and level, any bias in the IRIs may be rectified by calibration using the relationship determined between the computed IRIs. Thus, the correlations between IRIs were also evaluated. Table 9 shows the coefficient of determination, R^2, of the linear relationship determined between computed IRIs from a given profiler and the corresponding IRIs from the rod and level. The R^2 statistic ranges from 0 to 1. The closer this statistic is to unity, the better the correlation between two variables. The results summarized in Table 9 show that the IRIs from all profilers are highly correlated with the IRIs from the rod and level.

It is observed that the lowest R^2 is associated with the Surface Profiler. In evaluating the correlation between IRIs from a given profiler and the rod and level, a straight line relationship was assumed. Examination of the relationship between the computed IRIs from the Surface Profiler and the rod and level reveals a curvature or quadratic component as may be observed from Figure 25. This component was not considered in the determination of the relationship between these variables which may explain why a lower R^2 was obtained in comparison to the coefficients of determination determined for the other profilers.

Table 9 also shows the standard error of the estimate (SEE) associated with the linear relationship between the IRIs from a given profiler and the corresponding IRIs from the rod and level. The SEE is the root-mean-square error of the deviations about the fitted line. The lower this statistic, the better the accuracy in the linear relationship between two variables. The standard errors of the estimate given in Table 9 are fairly comparable between the different profilers investigated.

The observations presented suggest the need for periodic evaluations of pavement profilers when implementing a smoothness specification based on pavement profile. These evaluations are needed to verify that the profilers used for construction quality control and assurance yield acceptable data with respect to an established standard or reference. Recommendations to ensure that accurate, precise, uniform, and comparable profile measurements are obtained during construction are offered later in this report.

Table 9. Correlation Between Original IRIs from Profilers and from Rod & Level.

Profiler	R^2	SEE (mm/m)
CSC Digital Profilite	0.988	0.054
Walking Profiler	0.978	0.070
LISA	0.967	0.088
K. J. Law T6400	0.973	0.101
Construction Profiler	0.988	0.072
Laser/Rut Profiler	0.985	0.074
Surface Profiler	0.927	0.094

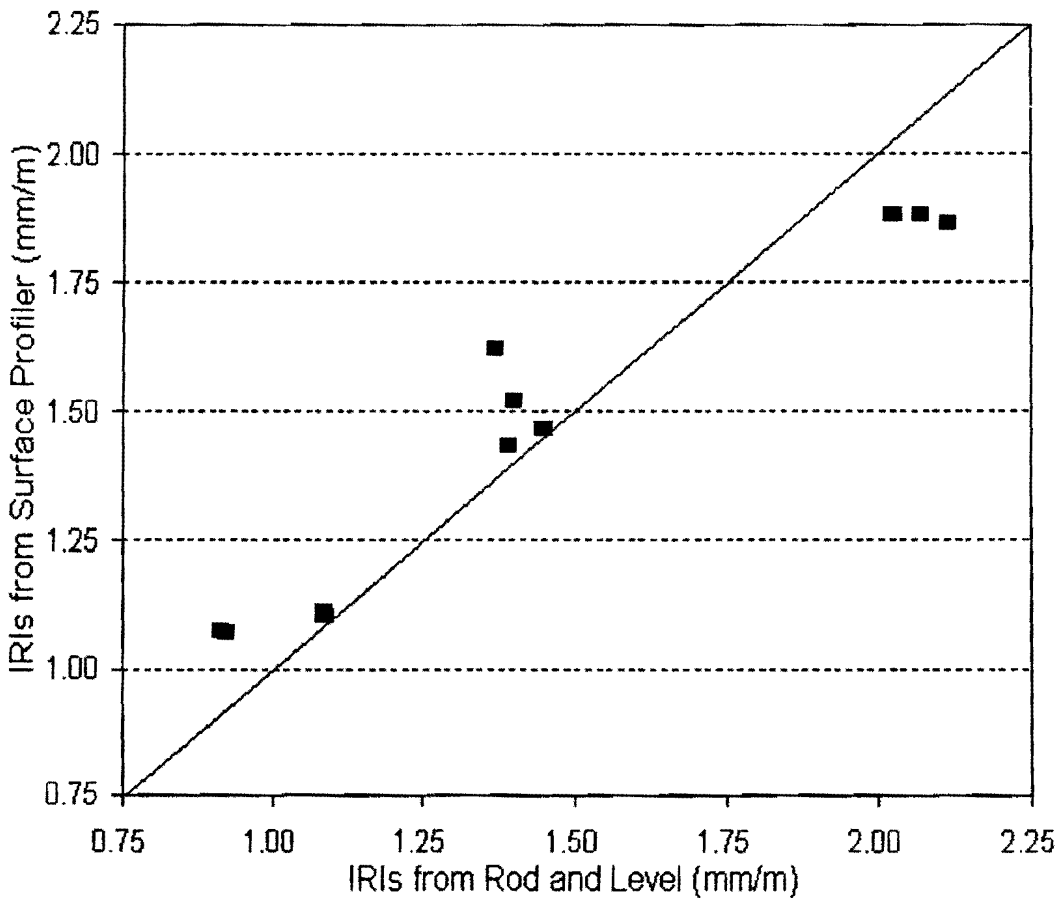

Figure 25. Relationship Between IRIs from Surface Profiler and IRIs from Rod & Level.

Repeatability of Computed IRIs

Table 10 presents the standard deviations of the computed IRIs from the profiles collected on the sites surveyed. Note that the statistics corresponding to the rod and level profiles vary because of differences between filters among the different profilers evaluated as given in Table 3. In the majority of cases, the standard deviations of the IRIs from the profilers tested are smaller than the corresponding standard deviations from rod and level data. Thus, while the repeatability of profiles from a given profiler may not be as good compared to the repeatability of rod and level profiles, the repeatability of computed IRIs is a different matter altogether. The repeatability of profiles is related to the point-to-point variability in the measured elevations. In contrast, the repeatability of IRIs is related to the variability in a summary statistic computed from measured profiles. These two measures of repeatability are not the same. The former is based on measured elevations while the latter is based on computed slope variables from the profile that also undergoes filtering during computation of the IRI statistic. In fact, the profile is filtered twice in the IRI algorithm – once, when it is smoothed using a moving average filter and the other during the quarter car simulation. Consequently, the results suggest the importance of evaluating a given profiler not merely on the basis of the profiles measured from it but also on the basis of its intended application. If this application requires the determination of a statistic from the measured profiles, then the profiler should also be evaluated on the basis of this statistic.

ACCURACY OF PROFILE MEASUREMENTS

In evaluating the accuracy of data from the different profilers relative to the rod and level profiles, two factors that limit this evaluation are noted.

1. The reporting interval varied between profilers as shown in Table 3.
2. There are no rod and level data on the lead-in for each site to evaluate the accuracy of data from the inertial profilers.

Because of differences in reporting intervals, an evaluation of profile accuracy can only be made by synchronizing the profiles so that elevations are reported at the same intervals. This

Table 10. Standard Deviations of IRI's from Original Profiles and from Rod and Level.

Profiler	Site	Average Standard Deviation (mm/m)	
		Profiler	Rod and Level[1]
CSC	Annex 1	0.0332	0.0524
	Annex 2	0.0332	0.0301
	SH47A	0.0255	0.0841
WPR	Annex 1	0.0035	0.0524
	Annex 2	0.0234	0.0301
	SH47A	0.0070	0.0841
LISA	Annex 1	0.0448	0.0462
	Annex 2	0.0551	0.0270
	SH47A	0.0341	0.0953
K. J. Law	Annex 1	0.0693	0.0523
	Annex 2	0.1086	0.0208
	SH47A	0.0451	0.0944
CPR	Annex 1	0.0235	0.0482
	Annex 2	0.0450	0.0302
	SH47A	0.0232	0.0976
LRP	Annex 1	0.0698	0.0482
	Annex 2	0.0336	0.0302
	SH47A	0.0366	0.0976
SP	Annex 1	0.0093	0.0482
	Annex 2	0.0839	0.0302
	SH47A	0.0189	0.0976

[1] Data taken on left wheelpaths of Annex 1, Annex 2, and SH47A sites over a 176 m interval.

is accomplished by a process of interpolation and/or decimation. Profile accuracy is then evaluated by comparing the synchronized profiles with the rod and level data.

This evaluation requires that the synchronized profiles be highly accurate with respect to the original profiles. To evaluate the accuracy in the synchronized profiles, researchers compared interpolated rod and level data with the corresponding original profiles. This evaluation was accomplished by first subsampling the original data so that elevations are spaced at 304.8 mm intervals. Researchers then used an interpolation algorithm by Stearns and David (1993) to interpolate the elevation midway between each pair of measured elevations in the subsampled data file. The interpolated data were then compared to the original data (collected at 152.4 mm intervals) to establish the accuracy of the interpolation. Figures 26 to 31 show the original and interpolated rod and level profiles on Annex 1, Annex 2, and SH47A. Each figure shows the profiles from replicate rod and level measurements. The profiles from repeat runs overlap demonstrating the excellent repeatability of the rod and level data. It is also observed that the original and interpolated profiles on a given site are in excellent agreement. To quantify the accuracy of the interpolated profiles, researchers calculated the differences between the interpolated and measured elevations, point-by-point. The average of these differences was then computed for each site to get an indication of the bias in the interpolation. In addition, the average of the absolute differences was computed to estimate the overall accuracy of the interpolated data. Table 11 summarizes the statistics determined. The average discrepancy as well as the average of the absolute discrepancies between original and interpolated elevations are given for each replicate run as well as for the mean profiles. In this evaluation, the mean profiles were determined by averaging the elevations, point-by-point, for both the original and interpolated data. The statistics shown reflect the inaccuracies that result from the interpolation. The magnitudes of the average discrepancies are very small and are of the order of the resolution of the digital level (0.030 mm) used to collect the elevation data. The averages of the absolute discrepancies for the mean profiles are 0.33, 0.18, and 0.22 mm for Annex 1, Annex 2, and SH47A, respectively. These average absolute errors are also small further indicating that synchronizing the profiles to the reference will provide a very close representation of the original profile for the purpose

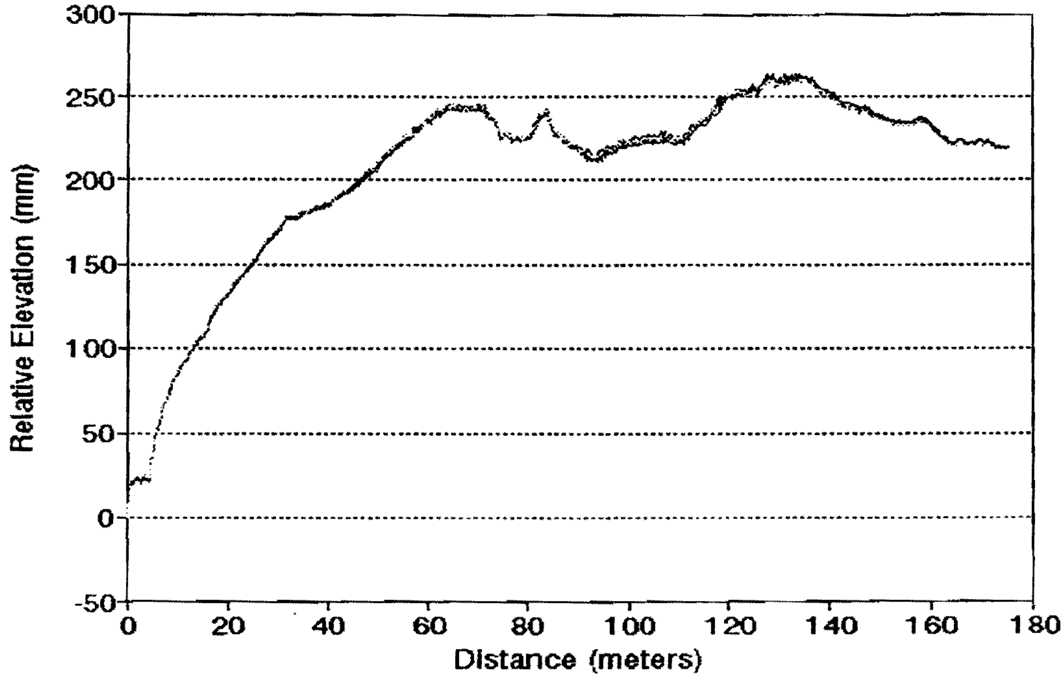

Figure 26. Original Rod & Level Profiles on Annex 1.

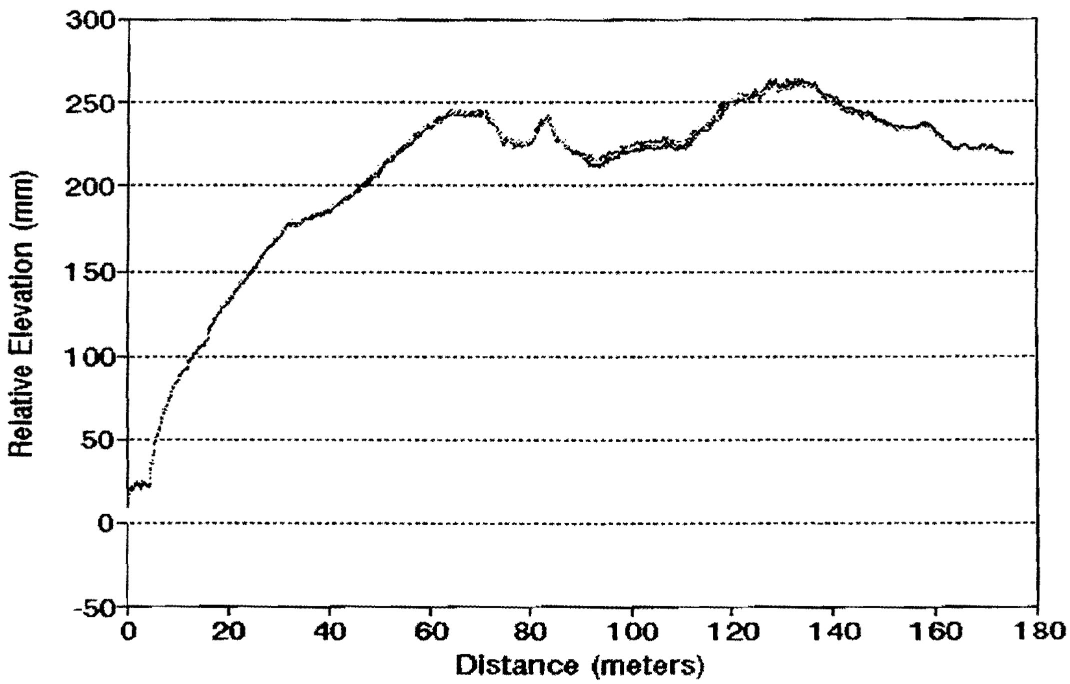

Figure 27. Interpolated Rod & Level Profiles on Annex 1.

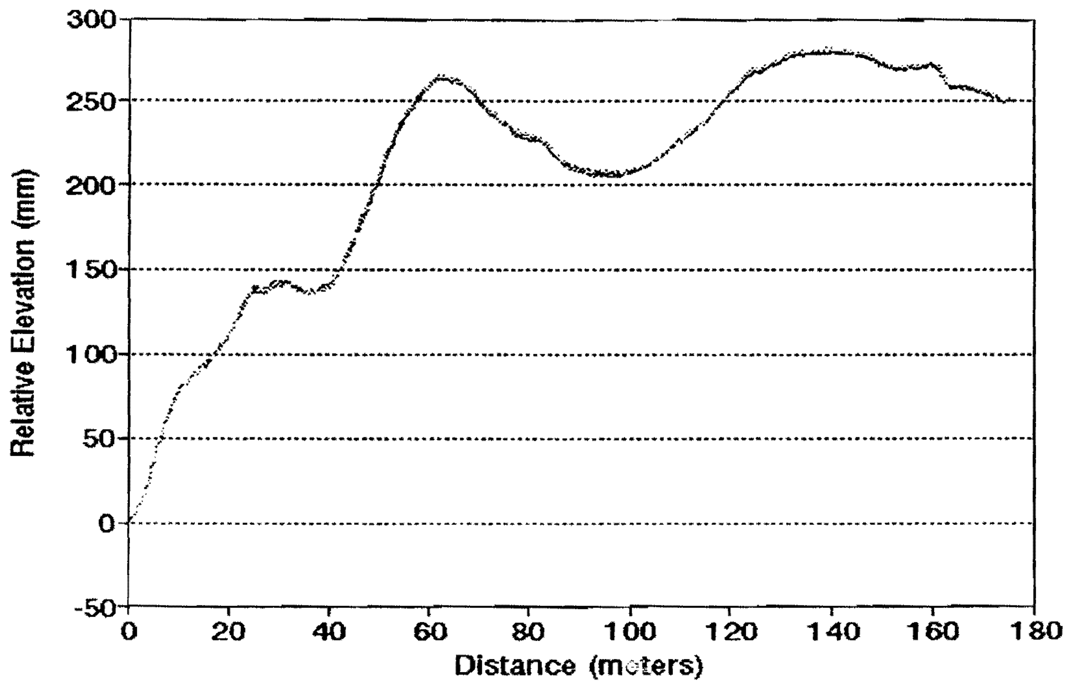

Figure 28. Original Rod & Level Profiles on Annex 2.

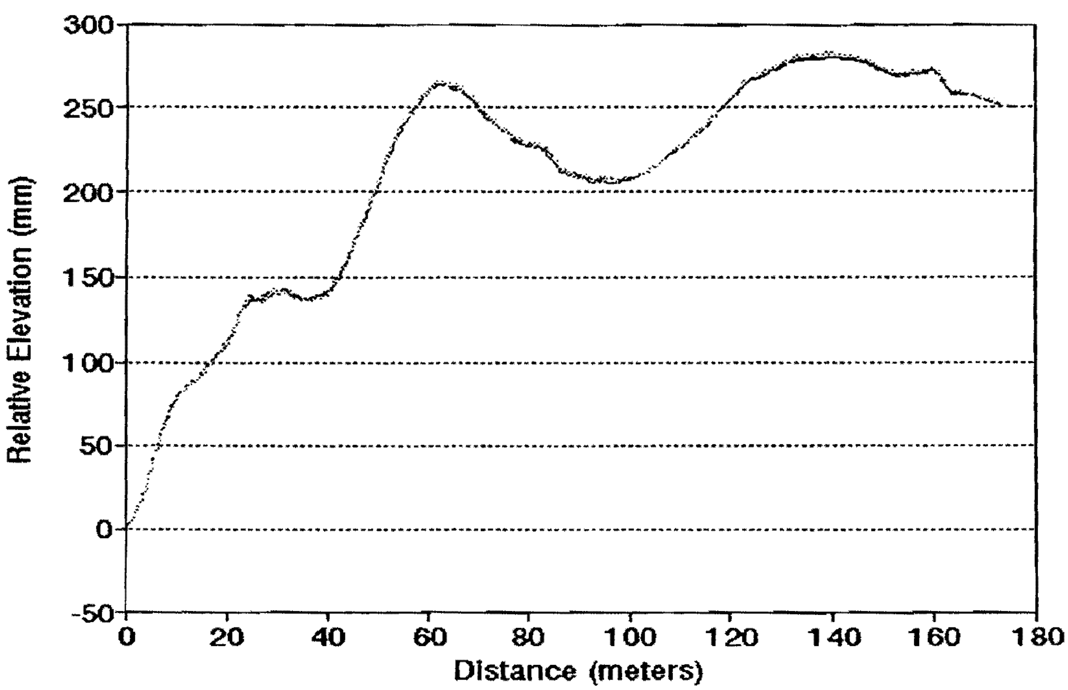

Figure 29. Interpolated Rod & Level Profiles on Annex 2.

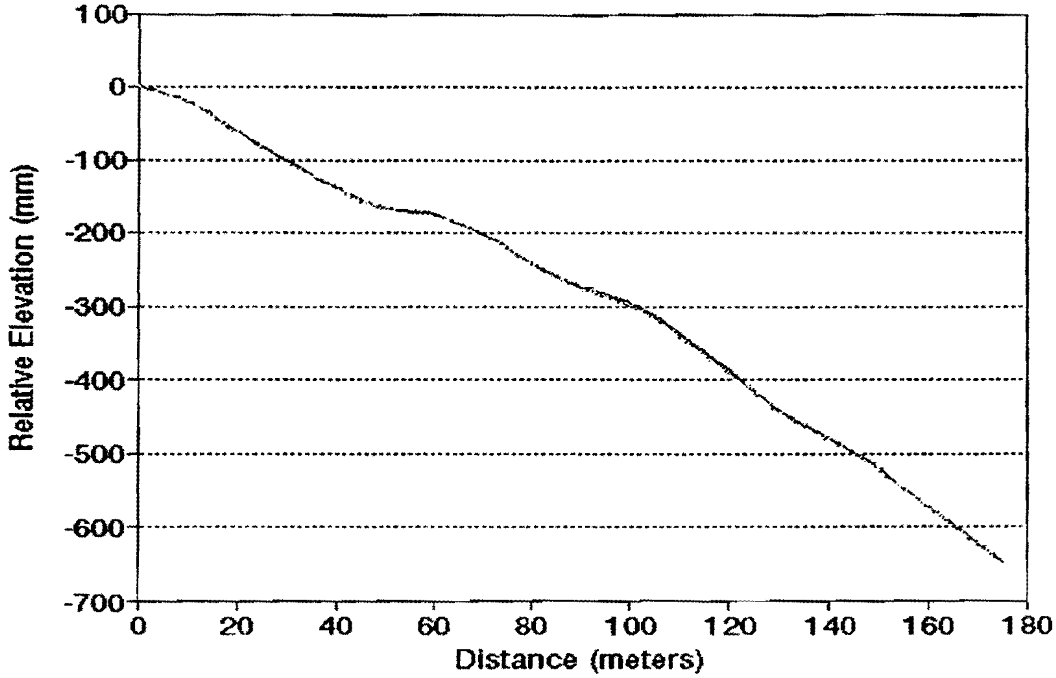

Figure 30. Original Rod & Level Profiles on SH47A (LWP, first 175.6 m).

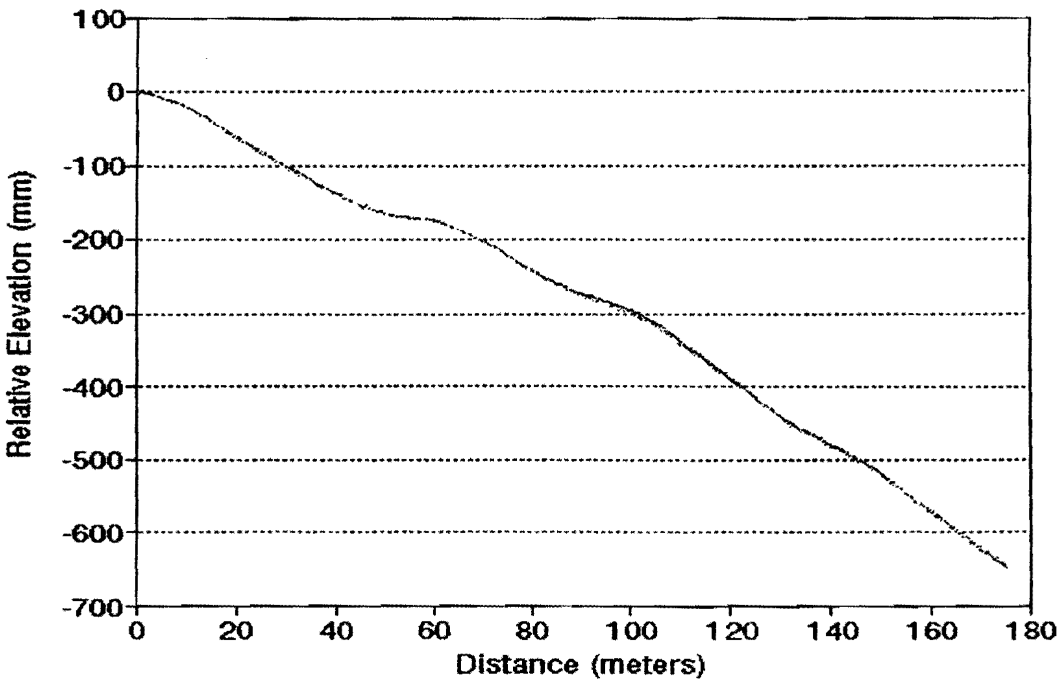

Figure 31. Interpolated Rod & Level Profiles on SH47A (LWP, first 175.6 m).

Table 11. Evaluation of the Accuracy of Interpolated Rod & Level Profiles.

Site	Run Number	Average Discrepancy (mm)	Average of Absolute Discrepancies (mm)
Annex 1	1	0.0503	0.5642
	2	0.0169	0.4115
	3	0.0254	0.4816
	4	0.0546	0.3862
	Mean Profile	0.0369	0.3322
Annex 2	1	0.0335	0.2981
	2	-0.0269	0.3261
	3	0.0039	0.3362
	4	-0.0363	0.3350
	5	0.0000	0.2938
	Mean Profile	-0.0052	0.1789
SH47A	1	0.0186	0.4328
	2	0.0044	0.4304
	3	0.0744	0.3459
	4	0.0671	0.2542
	Mean Profile	0.0411	0.2152

of evaluating point-to-point accuracy when reporting intervals vary between profiling methods.

Accuracy of CSC and WPR Profiles

The average absolute errors for the mean profiles in Table 11 may be used as benchmarks for establishing the accuracy of the unfiltered profiles from the CSC Digital Profilite and the Walking Profiler. Errors larger than those shown may be attributed to factors other than the interpolation done to synchronize the profiles. In connection with this, the average profiles on the different sites were computed based on the synchronized data from these devices. The point-to-point discrepancies between the average synchronized profile and the average rod and level profile on a given site were then computed. Table 12 summarizes the average discrepancy as well as the average of the absolute discrepancies determined for each site. Based on the statistics shown, it is concluded that the profiles from the Walking Profiler are more accurate relative to the rod and level data than the corresponding profiles from the CSC profiler. This may be observed in Figures 32 to 37 which compare the average synchronized profiles with the corresponding average rod and level profiles. Different y-axis scales are used in these figures to accentuate the differences between profiles from a given device and the corresponding rod and level profiles. Note that the roughness varies between test sites. There is a discernible bias in the profiles from these profilers as the discrepancies tend to get larger in magnitude with distance from the start of the measurements. The only exception is with the WPR data on Annex 2 which compare quite favorably with the rod and level data.

Table 12 shows that the average discrepancies computed from the synchronized WPR profiles are closer to zero than the corresponding statistics determined from the CSC profiles. This indicates that there is less bias in the WPR profiles compared to the CSC profiles, a finding that is also reflected in Figures 32 to 37. The averages of the absolute discrepancies are also significantly lower for the synchronized WPR profiles indicating better accuracy compared to the CSC profiles.

Table 12. Accuracy of Average Synchronized Profiles from the CSC and WPR.

Profiler	Site	Average Discrepancy (mm)	Average of Absolute Discrepancies (mm)
CSC	Annex 1	24.0694	24.0735
	Annex 2	-21.5753	21.5765
	SH47A	-39.1351	39.1351
WPR	Annex 1	6.4086	6.4184
	Annex 2	0.1316	0.6586
	SH47A	12.8118	12.8320

Figures 32 to 37 indicate that the average profiles from the CSC Digital Profilite and the Walking Profiler are highly correlated to the corresponding profiles from the rod and level. Both devices captured the shapes or trends in the rod and level data. However, in terms of matching the rod and level profiles, the figures also reveal that these devices lost track of the rod and level data, with the exception of the WPR profile on Annex 2 (Figure 36). Since the errors appear to be systematic, researchers investigated the potential improvement in accuracy if corrections are made using the rod and level elevation at the last point measured on each site. It is noted that the elevations were referred to the beginning location which was taken as the zero point for the profile measurements made with the CSC, WPR, and the rod and level. Consequently, to correct the profiles from the CSC and the WPR, the difference in the measured elevations at the last point, between the rod and level and the given profiler, was distributed to the other points on the wheelpath where data were taken. Figures 38 to 42 compare the corrected average profiles to the corresponding rod and level profiles. No correction was applied to the WPR profile on Annex 2 since the accuracy of the profile relative to the rod and level is quite acceptable.

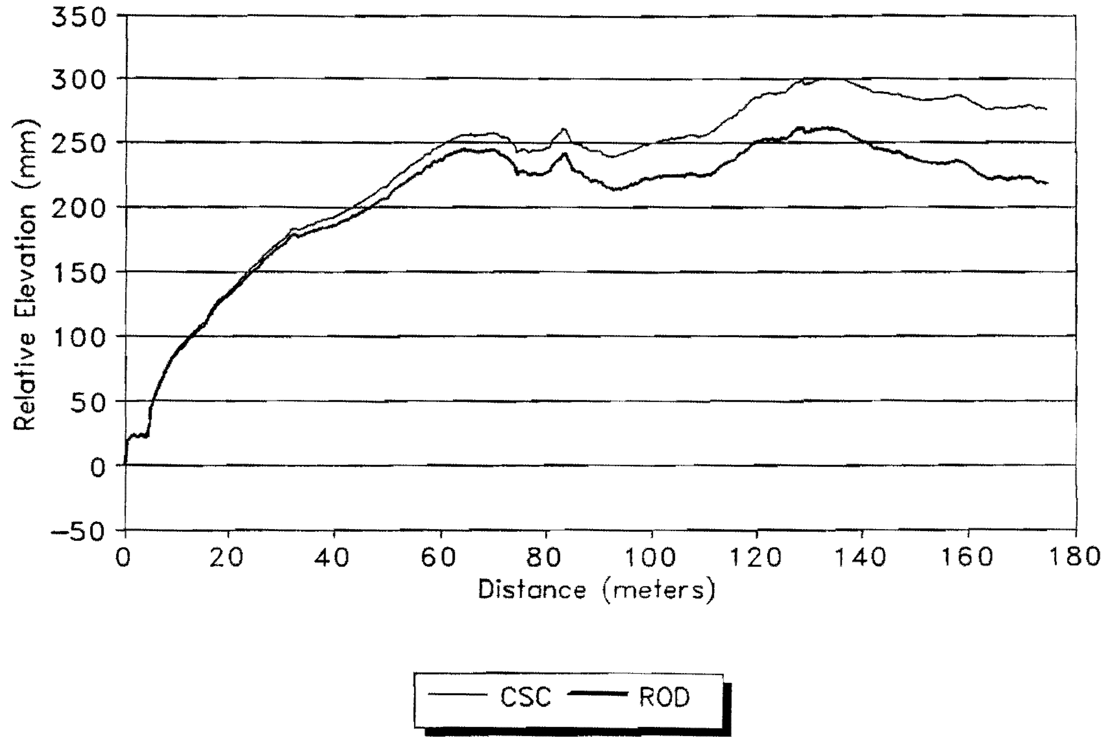

Figure 32. Average Synchronized CSC Profile vs Average Rod & Level Profile (Annex 1).

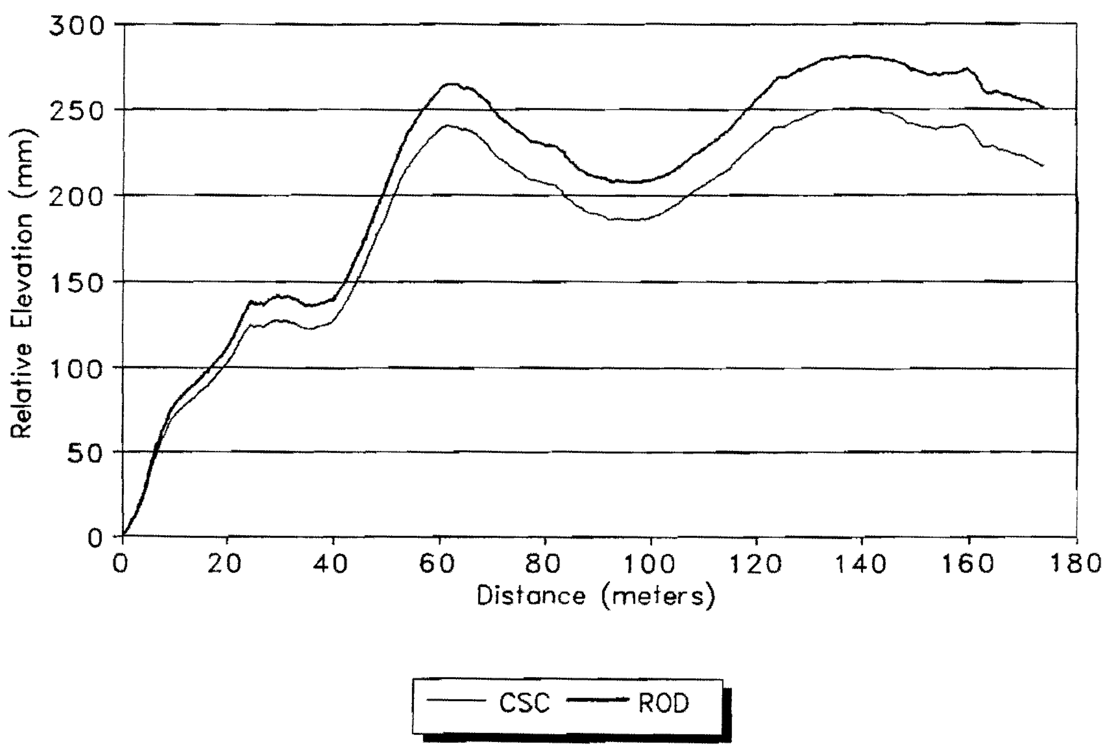

Figure 33. Average Synchronized CSC Profile vs Average Rod & Level Profile (Annex 2).

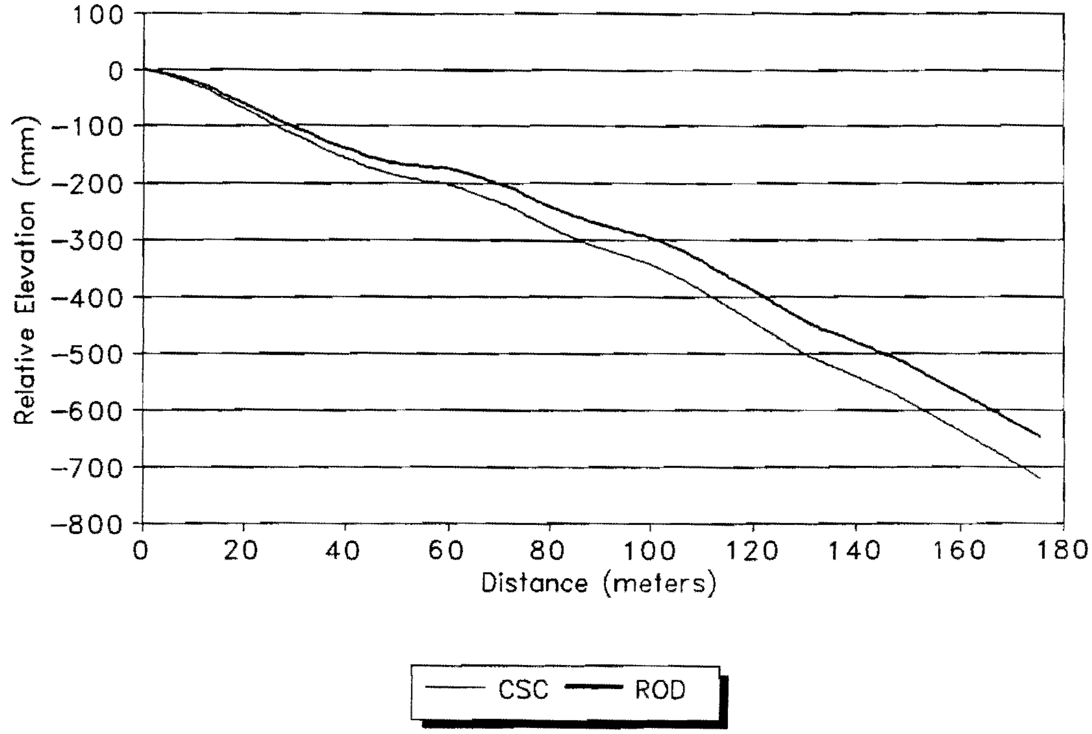

Figure 34. Average Synchronized CSC Profile vs Average Rod & Level Profile (SH47A).

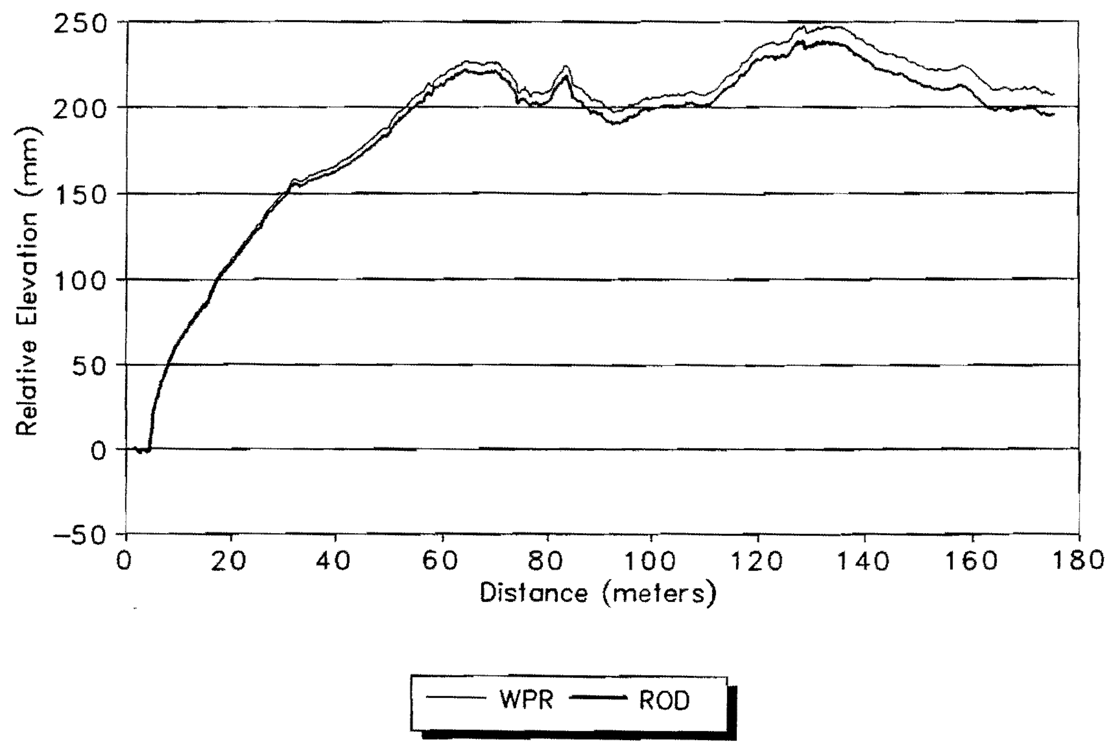

Figure 35. Average Synchronized WPR Profile vs Average Rod & Level Profile (Annex 1).

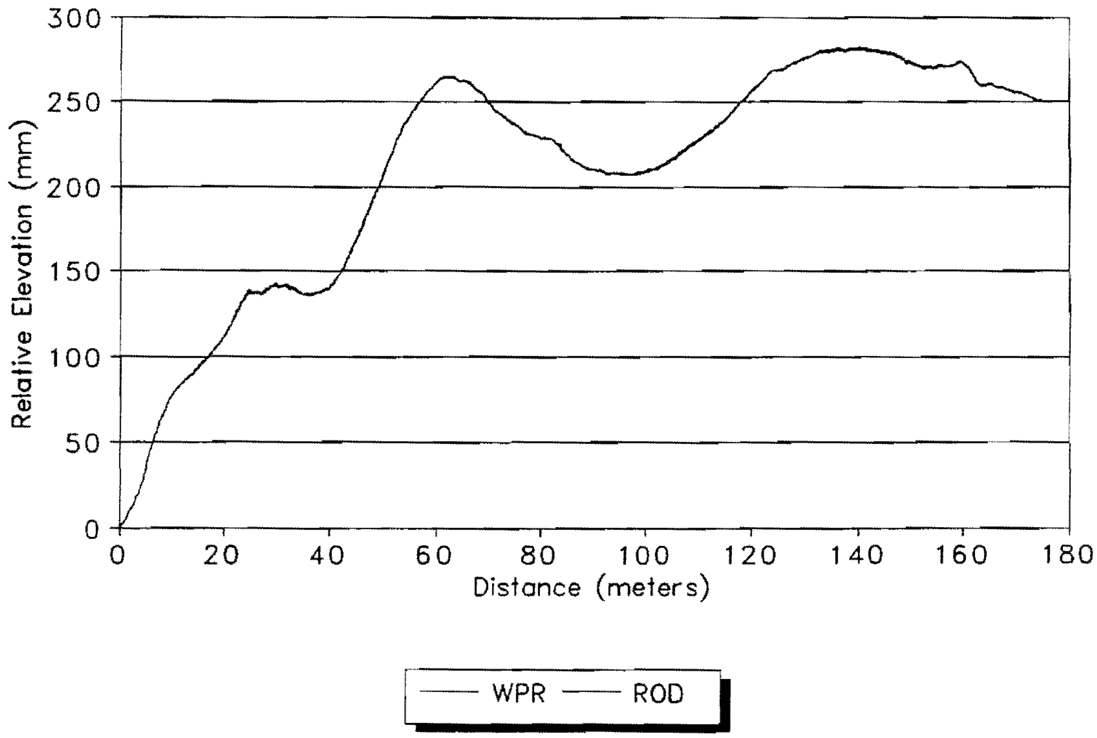

Figure 36. Average Synchronized WPR Profile vs Average Rod & Level Profile (Annex 2).

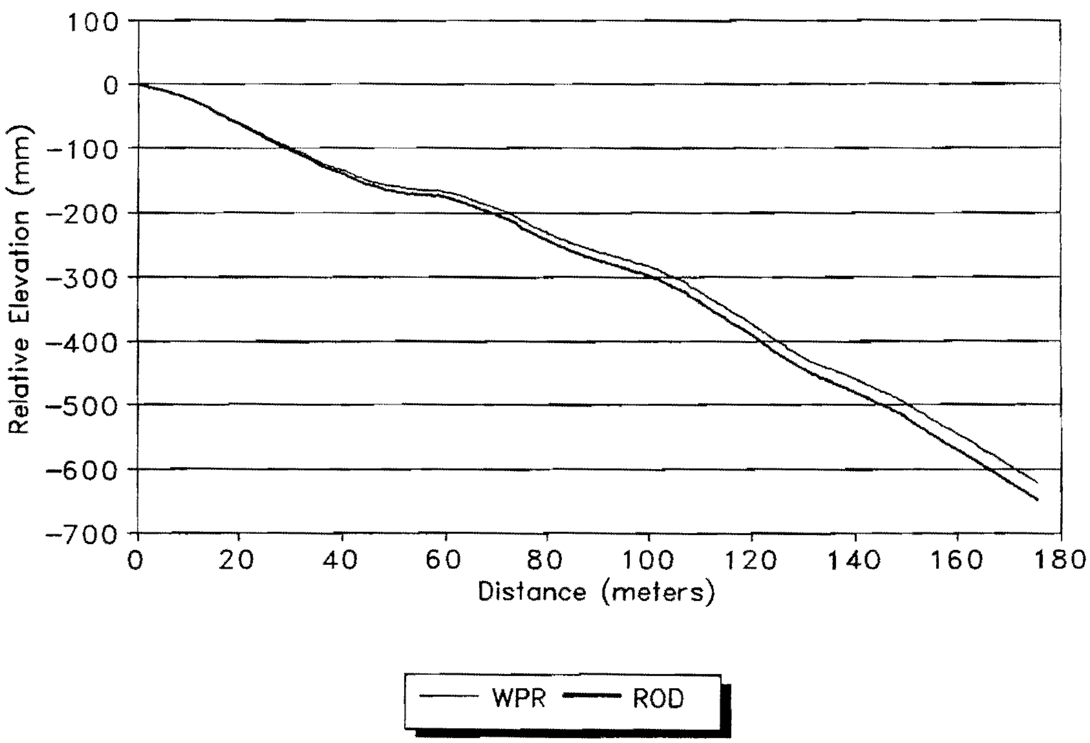

Figure 37. Average Synchronized WPR Profile vs Average Rod & Level Profile (SH47A).

Figures 38 to 42 show a significant improvement in the accuracy of the profiles from the CSC Digital Profilite and Walking Profiler. To quantify the improvement in accuracy, researchers computed the discrepancies between the corrected profile and the corresponding rod and level profile, point-by-point. The average of the discrepancies as well as the average of the absolute discrepancies were then determined for each site and reported in Table 13. By comparing the statistics given in this table with the corresponding statistics given in Table 12, the improvement in profile accuracy is made clear.

The results presented suggest the use of rod and level data to check the measurements made with profilers, such as the CSC Digital Profilite and the Walking Profiler. Unlike their inertial counterparts, devices that measure and integrate differential elevations are not self-correcting with respect to the problem of mistracking. This will be illustrated later. Thus, verifying the profiles from these devices is important.

In this regard, a closed-loop survey may be conducted, but the findings do not recommend this as a method for verifying the profiles from devices like the CSC and WPR. A closed-loop survey will not provide an independent check. It will show whether mistracking may have occurred, but using the same data to correct the profile is not advisable. In addition, a closed-loop survey may actually be more time consuming and labor intensive compared to collecting a few measurements with the rod and level. As illustrated in Figures 38 and 39, the WPR profiles were made to match very closely with the rod and level profiles based on a correction that used only the difference in the measured elevations at the end point. For this purpose, only two rod and level measurements are necessary, one at the beginning, and the other at the end of the run. In actual applications, rod and level measurements at intermediate locations may be advisable. Figures 40 to 42 show that the correction applied did not work quite as well with the CSC profiles as it did with the WPR profiles. For a given site, there are locations along the wheelpath where the differences are still quite noticeable.

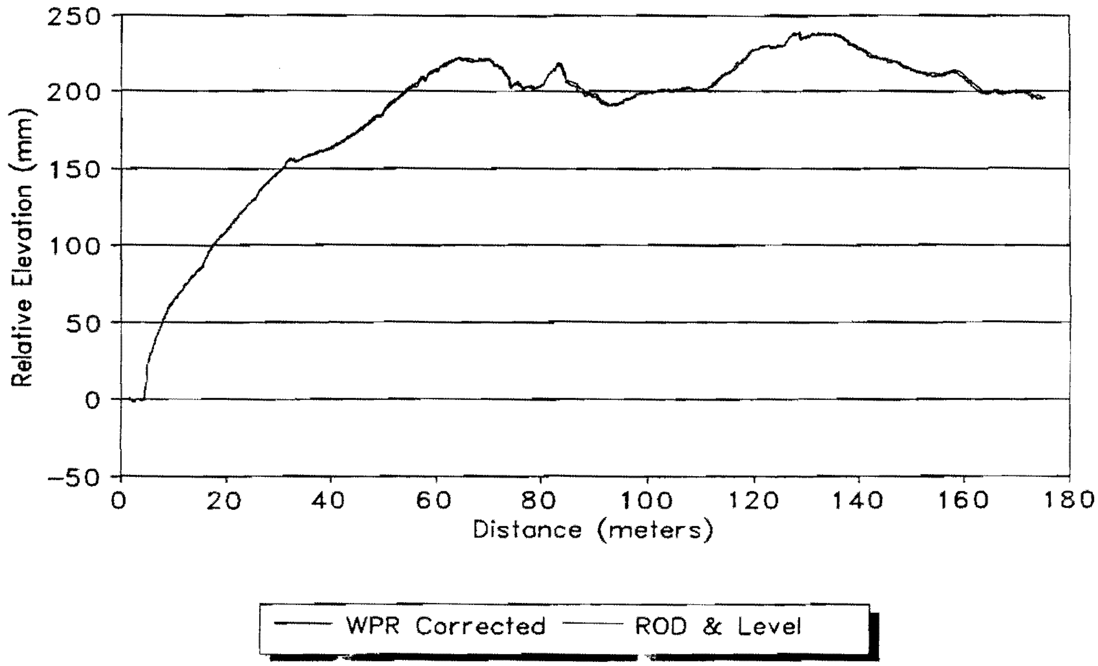

Figure 38. Comparison of Corrected Average WPR Profile to Average Rod & Level Profile on Annex 1.

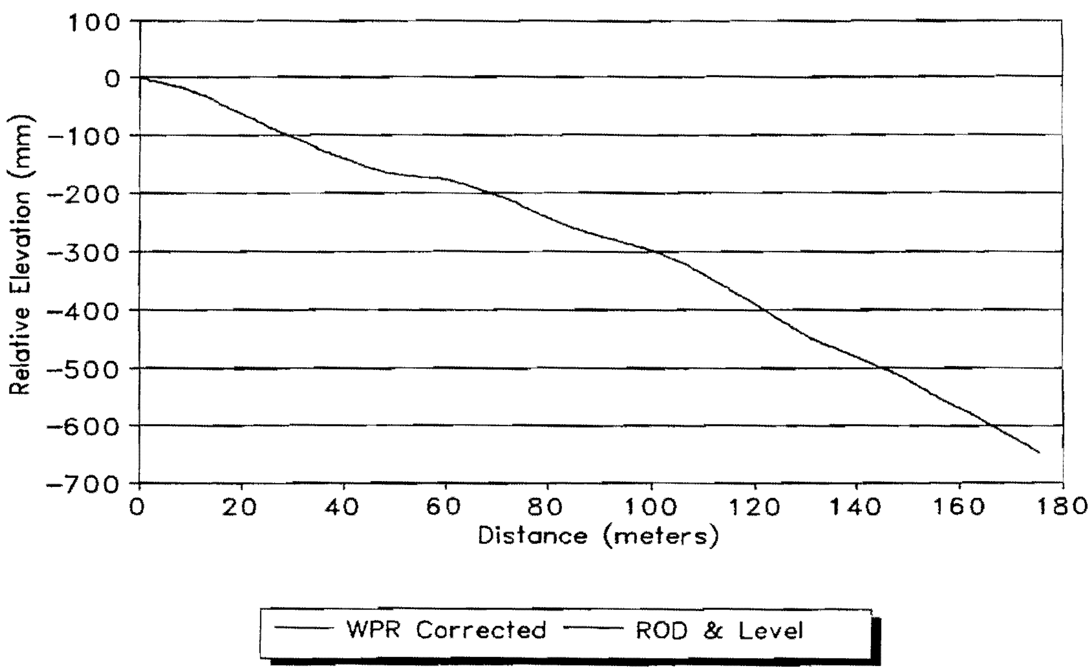

Figure 39. Comparison of Corrected Average WPR Profile to Average Rod & Level Profile on SH47A.

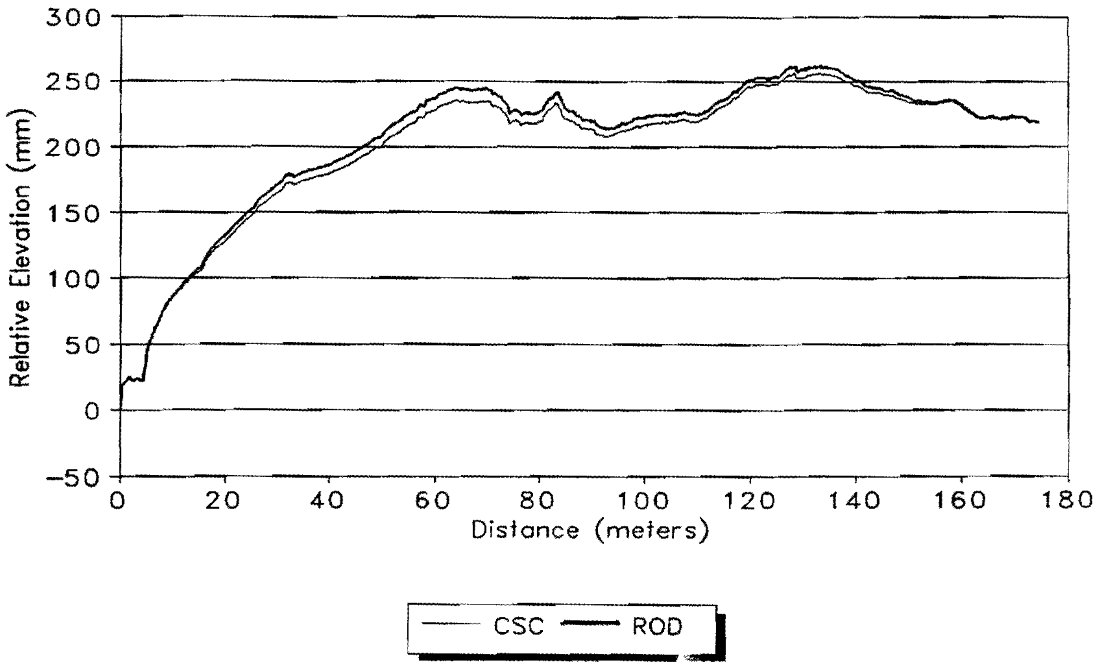

Figure 40. Comparison of Corrected Average CSC Profile to Average Rod & Level Profile on Annex 1.

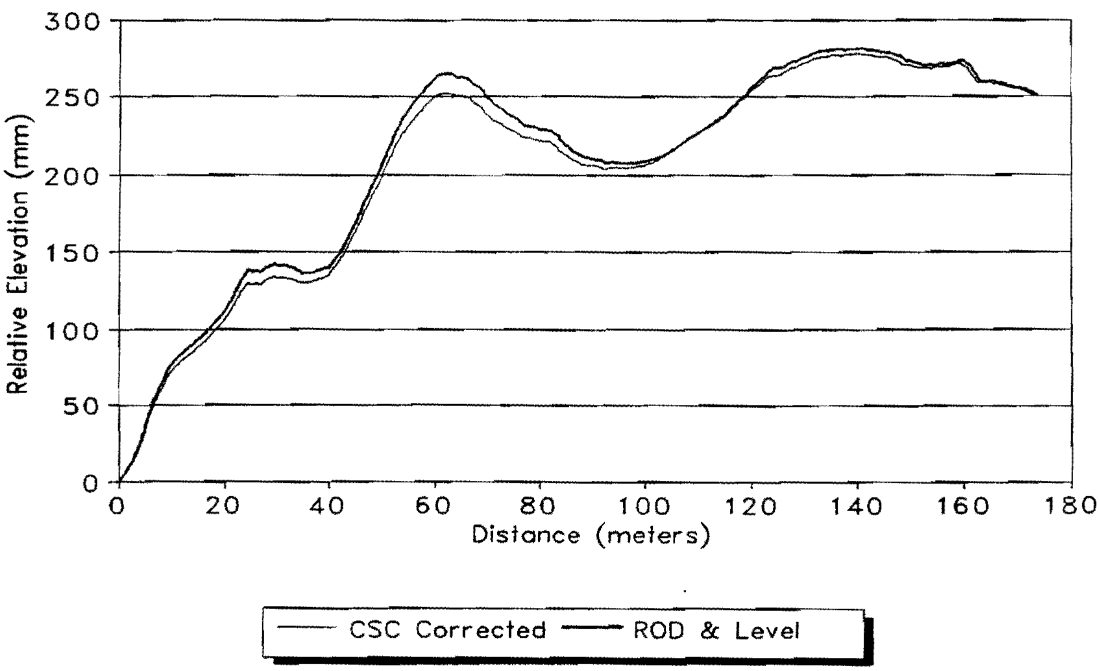

Figure 41. Comparison of Corrected Average CSC Profile to Average Rod & Level Profile on Annex 2.

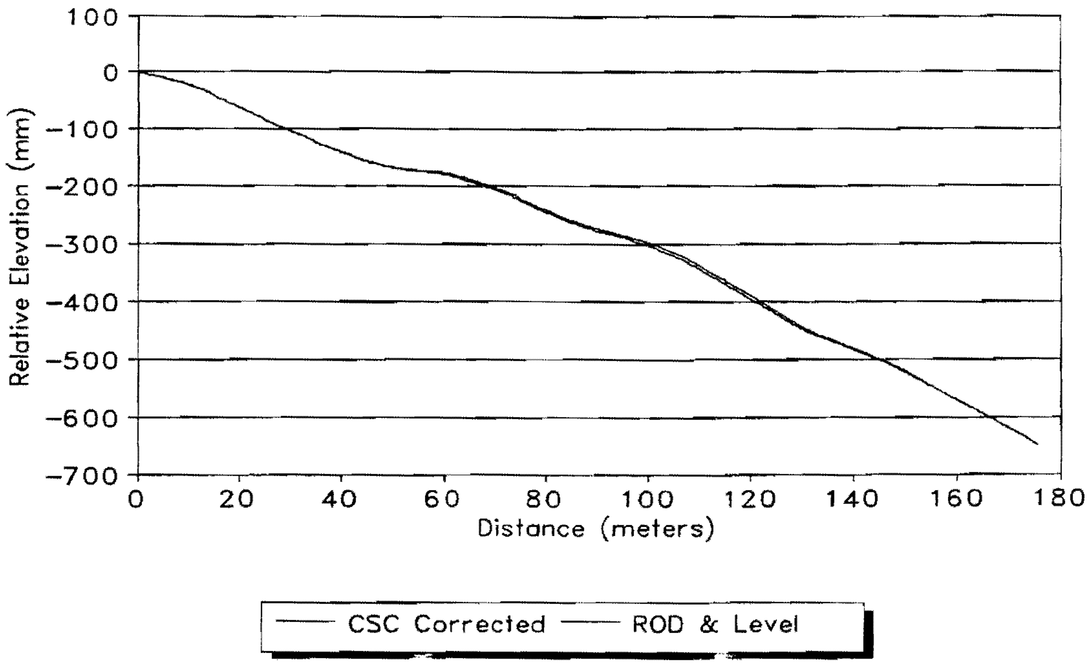

Figure 42. Comparison of Corrected Average CSC Profile to Average Rod & Level Profile on SH47A.

Table 13. Accuracy of Corrected Average Profiles from the CSC and WPR.

Profiler	Site	Average Discrepancy (mm)	Average of Absolute Discrepancies (mm)
CSC	Annex 1	-5.1484	5.1809
	Annex 2	-4.8496	4.8545
	SH47A	-2.5000	2.5427
WPR	Annex 1	0.7504	1.0409
	SH47A	-0.3229	0.5435

The determination of the required number of rod and level measurements is beyond the scope of this investigation. If the need arises, this can be a subject of another study. It is clear, however, that significant reductions in profile measurement error were achieved from corrections based only on the difference in end point elevations. This finding indicates that, as a minimum, rod and level measurements should be taken at the beginning and end of a run to verify the output from devices like the CSC Digital Profilite and the Walking Profiler.

Accuracy of Profiles from Inertial Profilers

With respect to evaluating the accuracy of the profiles from the inertial profilers, the lack of rod and level data on the lead-in for each site makes this task relatively more difficult. Not only must the profiles be synchronized, but the effect of the lead-in on the filtered profiles needs to be established. Researchers evaluated the effect of the lead-in profile using data from the rod and level surveys conducted on the different test sites. The results from this evaluation show that in the absence of lead-in data, the initial portion of the filtered profile will be different from the corresponding profile determined when lead-in data are available for the filtering. The differences will tend to decrease the accuracy of the measured profiles and bias the evaluation of point-to-point accuracy unless accounted for. Consequently, researchers made an attempt to evaluate the effect of lead-in data on the filtering of pavement profiles. The results of this investigation (presented in Appendix B) showed that filtered profiles determined with and without a lead-in exhibit differences that extend a distance of about 1.5 times the cutoff wavelength specified for the filter. Although the profiles are different at the start of the measurements, they eventually converge and track on each other beyond this distance from the beginning location. In view of this finding, researchers evaluated the accuracy of the data from the inertial profilers using the elevations measured at distances greater than 1.5 times the cutoff wavelength from the beginning of a site. Since the cutoff wavelength used for the profile measurements is 33 m, elevation data located beyond 49.5 m from the beginning of a site were used to evaluate the accuracy of the measurements. The 33 m cutoff wavelength corresponds to the LISA setting. Unlike the other inertial profilers where this parameter may be set via software, the cutoff wavelength for the LISA is fixed. Thus, profile measurements with the inertial profilers were collected using a 33 m cutoff wavelength for comparison purposes.

The data from the inertial profilers were initially synchronized to get elevations at 152.4 mm intervals (the distance between rod and level measurements). Following ASTM E 950, the average synchronized profile for a given profiler and site was determined by getting the mean of the elevations from repeat runs on a point-by-point basis. This average synchronized profile was then compared to the corresponding average profile determined from rod and level measurements made on the site. Specifically, differences in elevations were computed, point-by-point. The average of these discrepancies as well as the average of the absolute discrepancies were then determined and reported in Table 14. Figures 43 to 57 compare the average synchronized profiles from the different profilers with the corresponding average profiles from the rod and level (represented by the bold solid line in each figure).

The average discrepancy is a measure of the bias in the data from a given profiler. It indicates the presence of consistent or systematic differences between a given profile and the reference profile. The closer this statistic is to zero, the lesser the bias in the profile measurements relative to the reference used. According to ASTM E 950, the average discrepancy must not exceed 1.25 mm for a Class 1 inertial profiler. From the average discrepancies given in Table 14, all of the inertial profilers satisfy this requirement. It appears, therefore, that the ASTM E 950 requirements on profiler bias are rather lenient and do not provide enough differentiation. In addition, no similar specification is given for the average of the absolute discrepancies.

It is noted that bias and average absolute discrepancy are different measures. A profile may not match the reference very well but still show no bias if the differences cancel out, i.e., are not consistent or systematic. Likewise, a profile may be very accurate, in terms of the average absolute discrepancy, but show a discernible bias. Consequently, it is necessary to consider these two statistics when evaluating the point-to-point accuracy of profiles. A proposed procedure is given in Appendix D which presents guidelines for evaluating pavement profilers developed from the experience gained in the present study.

Table 14. Accuracy of Profiles from Inertial Profilers.

Profiler	Site	Average Discrepancy (mm)	Average of Absolute Discrepancies (mm)
LISA	Annex 1	0.1170	1.1627
	Annex 2	0.6062	2.3803
	SH47A	0.0156	1.2382
T6400	Annex 1	0.0079	2.4787
	Annex 2	0.3843	1.8495
	SH47A	-0.0327	0.9126
CPR	Annex 1	-0.0700	1.3183
	Annex 2	0.1478	1.4391
	SH47A	-0.0404	0.7826
LRP	Annex 1	-0.0591	0.7123
	Annex 2	0.0510	1.1062
	SH47A	-0.0758	0.6841
SP	Annex 1	-0.0047	0.7916
	Annex 2	0.0627	1.2133
	SH47A	-0.0542	0.6782

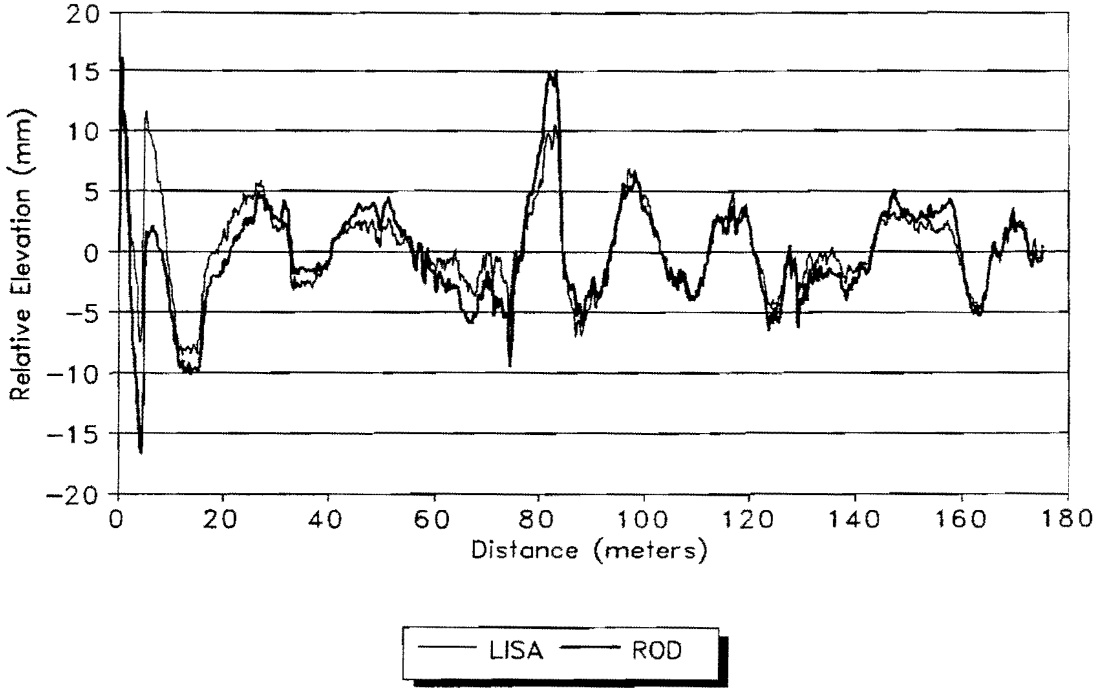

Figure 43. Average Synchronized LISA Profile vs Average Filtered Rod & Level Profile (Annex 1).

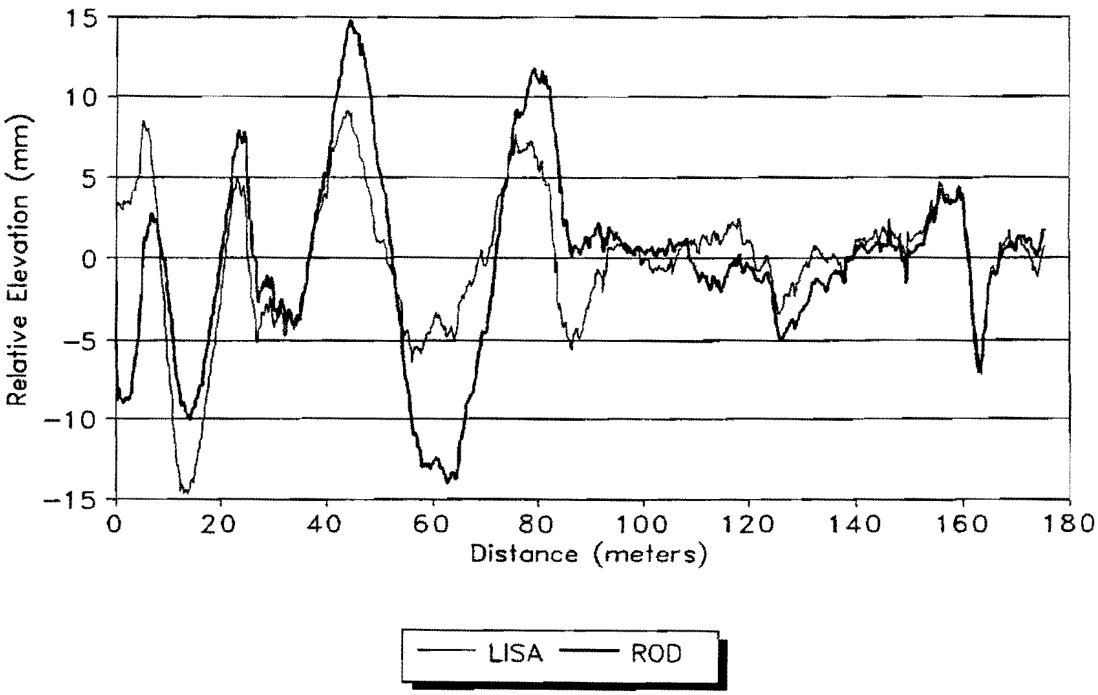

Figure 44. Average Synchronized LISA Profile vs Average Filtered Rod & Level Profile (Annex 2).

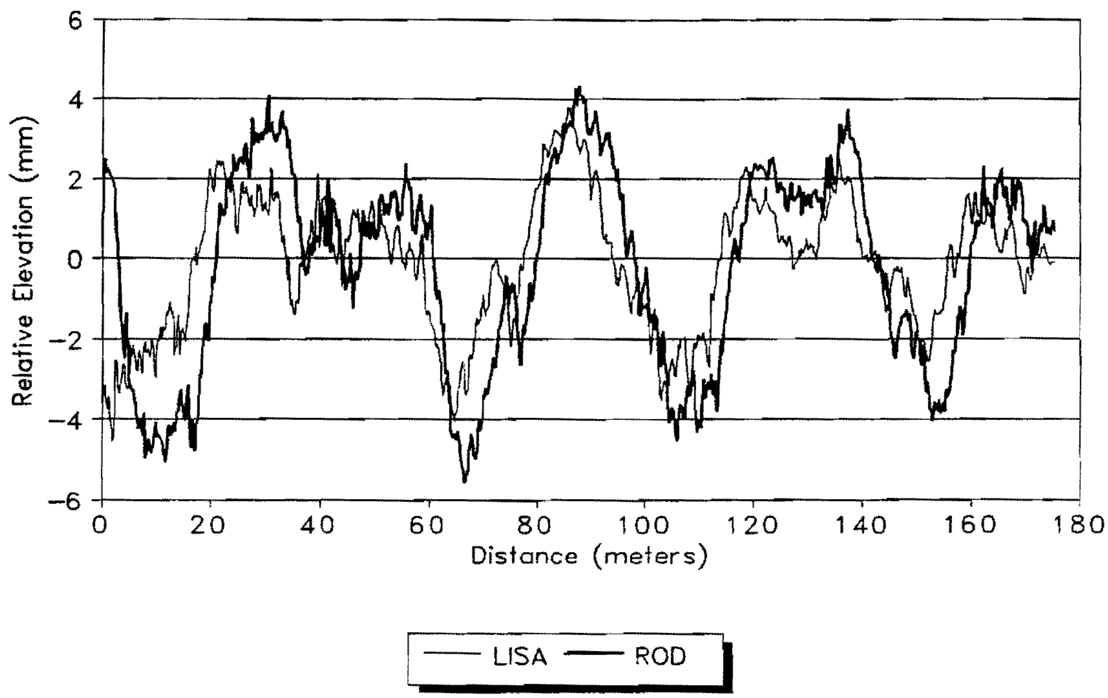

Figure 45. Average Synchronized LISA Profile vs Average Filtered Rod & Level Profile (SH47A).

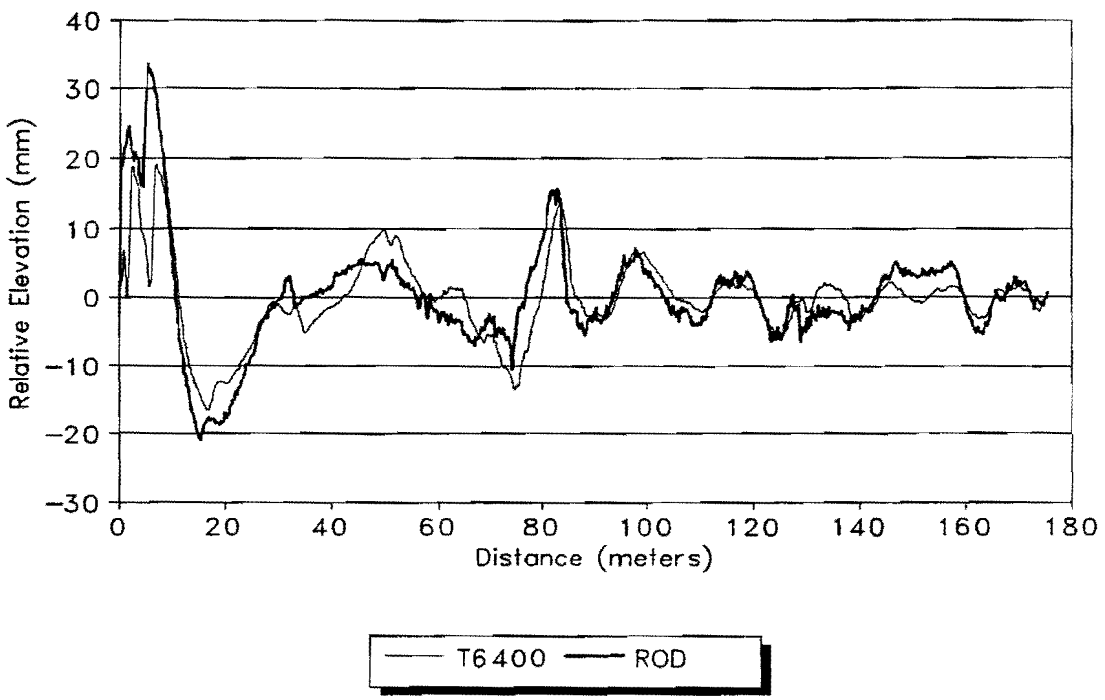

Figure 46. Average Synchronized T6400 Profile vs Average Filtered Rod & Level Profile (Annex 1).

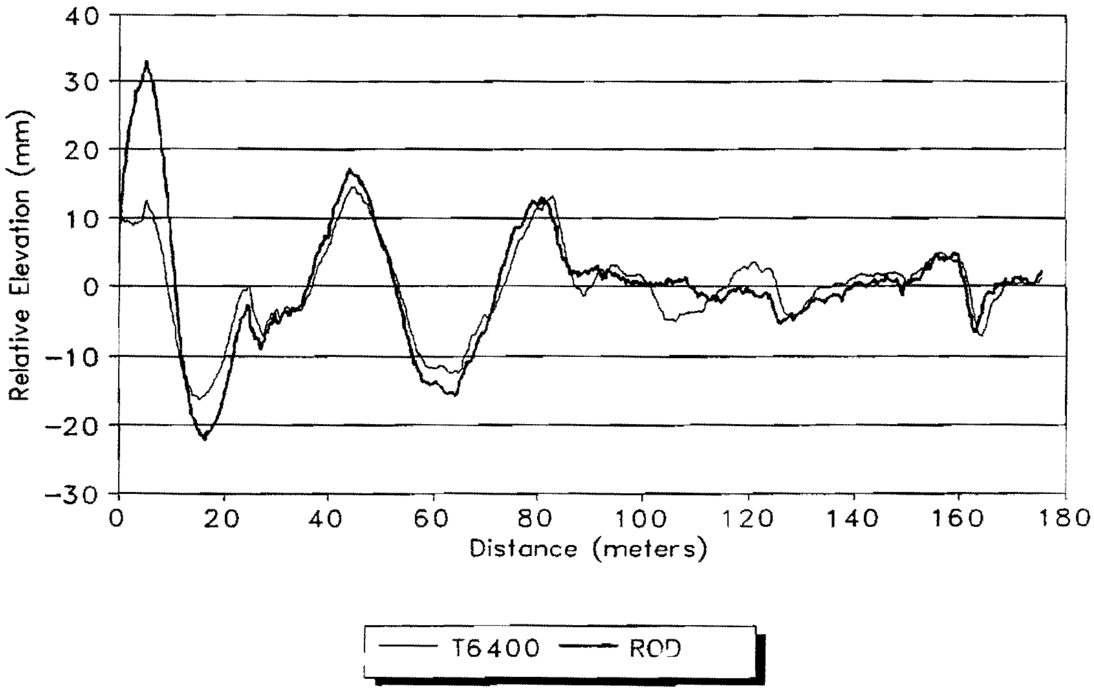

Figure 47. Average Synchronized T6400 Profile vs Average Filtered Rod & Level Profile (Annex 2).

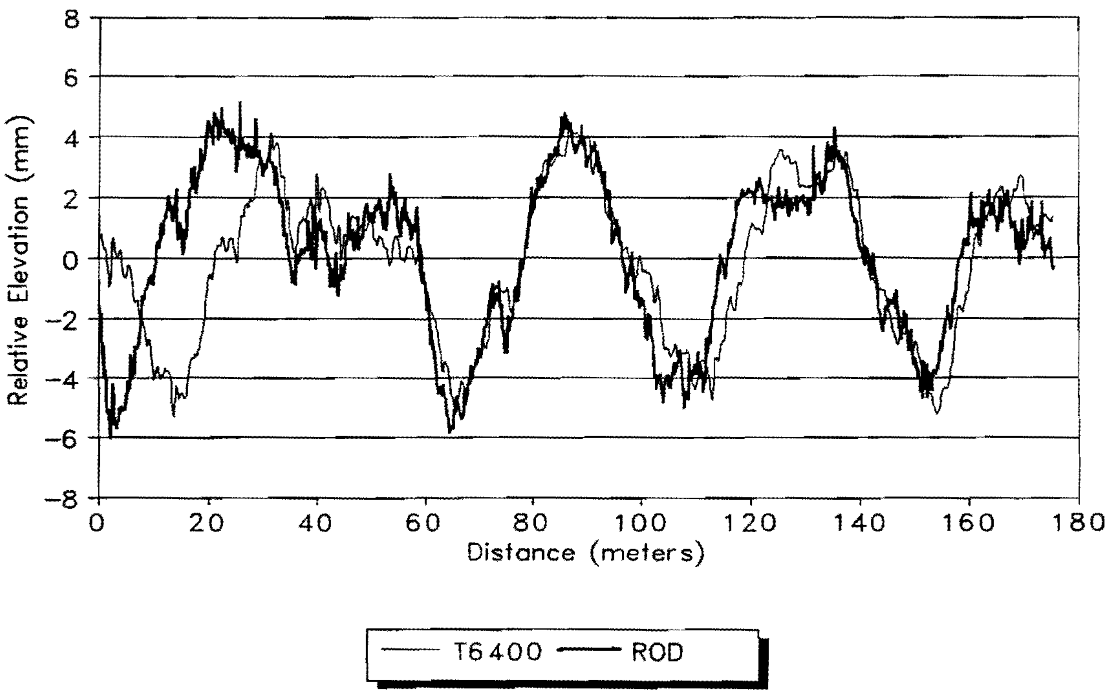

Figure 48. Average Synchronized T6400 Profile vs Average Filtered Rod & Level Profile (SH47A).

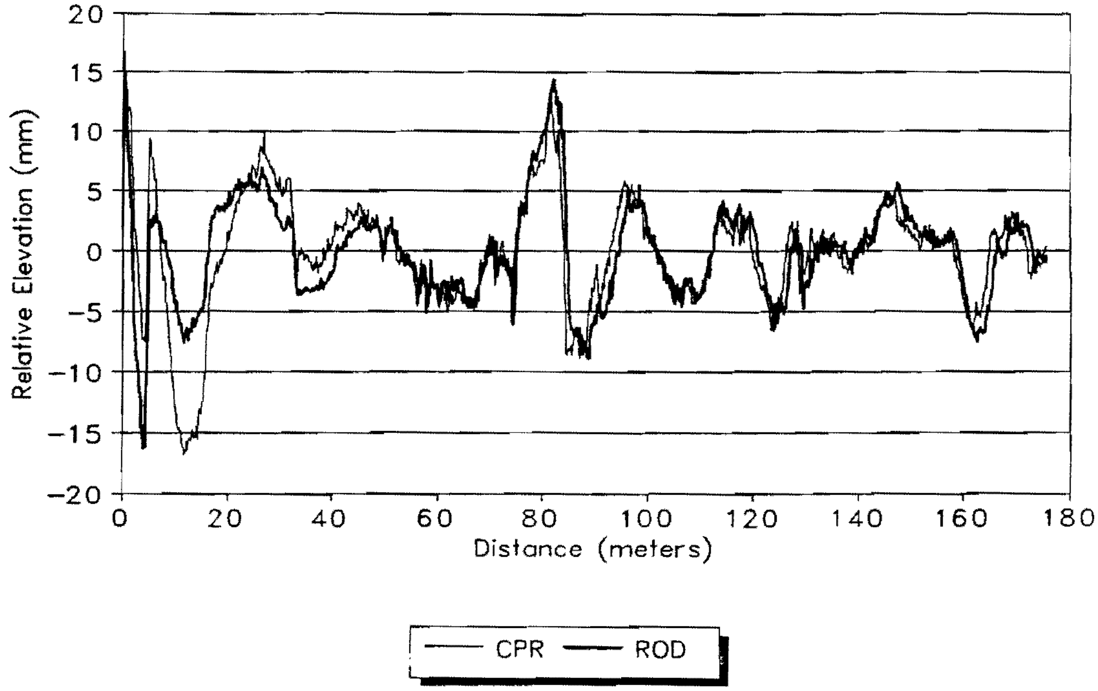

Figure 49. Average Synchronized CPR Profile vs Average Filtered Rod & Level Profile (Annex 1).

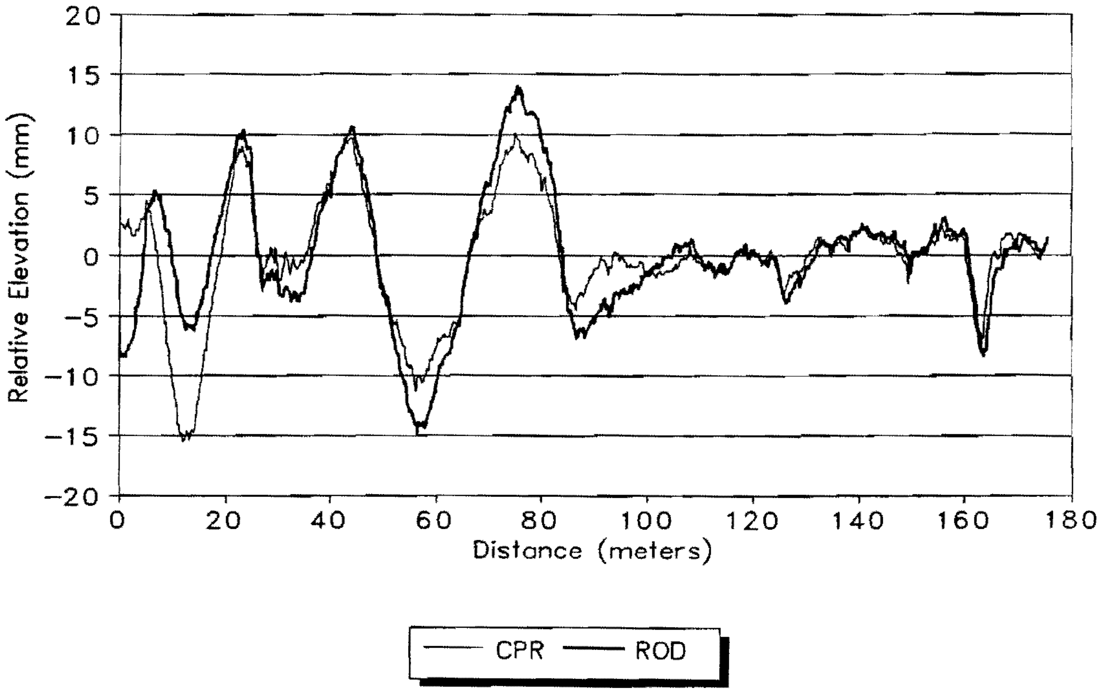

Figure 50. Average Synchronized CPR Profile vs Average Filtered Rod & Level Profile (Annex 2).

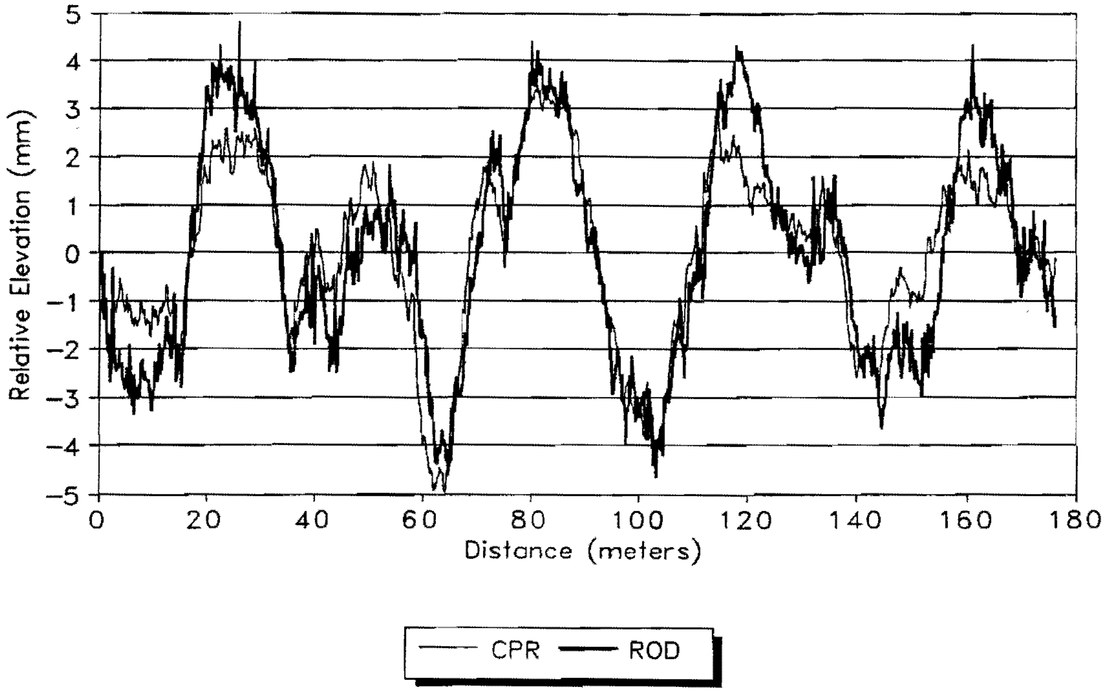

Figure 51. Average Synchronized CPR Profile vs Average Filtered Rod & Level Profile (SH47A).

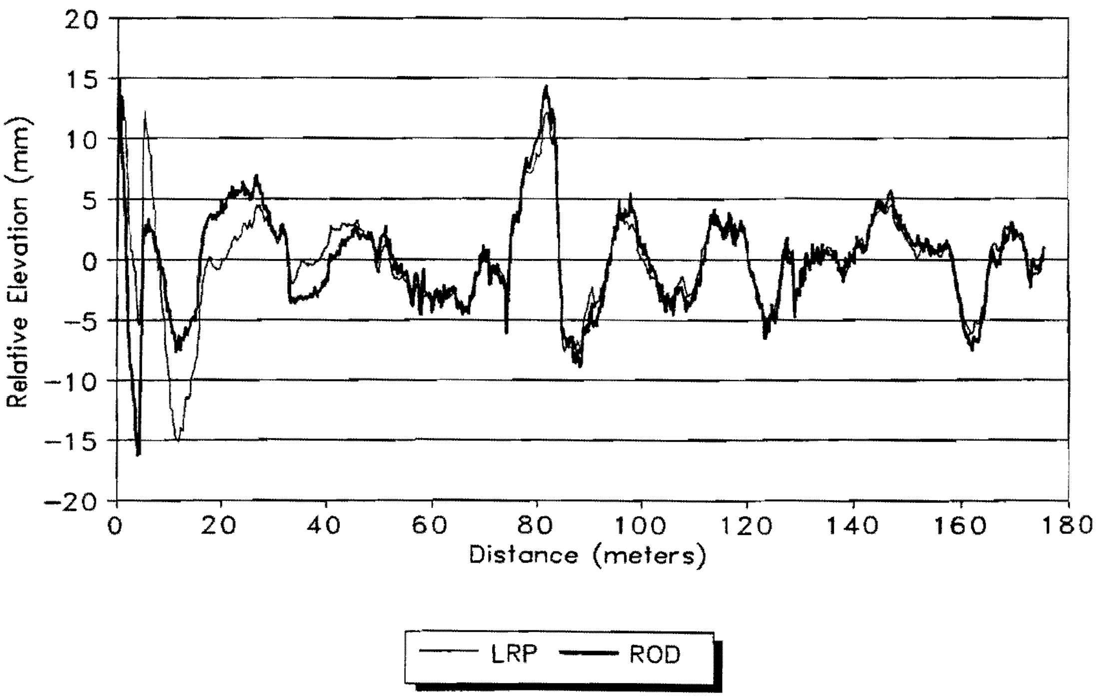

Figure 52. Average Synchronized LRP Profile vs Average Filtered Rod & Level Profile (Annex 1).

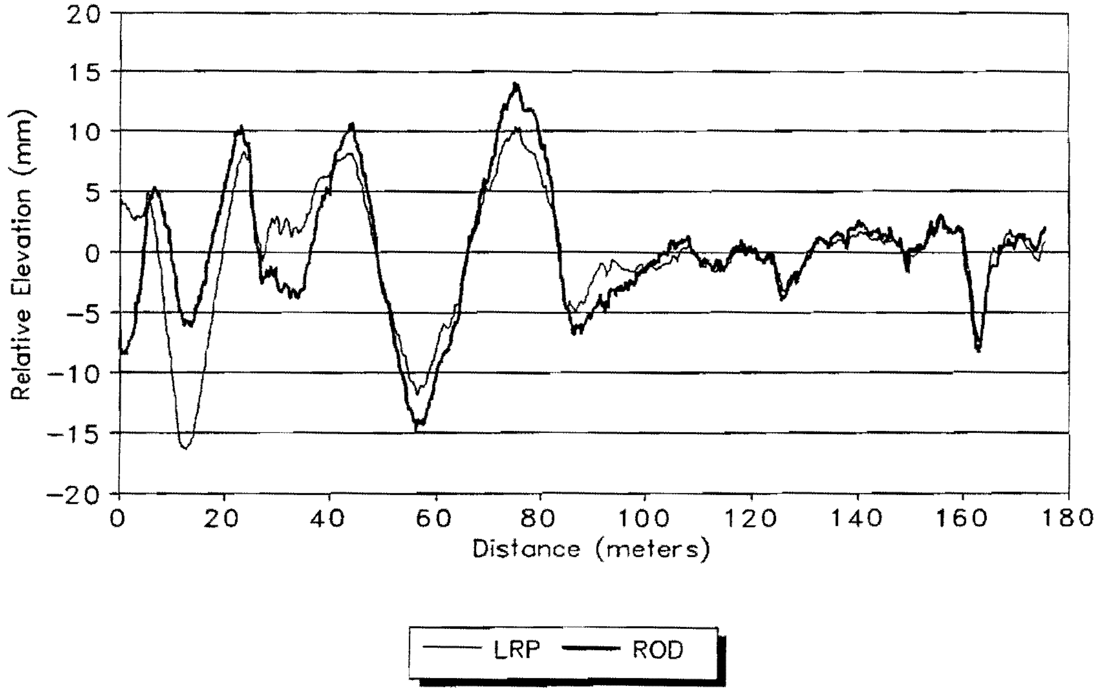

Figure 53. Average Synchronized LRP Profile vs Average Filtered Rod & Level Profile (Annex 2).

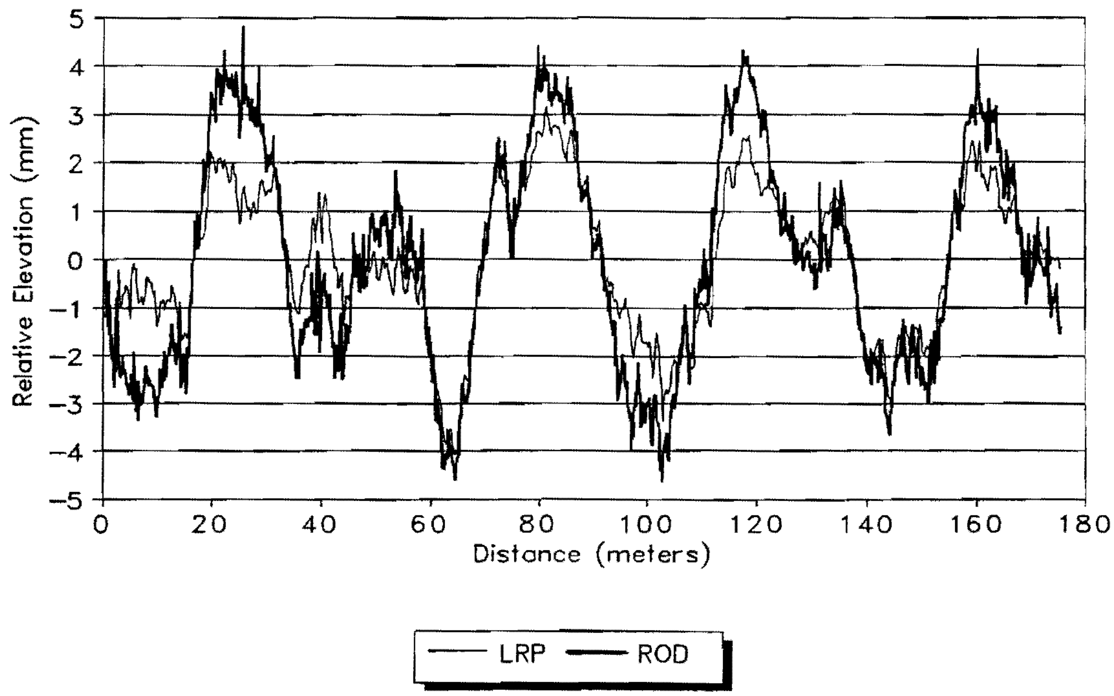

Figure 54. Average Synchronized LRP Profile vs Average Filtered Rod & Level Profile (SH47A).

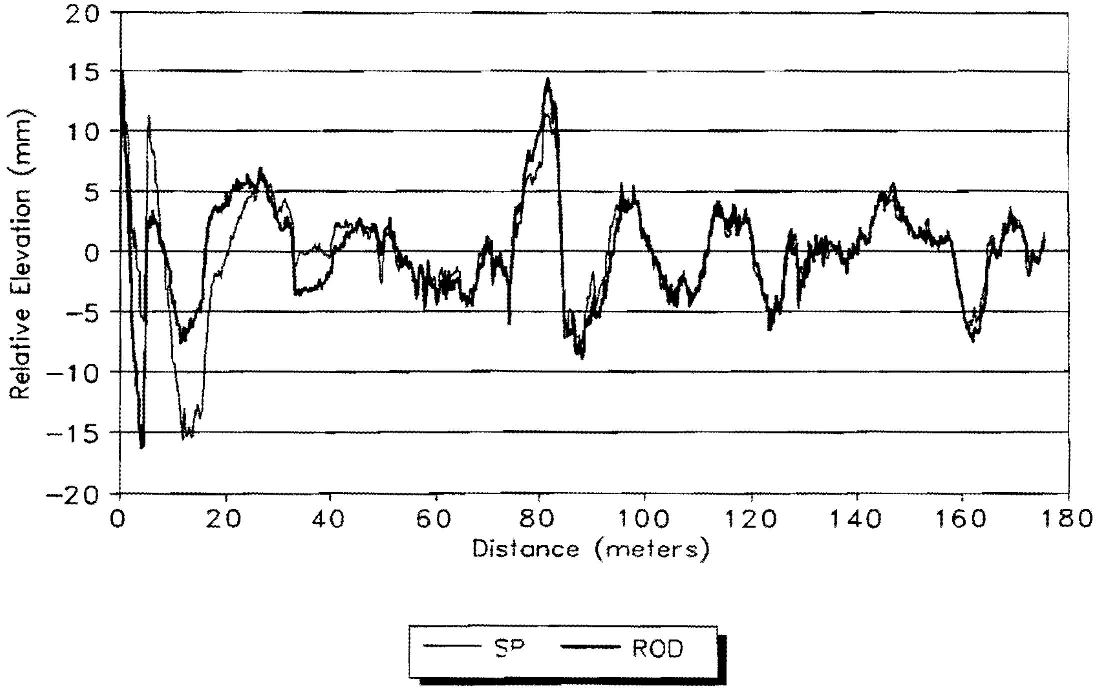

Figure 55. Average Synchronized Profile from Surface Profiler vs Average Filtered Rod & Level Profile (Annex 1).

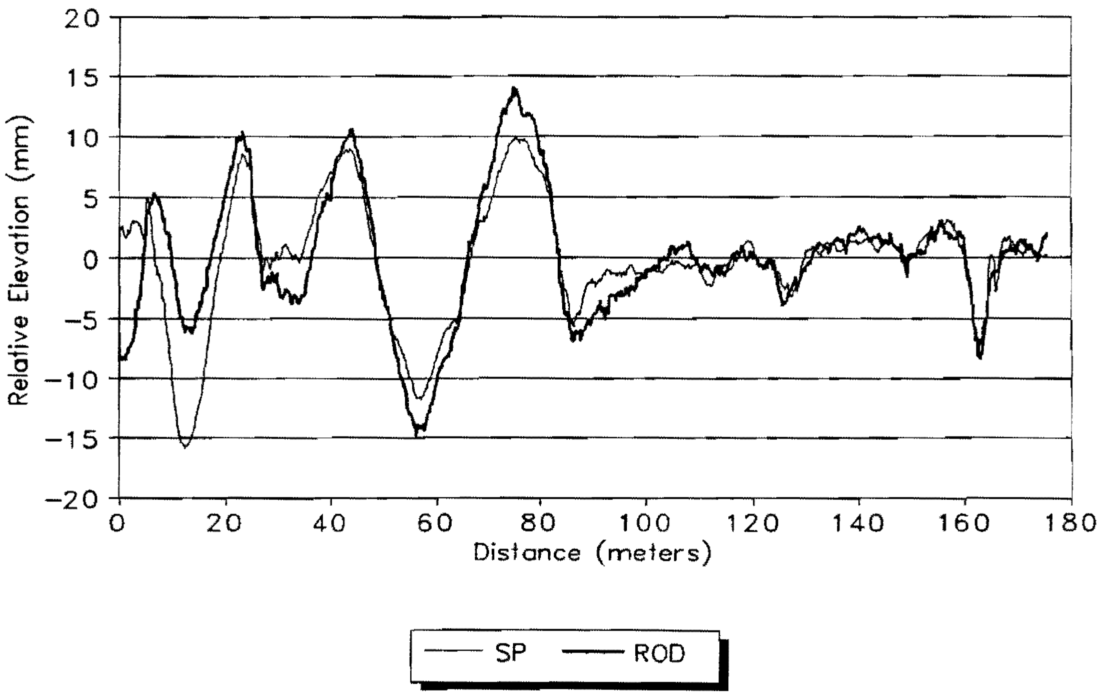

Figure 56. Average Synchronized Profile from Surface Profiler vs Average Filtered Rod & Level Profile (Annex 2).

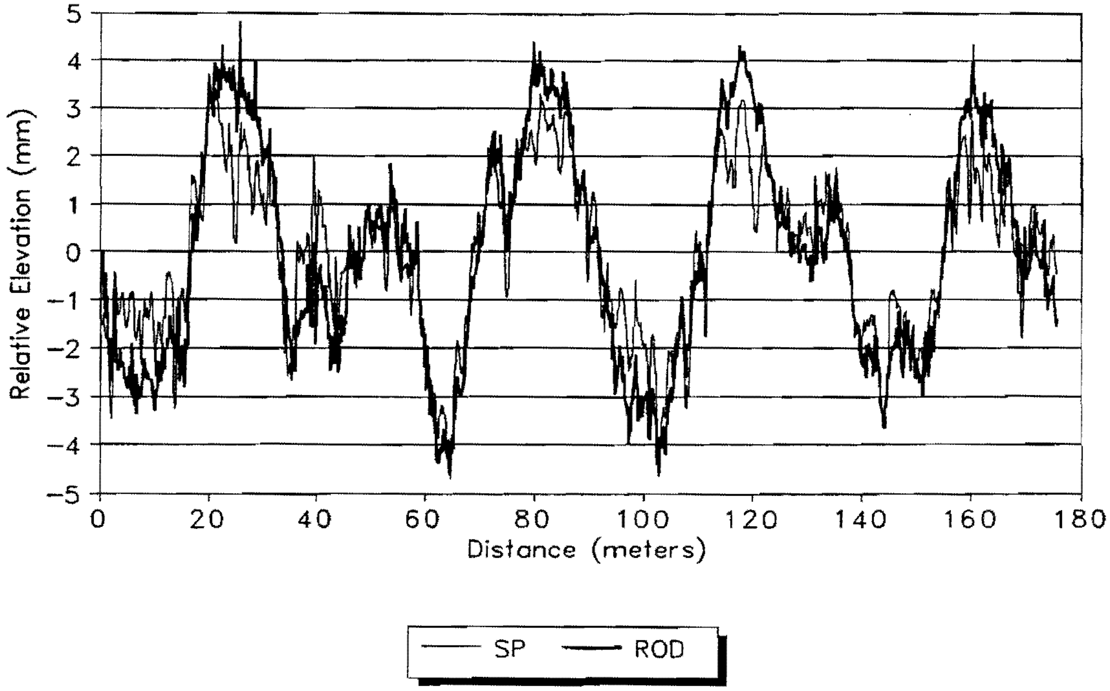

Figure 57. Average Synchronized Profile from Surface Profiler vs Average Filtered Rod & Level Profile (SH47A).

In terms of the average of the absolute discrepancies, the results in Table 14 prompt the following observations:

1. Among the three lightweight inertial profilers, the Construction Profiler gave measurements that compared most favorably with the rod and level data.
2. Among the five inertial profilers tested, the van-mounted profilers demonstrated the best match to the reference profiles.

OBSERVATIONS FROM PROFILE MEASUREMENTS ON SIMULATED BUMPS

TxDOT's current smoothness specification based on the profilograph includes a requirement that the finished surface should have no bumps greater than 7.62 mm over a base length of 7.62 m. Where bumps are detected, the contractor is required to correct the profile at those locations. To investigate the application of a bump requirement in a smoothness specification based on the profilers evaluated in this study, researchers fabricated simulated bumps of various heights and base lengths as shown in Table 15. These bumps are made of

Table 15. Simulated Bumps Used in the Study.

Bump Number	Bump Height (mm)[1]	Base Length (m)
1	26.2	1.22
2	9.7	2.44
3	23.1	1.22
4	28.9	0.61
5	27.8	2.44
6	34.3	1.22
7	13.2	0.61

[1] Determined from rod and level after placement of bumps.

silicon rubber and have a smooth tapered profile as may be observed from Figure 58. The simulated bumps were placed at selected intervals along the left wheelpath of Annex 2 and profile measurements were taken with the bumps in place to evaluate the accuracy with which the locations and heights of the bumps may be determined using the profilers investigated in this study. Researchers realize that all of the fabricated bumps are larger than the tolerance specified in the current smoothness specification. Nevertheless, the data from the measurements on the simulated bumps allowed researchers to evaluate differences in profiler response to the bumps used in this investigation. The findings generated are of practical significance to the application of profilers for QC/QA of pavement smoothness during construction.

Comparison of Profile Data on Bumps

Figure 59 illustrates the profiles measured with the Walking Profiler on Annex 2 from runs made with and without the simulated bumps. The topmost curve in the figure is the profile measured during the first run on Annex 2 with the simulated bumps in place. For some reason, this profile is different from the other two runs made with the bumps on the surface. The profile from the first run is shifted up right at the beginning and prior to the bumps which appear as spikes in the profiles. For this reason, this run is considered extraneous. The

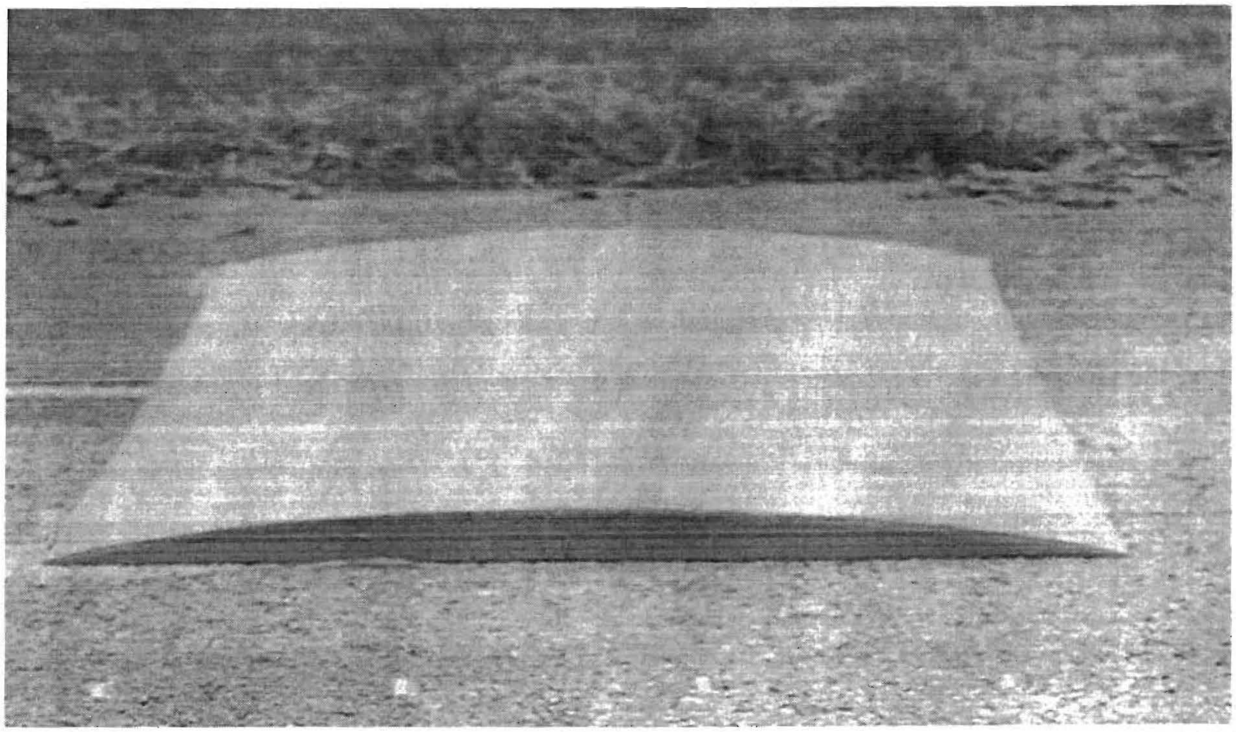

Figure 58. Example of Simulated Bump Used in Evaluation of Profilers.

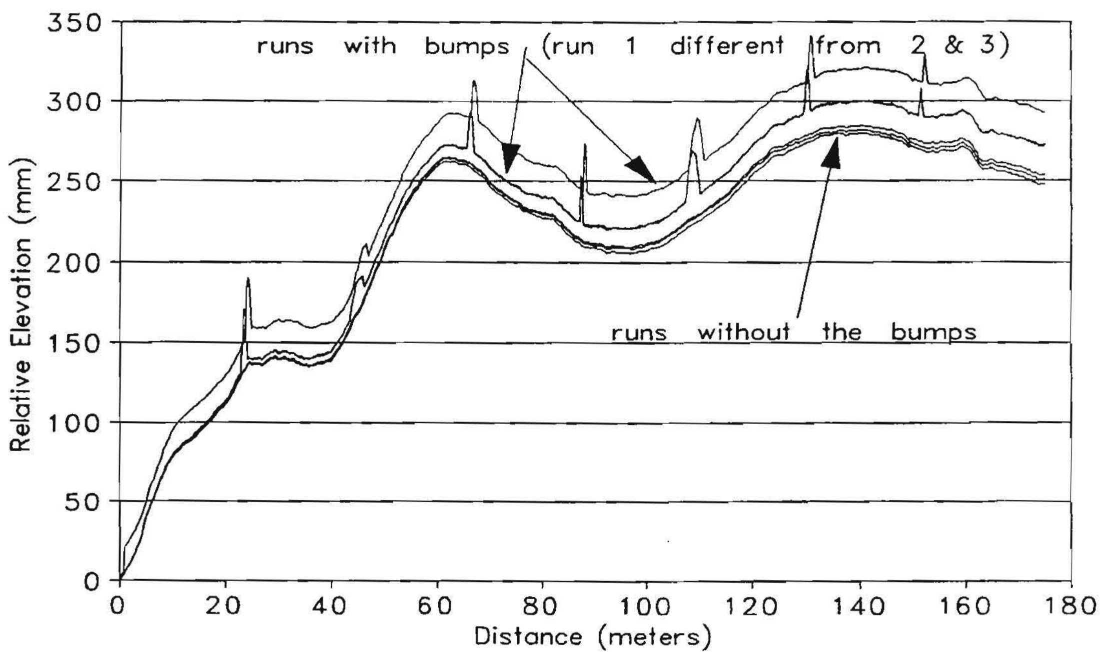

Figure 59. Profiles Measured on Annex 2 with and Without the Simulated Bumps Using the Walking Profiler.

profiles from the other two runs fall on top of each other. It is also observed that, prior to the first bump, the profiles from these two runs match the profiles from the three runs made without the simulated bumps, which is to be expected. However, after the first bump, the profiles from these two runs start to diverge from the profiles measured without the bumps instead of tracking back the pavement surface. Figure 59 clearly shows that the bumps affected the profile measurement. Note that the error due to mistracking increased with each bump traversed and that the profiles never got back on track between bumps. This observation brings up the need for verifying the profile measurements from devices that measure and integrate differential elevations to estimate the true profile. As a minimum, rod and level measurements should be made at the beginning and ending locations of the path profiled to check against mistracking and to reduce the error associated with it.

It is of interest to examine the response of inertial profilers to the simulated bumps. Figure 60 illustrates the profiles measured with and without the simulated bumps using TxDOT's Surface Profiler. It is observed that the bumps appear distorted in the measured profile as evidenced by the sharp drop in the relative elevations after each bump. This distortion, which is seen as an asymmetry in the bump profile, is an artifact of the filtering. However, between bumps, the profile recovers and gets back on the pavement surface. This self-correcting capability was observed for all four inertial profilers evaluated in this study.

Determination of Bump Locations and Bump Heights

Table 16 shows the locations of the bump peaks as determined from the profiles taken with the simulated bumps in place. The locations given are referred from the start of Annex 2. It is observed that the bump locations from the different profilers are very much comparable. The variability in the estimated locations of a given bump, as measured by the coefficient of variation (CV), is small and varies from 0.17 to 1.09 percent for all bumps profiled. In practical terms, one can use the profile from any of the profilers to find the simulated bumps in the field.

Researchers determined the heights of the bumps using a procedure similar to the one established for the profilograph. The profile of a given bump was plotted and the bump height

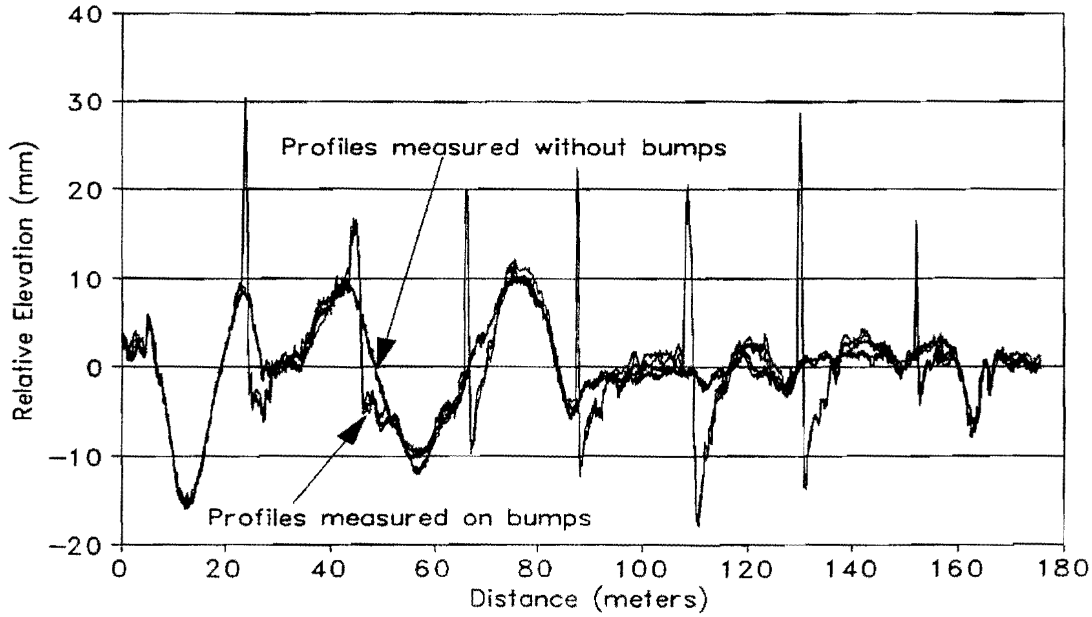

Figure 60. Profiles Measured on Annex 2 with and Without the Simulated Bumps Using TxDOT's Surface Profiler.

Table 16. Bump Locations Determined from Profile Data on Simulated Bumps.

Profiler	Location of Bump Peak (m)						
	Bump 1	Bump 2	Bump 3	Bump 4	Bump 5	Bump 6	Bump 7
CSC	23.62	45.72	66.04	87.38	108.97	130.05	151.38
WPR	23.65	45.85	66.36	87.59	109.07	130.30	151.78
LISA	23.53	44.63	66.18	87.63	108.83	130.28	151.71
T6400	23.83	45.66	66.64	87.82	109.30	130.83	153.11
CPR	23.47	45.57	66.15	87.69	108.60	130.23	152.32
LRP	23.69	44.81	66.37	87.84	108.87	130.52	152.62
SP	23.59	44.84	66.18	87.58	108.64	130.08	152.19
ROD	23.71	45.69	66.32	87.63	109.00	130.27	152.25
Standard Dev. (m)	0.11	0.49	0.18	0.15	0.23	0.25	0.55
CV (%)	0.48	1.09	0.28	0.17	0.21	0.19	0.36

was referred from the line segment formed by connecting the beginning and ending points of a bump. Table 17 shows the bump heights determined from the CSC and WPR profiles. Since elevations are reported at intervals of 254 and 241 mm for the CSC and WPR, respectively, researchers found it necessary to draw a smooth curve through the measured points on a given bump. Thus, some of the bump heights presented in Table 17 are based on the fitted curve, i.e., an interpolation, in lieu of an actual measurement that coincided with the peak of the bump. For the bump profiles taken with the rod and level, measurements on the simulated bumps were made at 76.2 mm intervals so that curve fitting was not as necessary compared with the CSC and WPR data.

Table 17 shows significant discrepancies between the estimated bump heights, particularly for bumps 3, 4, and 6. While there may be errors associated with the curve fitting done to estimate the bump height, the primary reason for the discrepancies is believed to be the inaccuracies in the bump profiles measured with the CSC and WPR. These inaccuracies are also found in the bump profiles from the inertial profilers as illustrated in Figure 60. The distortion in the profile immediately after a bump makes it difficult to measure the bump height as the baseline is skewed. Consequently, bump heights were not determined from the inertial profiler data.

If bump heights cannot be accurately determined, it will be inappropriate to include a permissible bump criterion in a profile-based smoothness specification. This points to the need for evaluating the applicability of a bump height criterion in a profile-based smoothness specification and investigating techniques to reduce or counteract the distortion caused by filtering of the bump profile. An alternative is to develop and use a smoothness statistic, calculated from pavement profile, that accounts for the effects of bumps based on criteria such as ride quality and pavement damage. Researchers are of the opinion that this approach is simpler and more meaningful since it ties the evaluation of the surface defect directly to the criteria used in the smoothness specification.

Table 17. Bump Heights Determined from CSC and WPR Profiles.

Bump	Bump Height (mm)		
	CSC Digital Profilite	Walking Profiler	Rod & Level
1	25.6	27.6	26.2
2	11.3	9.6	9.7
3	21.5	17.6	23.1
4	19.7	23.6	28.9
5	25.5	24.7	27.8
6	23.8	24.2	34.3
7	10.6	11.1	13.2

CHAPTER III
SUMMARY AND RECOMMENDATIONS

This study aimed to establish the availability of equipment for developing and implementing a smoothness specification based on pavement profile. For this purpose, comparative evaluations were made between rod and level profiles and corresponding data from available pavement profilers. Based on the results of these comparisons, it is clear that:

1. devices are available for collecting profile data that are accurate and repeatable; and
2. the availability of lightweight profilers makes it viable for highway agencies to develop and implement profile-based smoothness specifications, particularly for Portland cement concrete pavements.

The experience with the equipment evaluation revealed a greater variety in the profilers available, ranging from automated devices that provide unfiltered or true profiles, lightweight inertial profilers mounted on tractors or golf carts, automated portable profiling equipment that may be mounted on any conventional vehicle, and the traditional van-mounted inertial profilers. There are more options available to highway agencies and the paving industry, and profilers can be purchased relatively cheap. More important, the availability of lightweight profilers allows highway agencies to use profile measurements as a basis for evaluating the quality of pavement smoothness on construction projects, for both bituminous and concrete pavements. The practical significance of this for pavement management is that it allows highway agencies to implement a consistent measure of pavement smoothness throughout the life-cycle of a given roadway. In Texas, new or resurfaced pavements are accepted based on the profile index from a profilograph. However, once the pavement is put into service, its smoothness over time is monitored using the Present Serviceability Index computed from pavement profile. Additionally, if the pavement is included in the Highway Performance Monitoring System (HPMS) data base, the department is required to report the IRI from the measured profile. This situation exists in many other highway agencies. Having the initial surface profile allows highway agencies to tie the as-built smoothness to the rest of the performance history on a given segment which will benefit pavement management, particularly in establishing the effect of initial smoothness on pavement performance.

Changing over to a different method of evaluating pavement smoothness during construction requires considerable thought. Although profilers are relatively more affordable now than they were a few years ago, the capital expense, particularly for a lightweight inertial profiler, is about 1.5 to 2 times the initial cost of an automated profilograph. However, the comparison is not straightforward since profile measurements with inertial profilers are easier, faster, and more accurate. It is not the intent of this report to debate the pros and cons of converting from a profilograph-based smoothness specification to one that is based on profiles measured using the types of equipment evaluated in this study. Rather, the objective is to provide information on available profilers that are useful to highway agencies considering the development and implementation of a profile-based smoothness specification. When implementing such a specification, there is a need to verify that the profilers used for construction quality control and assurance yield acceptable data with respect to an established standard or reference. Applicable guidelines for evaluating pavement profilers are given in Appendix D of this report. To ensure that accurate, precise, uniform, and comparable profile measurements are obtained during construction, a facility should be constructed for evaluating pavement profilers. In connection with this, the researchers offer the following recommendations:

1. The calibration facility should have at least two sections, one smooth and the other, medium-smooth. The profiles on these calibration sections should be measured on a regular basis with static methods such as the rod and level, Dipstick, or other suitable devices that provide true profiles and meet the resolution requirements of ASTM E 1364. For the purpose of establishing a reference to evaluate profile equipment, rod and level measurements should conform, as a minimum, to the requirements for a second order, Class II survey, established by the Federal Geodetic Control Committee (FGCC) and specified in Section 3.5 of the FGCC Standards and Specifications for Geodetic Control Networks (1993). Applicable provisions of this specification are

given in Appendix E. In addition, guidelines for rod and level surveys have been established by the Strategic Highway Research Program (SHRP, 1994).

2. It is recommended that each calibration section have a length equal to the test interval used in the current profilograph specification. This interval is 161 m in the existing TxDOT smoothness specification. There should be sufficient lead-in to each section so that inertial profilers can reach the required operational speed, and the accelerometers can stabilize prior to the start of the section. As a guideline, the length of this lead-in should be at least 1.5 times the cutoff wavelength of the filter used, based on the evaluation presented in Appendix B. A length equal to twice the cutoff wavelength is recommended. The lead-in profiles should be measured on a regular basis just like the profiles of the calibration sections to evaluate the accuracy of profiles from a given inertial profiler. Sufficient distance must also be available beyond the end of a calibration section for an inertial profiler to slow down and come to a halt.
3. The evaluation of pavement profilers should be made not only on the basis of measured profiles but also on profile-based statistics that are determined as part of the intended profiler applications.

A set of standard parameters should also be established for the operation of inertial profilers on paving projects where the smoothness specification is enforced. For Texas, researchers recommend adopting the same filter and cutoff wavelength presently implemented in TxDOT's profilers. This will provide for consistency between profile measurements made in conjunction with the smoothness specification, and those that are conducted as part of TxDOT's pavement condition surveys, sponsored research projects, field investigations, and other activities for which profiles are collected. In addition, researchers recommend a reporting interval of 150 mm or less and a resolution of 0.1 mm or finer for the reported elevations. Most inertial profilers already meet or exceed these proposed requirements. The Laser Rut/Profiler evaluated in this study has already been modified by TxDOT to report elevations at 143 mm spacings in lieu of 266 mm, the interval at which profile data were collected herein.

For consistency in the evaluation of pavement smoothness from profile measurements, data collected using devices that measure and integrate differential elevations must also be filtered using the specified filter. To guard against mistracking, it is advisable that rod and level measurements be made at the beginning and end of a test segment to verify the profiles from these devices and to adjust the profiles as appropriate.

Finally, the evaluation of profile data taken on simulated bumps suggests that a permissible bump criterion, as applied in the existing profilograph specification, is not applicable in a profile-based specification. While the results show clearly that bumps can be detected and located from the data taken with the profilers evaluated, bump heights were not accurately determined. Bump heights estimated from the CSC and WPR profiles showed significant discrepancies with respect to rod and level data taken on the same bumps. Researchers surmise that these discrepancies result mainly from the inaccuracies in the CSC and WPR profile data measured with the simulated bumps in place. With respect to the inertial profilers, it was not possible to estimate the bump height because of the distortion in the bump profile attributed to filtering. This distortion skews the baseline for measuring the bump height according to the procedure used in the existing profilograph specification. In view of these findings, there is a need to evaluate the applicability of a bump height criterion in a profile-based smoothness specification, and to investigate techniques to reduce or counteract the distortion caused by filtering of the bump profile. An alternative is to develop and use a smoothness statistic, calculated from pavement profile, that accounts for the effects of bumps based on criteria such as ride quality and pavement damage. Researchers are of the opinion that this approach is simpler and more meaningful since it ties the evaluation of the surface defect directly to the criteria used in the smoothness specification.

REFERENCES

1. Federal Geodetic Control Committee. *Standards and Specifications for Geodetic Control Networks.* Rockville, Maryland, 1993.
2. Fernando, E. G. *Development of a Profile-Based Smoothness Specification for Asphalt Concrete Overlays.* Research Report 1378-3F, Texas Transportation Institute, Texas A&M University, College Station, TX, 1998.
3. Kulakowski, B. T., and J. C. Wambold. *Development of Procedures for the Calibration of Profilographs.* Research Report 8920, Pennsylvania Transportation Institute, The Pennsylvania State University, University Park, PA, 1989.
4. Sayers, M. W. *On the Calculation of International Roughness Index from Longitudinal Road Profile.* Transportation Research Record 1501, Transportation Research Board, Washington, D. C., 1995, pp. 1-12.
5. Sayers, M. W., T. D. Gillespie, and W. D. Paterson. *Guidelines for the Conduct and Calibration of Road Roughness Measurements.* World Bank Technical Paper 46, World Bank, Washington, D. C., 1986.
6. Sayers, M. W., T. D. Gillespie, and C. Queiroz. *International Experiment to Establish Correlations and Standard Calibration Methods for Road Roughness Measurements.* World Bank Technical Paper 45, World Bank, Washington, D. C., 1986.
7. Scofield, L. *Profilograph Limitations, Correlations, and Calibration Criteria for Effective Performance-Based Specifications.* NCHRP Project 20-7, Task 53, National Cooperative Highway Research Program, Washington, D. C., 1993.
8. Stearns, S. D., and R. A. David. *Signal Processing Algorithms in FORTRAN and C.* Prentice Hall Signal Processing Series, New Jersey, 1993.
9. Strategic Highway Research Program. *Manual for Profile Measurement: Operational Field Guidelines.* SHRP-P-378, National Research Council, Washington, D. C., 1994.

APPENDIX A

ORIGINAL PROFILE MEASUREMENTS FROM TEST SITES

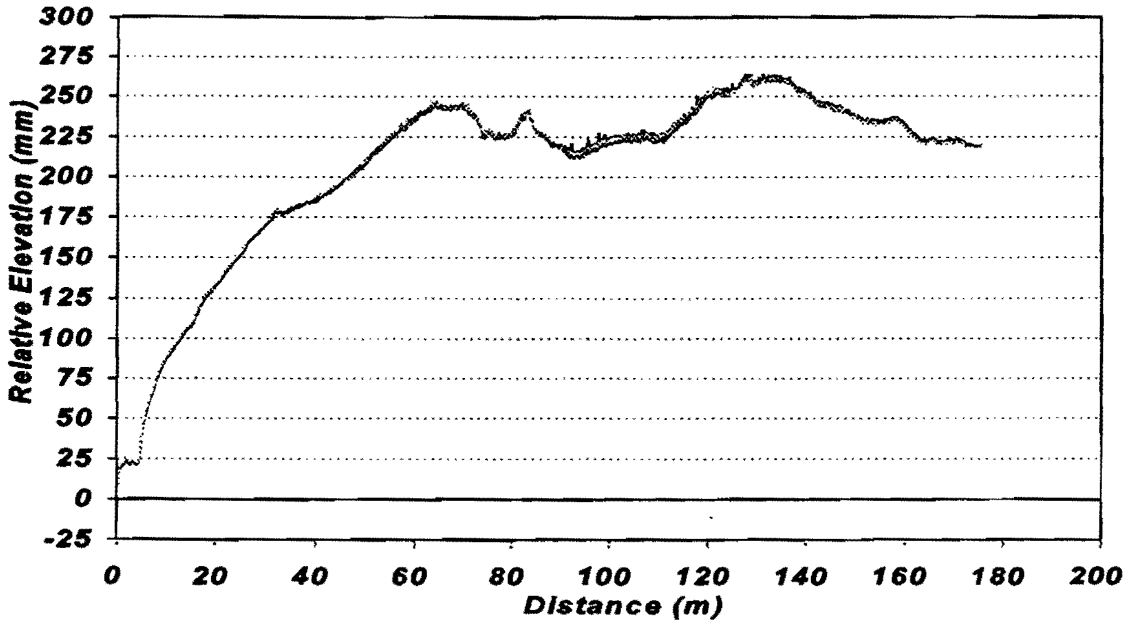

Figure A1. Original Profiles from Rod & Level on Annex 1 Site.

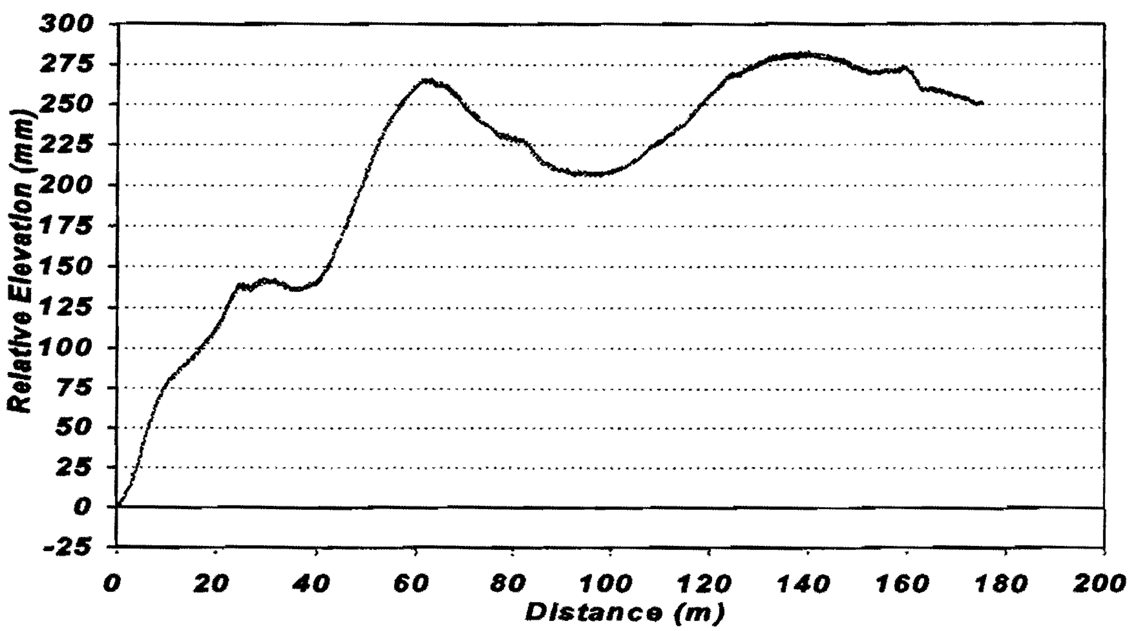

Figure A2. Original Profiles from Rod & Level on Annex 2 Site.

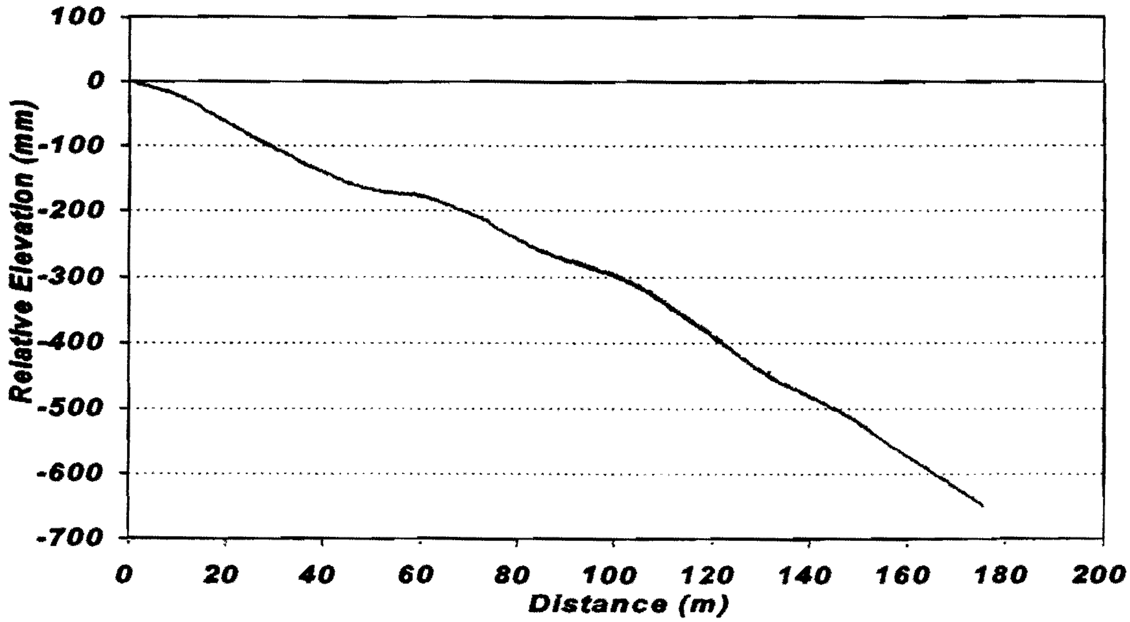

Figure A3. Original Profiles from Rod & Level on SH47A, LWP.

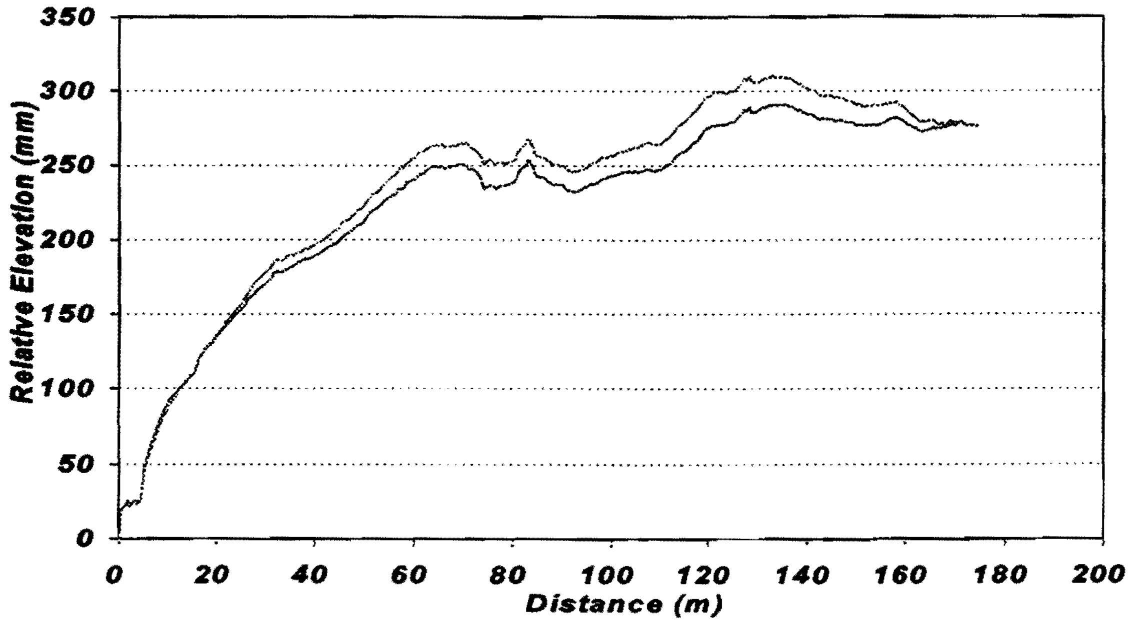

Figure A4. Original Profiles from CSC Digital Profilite on Annex 1 Site.

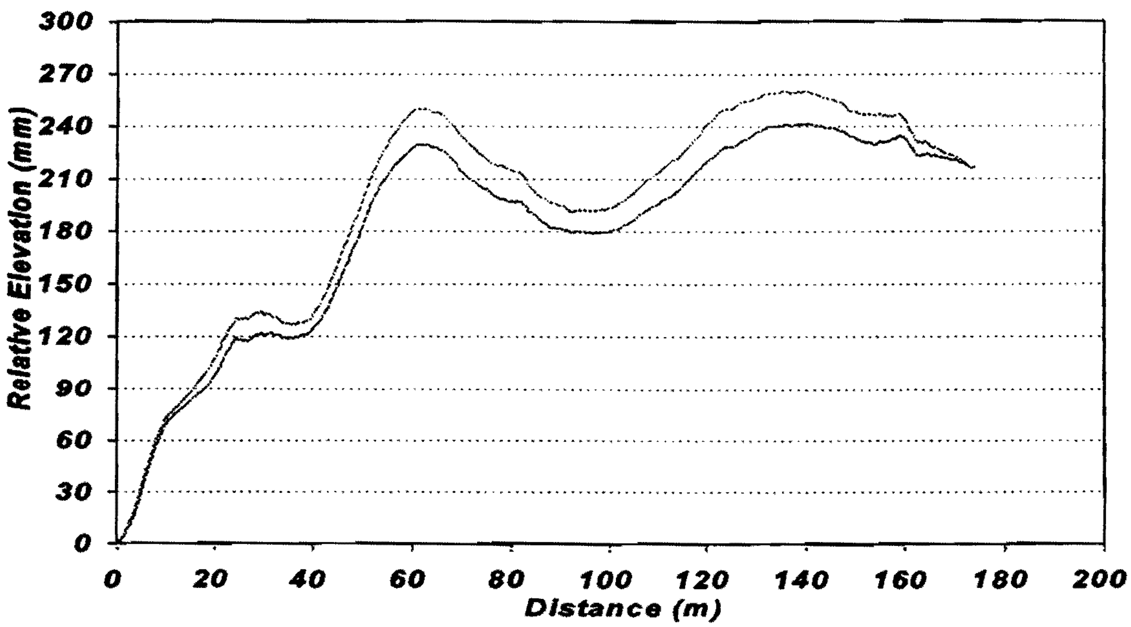

Figure A5. Original Profiles from CSC Digital Profilite on Annex 2 Site.

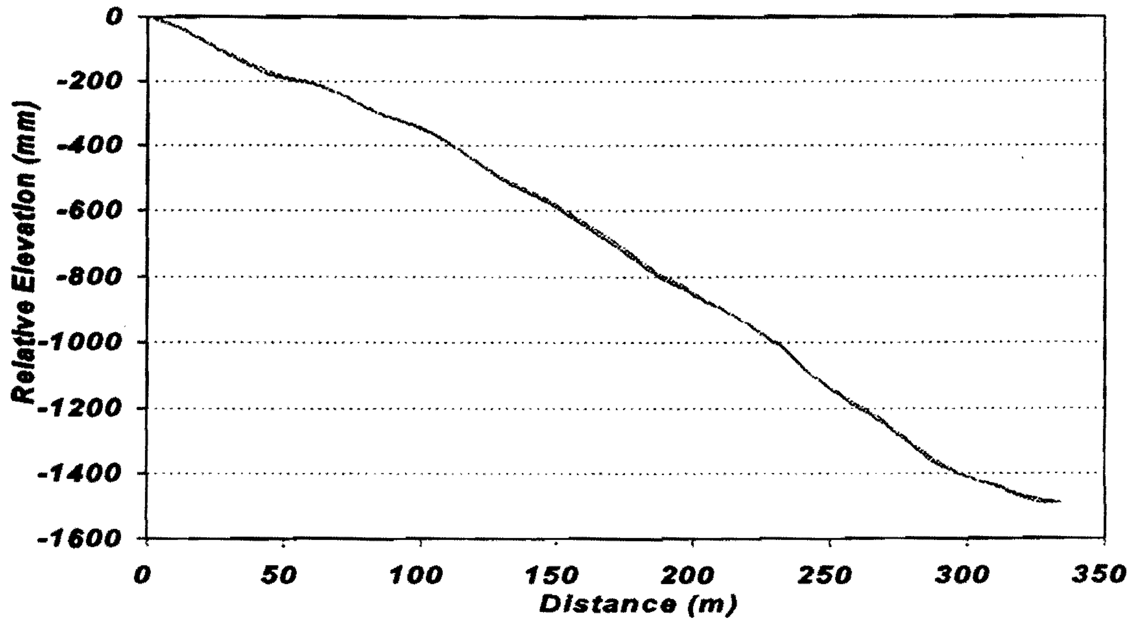

Figure A6. Original Profiles from CSC Digital Profilite on SH47A, LWP.

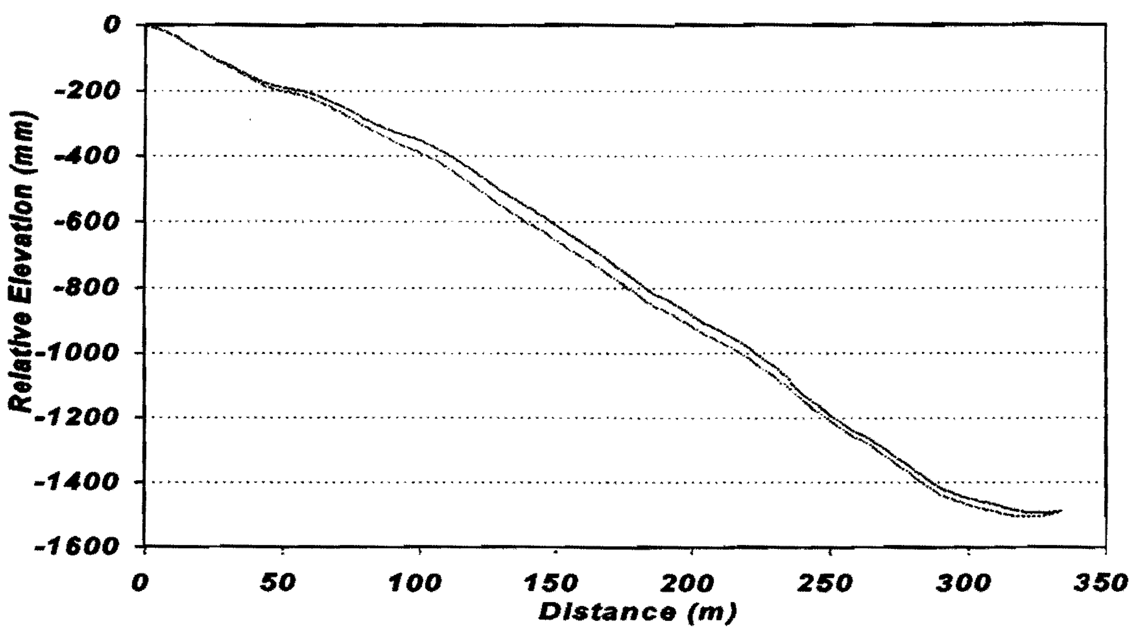

Figure A7. Original Profiles from CSC Digital Profilite on SH47A, RWP.

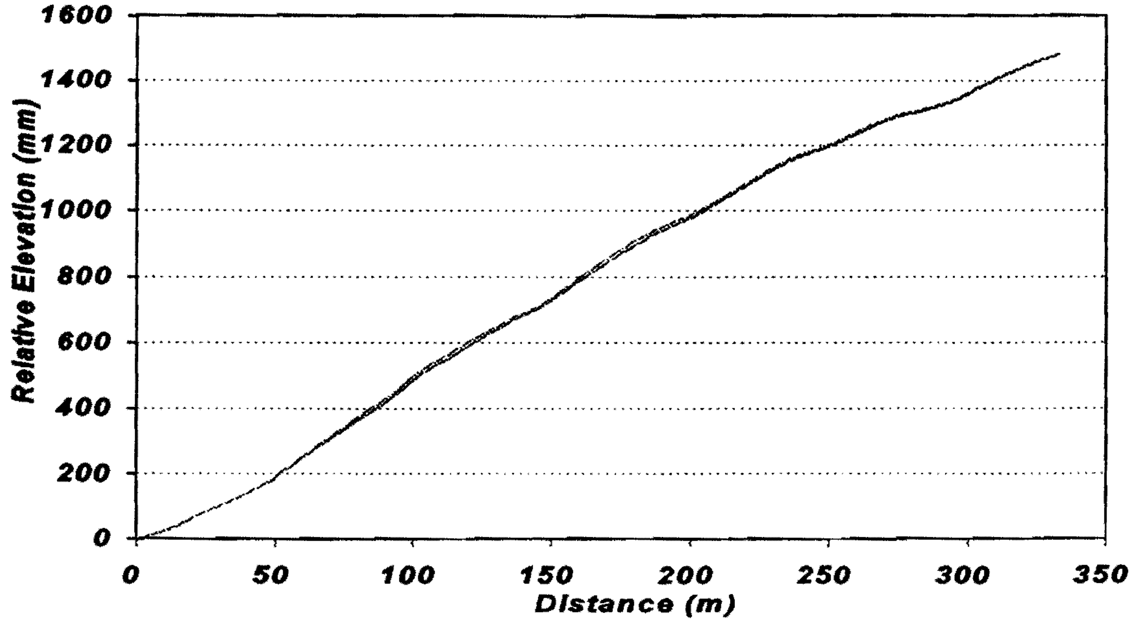

Figure A8. Original Profiles from CSC Digital Profilite on SH47B, LWP.

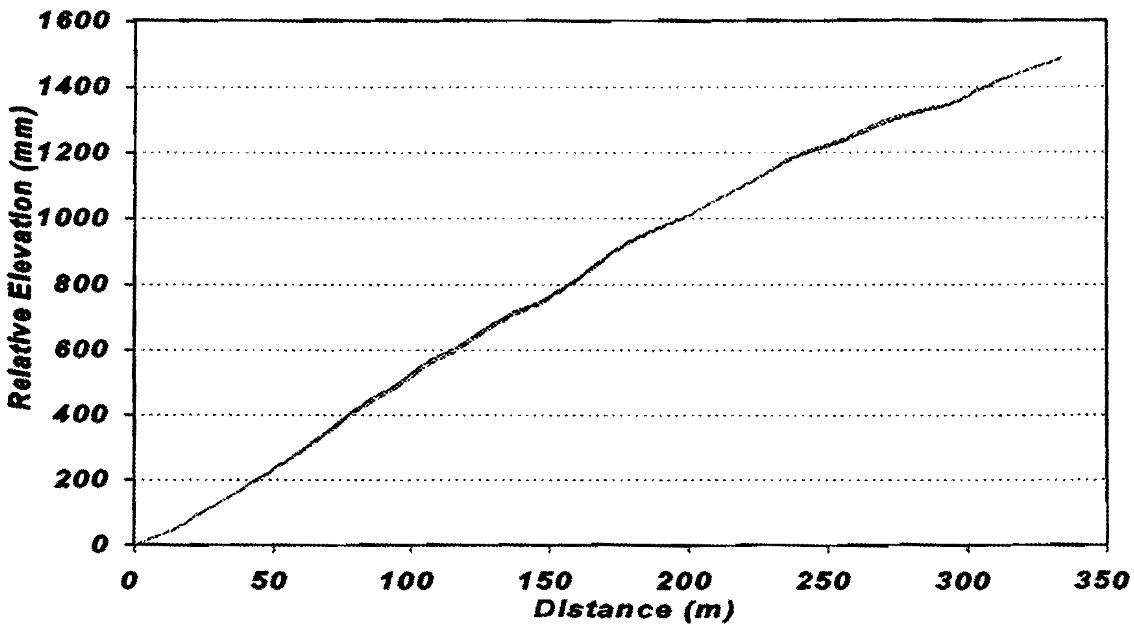

Figure A9. Original Profiles from CSC Digital Profilite on SH47B, RWP.

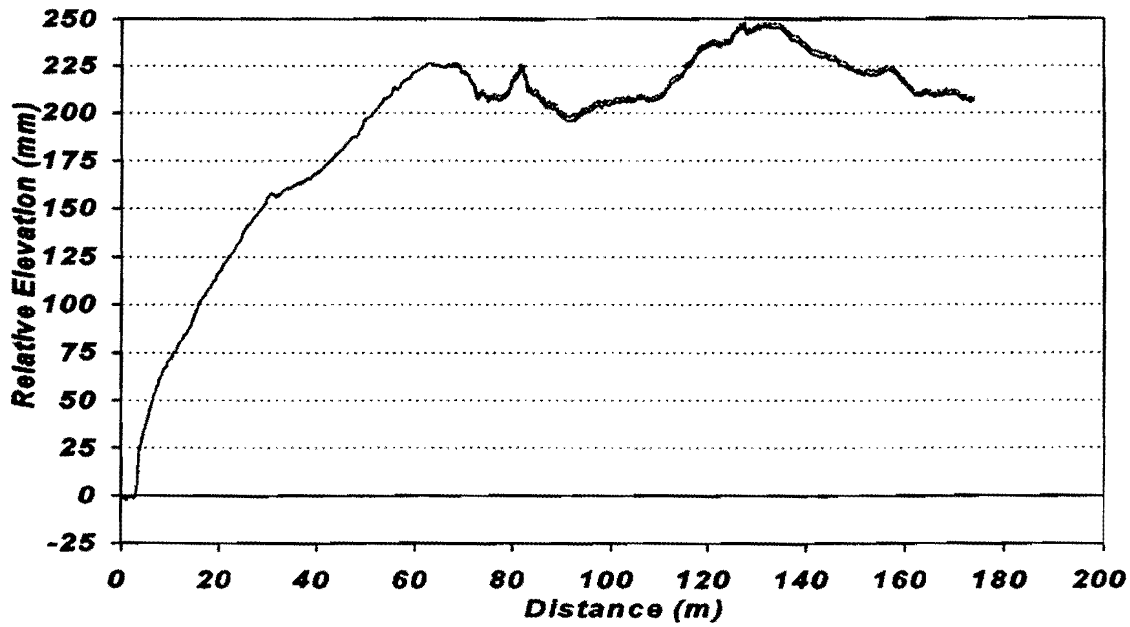

Figure A10. Original Profiles from Walking Profiler on Annex 1 Site.

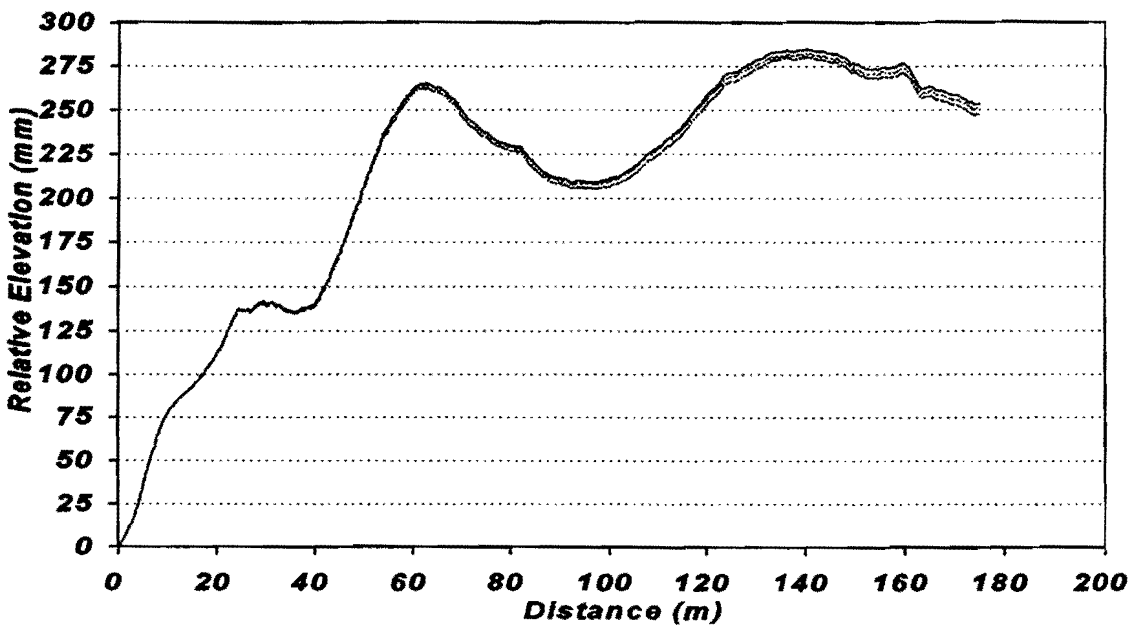

Figure A11. Original Profiles from Walking Profiler on Annex 2 Site.

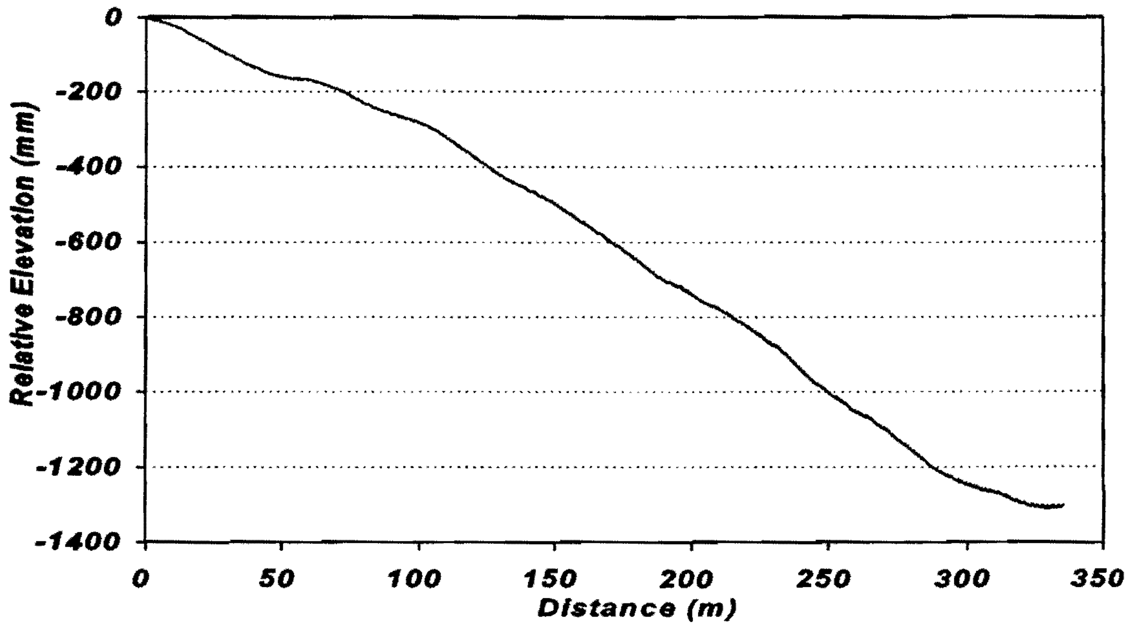

Figure A12. Original Profiles from Walking Profiler on SH47A, LWP.

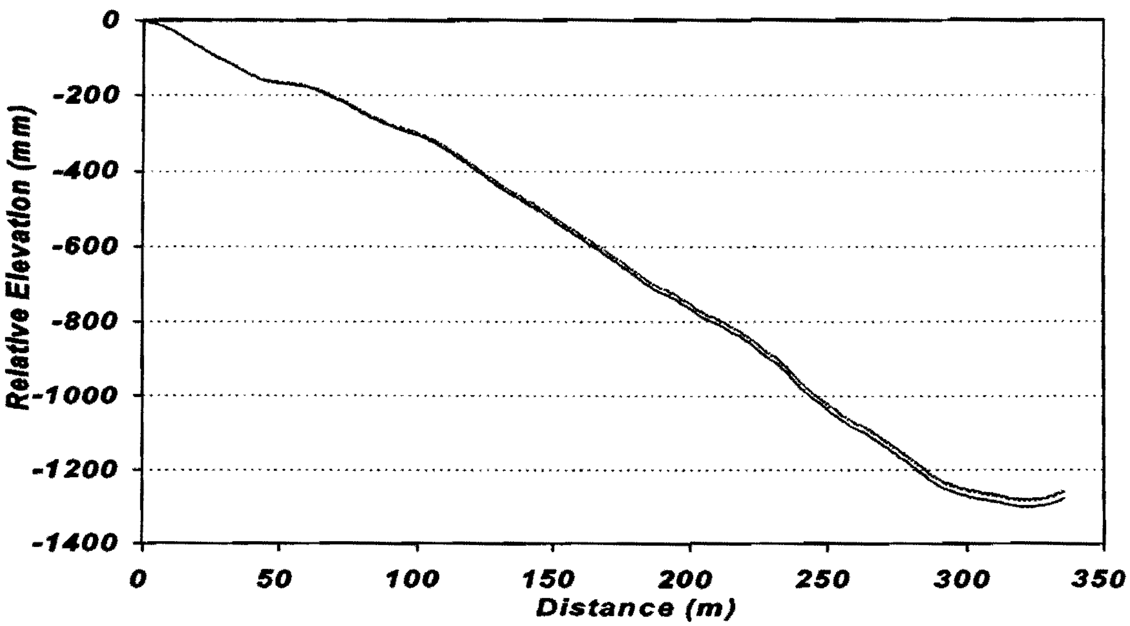

Figure A13. Original Profiles from Walking Profiler on SH47A, RWP.

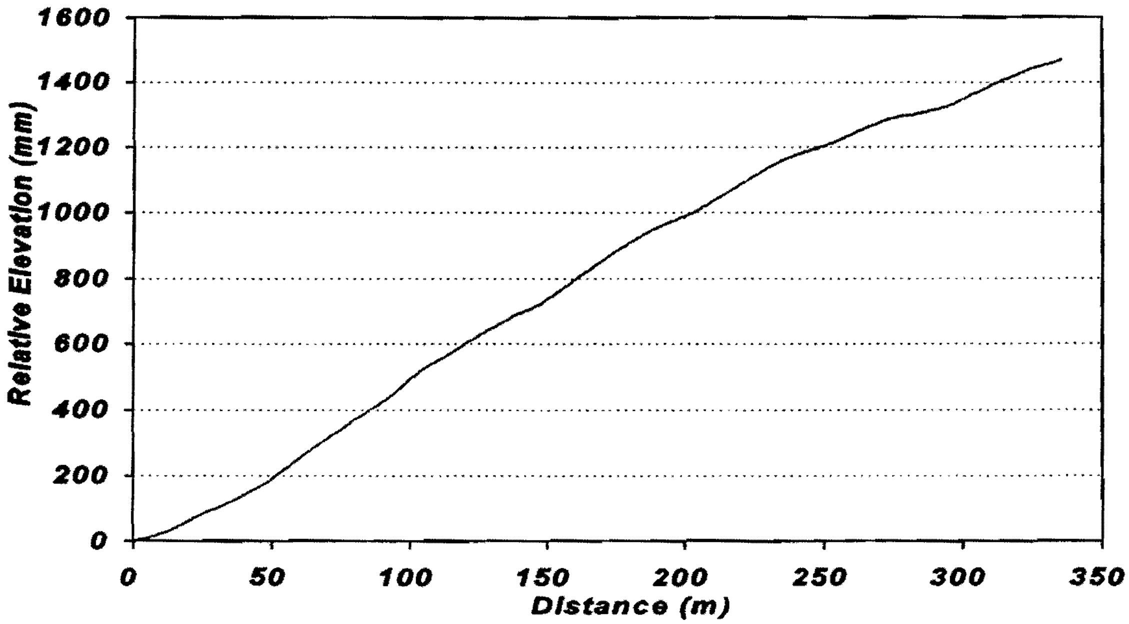

Figure A14. Original Profiles from Walking Profiler on SH47B, LWP.

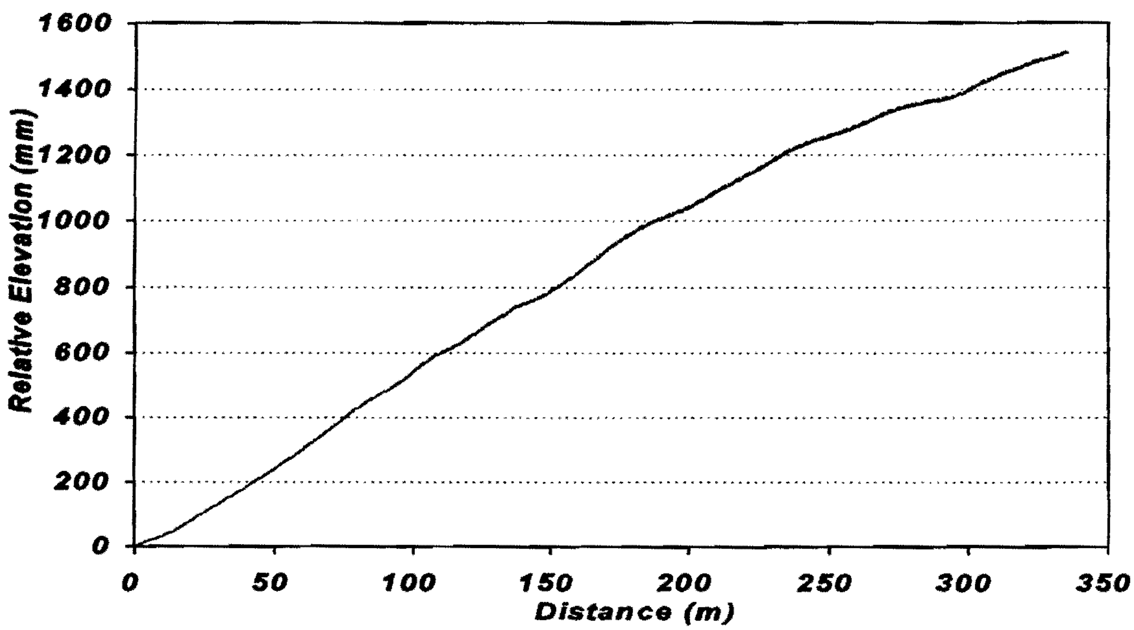

Figure A15. Original Profiles from Walking Profiler on SH47B, RWP.

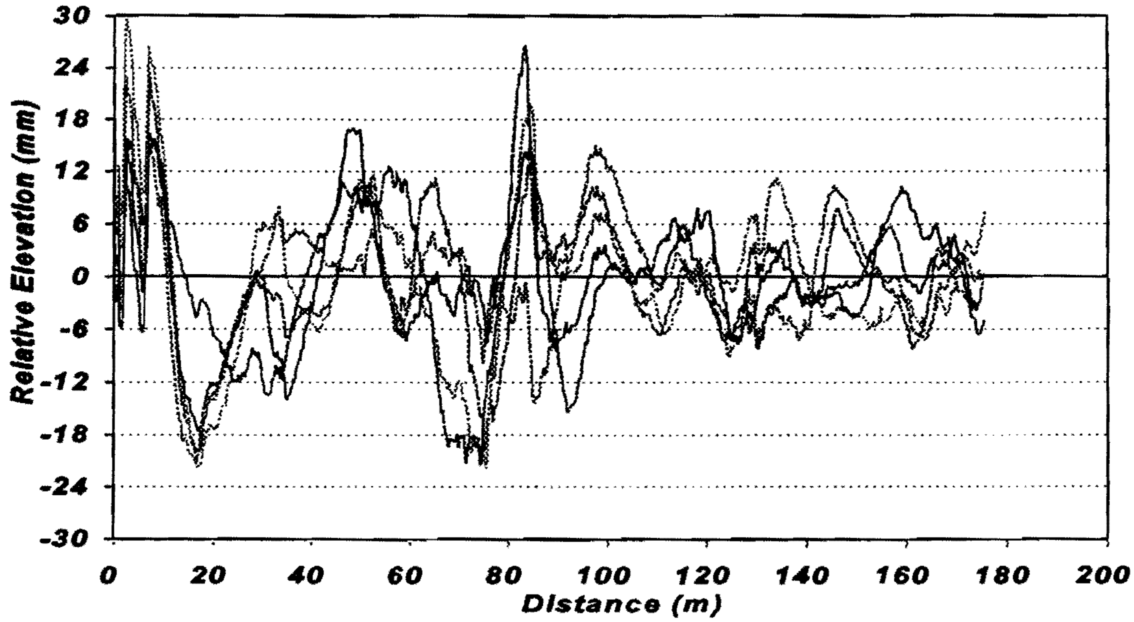

Figure A16. Original Profiles from K. J. Law T6400 Profiler on Annex 1 Site.

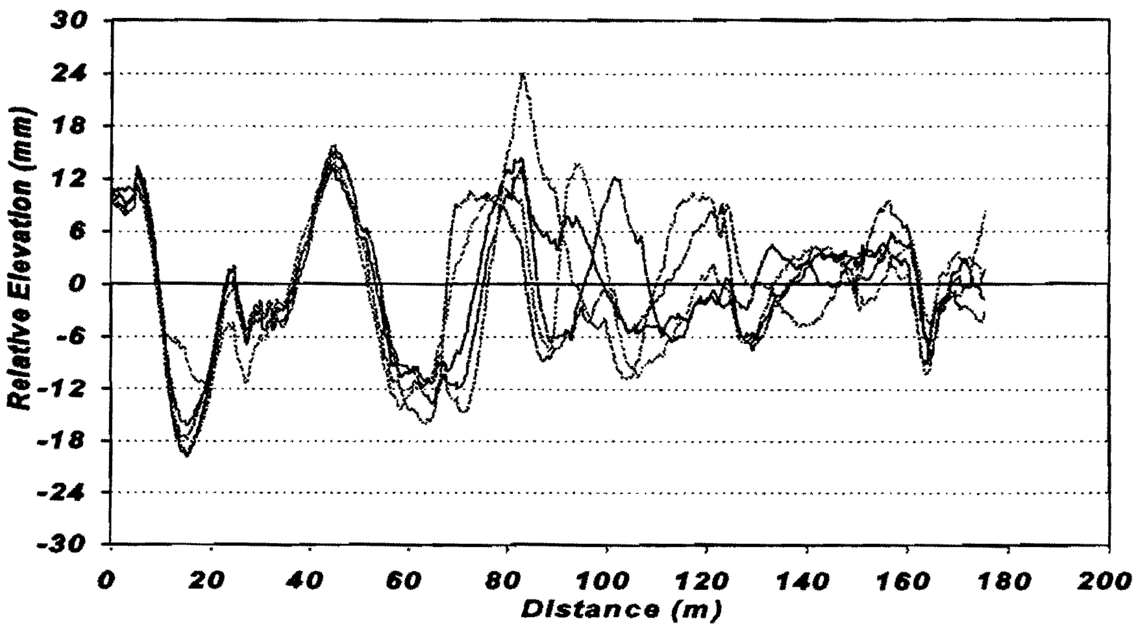

Figure A17. Original Profiles from K. J. Law T6400 Profiler on Annex 2 Site.

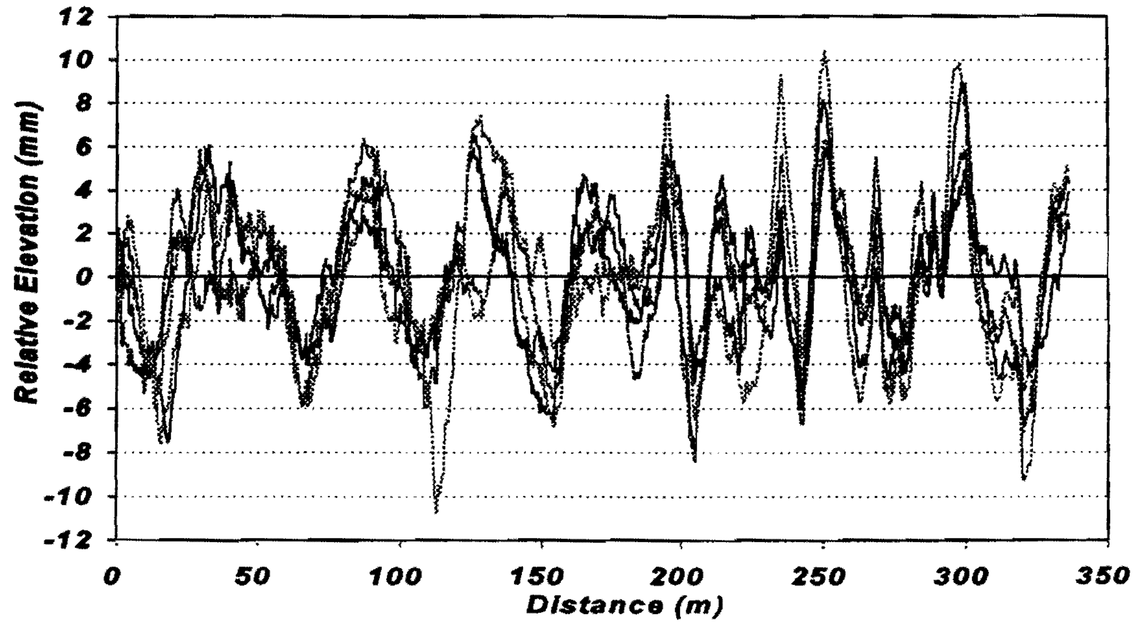

Figure A18. Original Profiles from K. J. Law T6400 Profiler on SH47A, LWP.

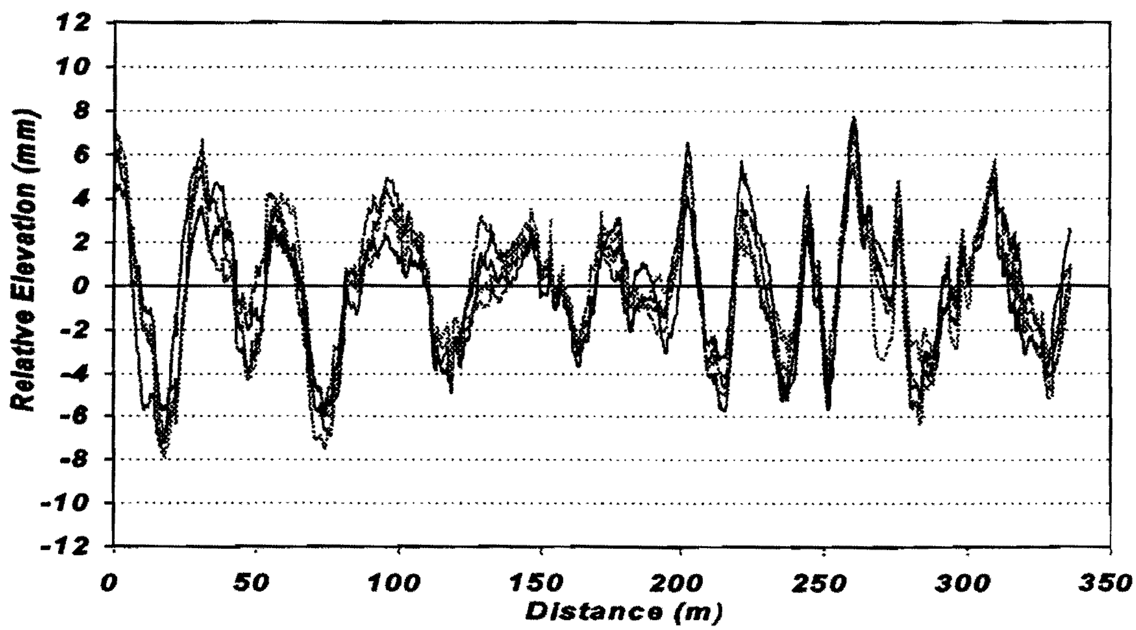

Figure A19. Original Profiles from K. J. Law T6400 Profiler on SH47A, RWP.

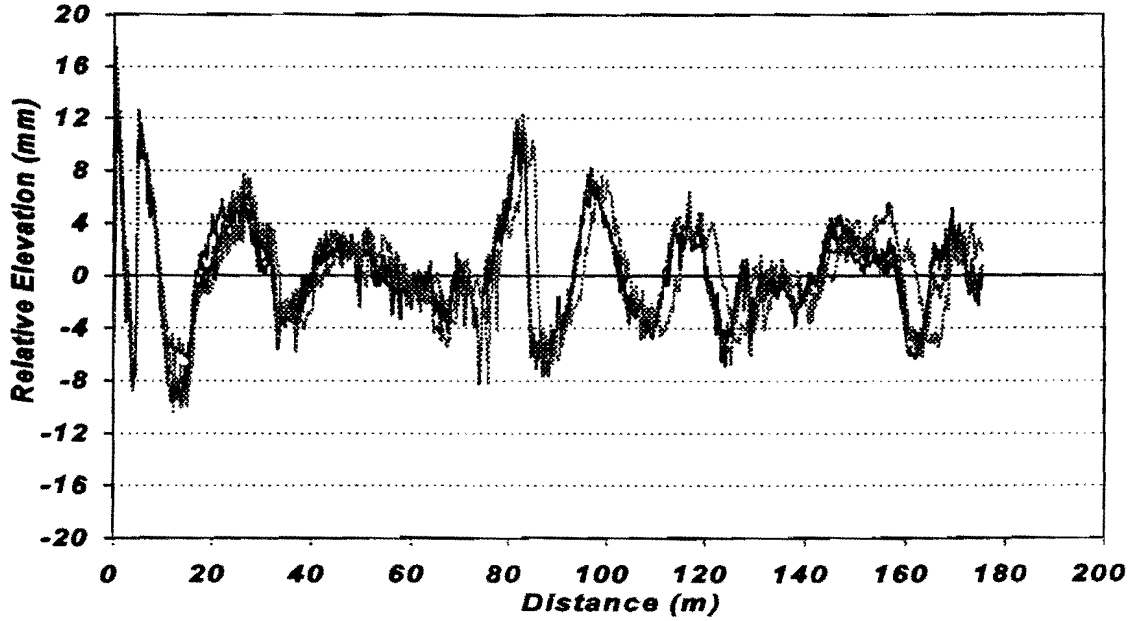

Figure A20. Original Profiles from LISA on Annex 1 Site.

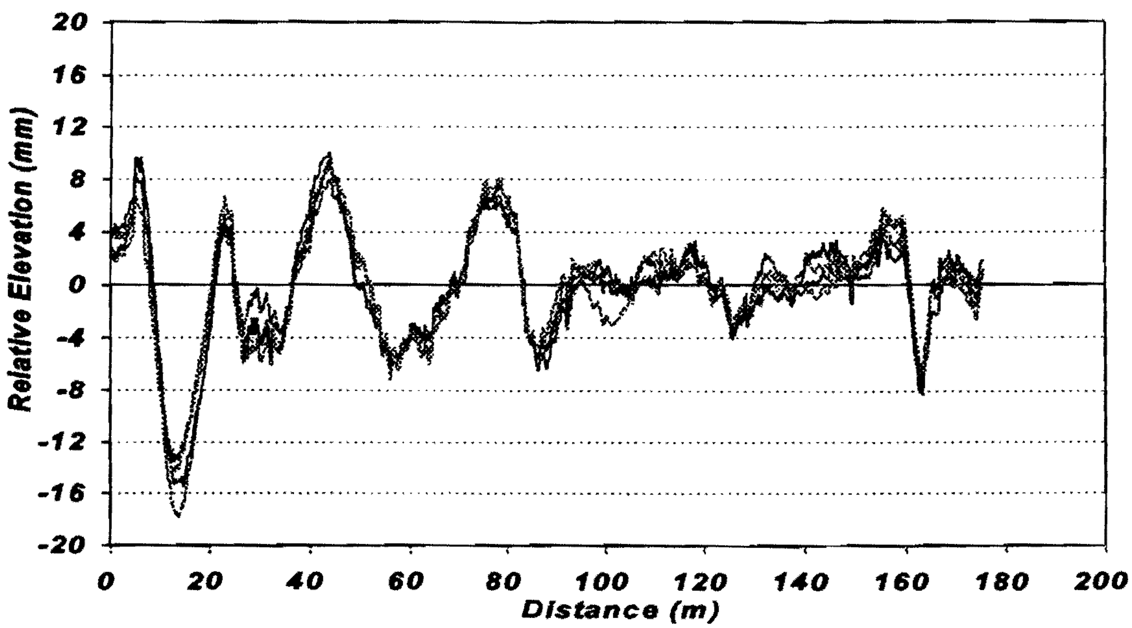

Figure A21. Original Profiles from LISA on Annex 2 Site.

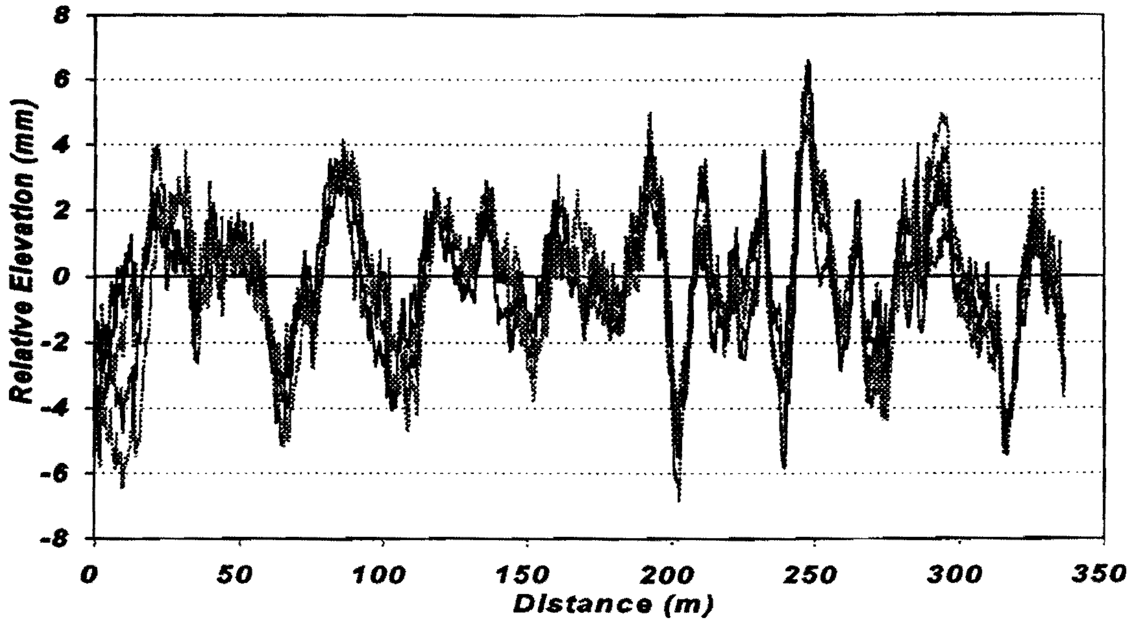

Figure A22. Original Profiles from LISA on SH47A, LWP.

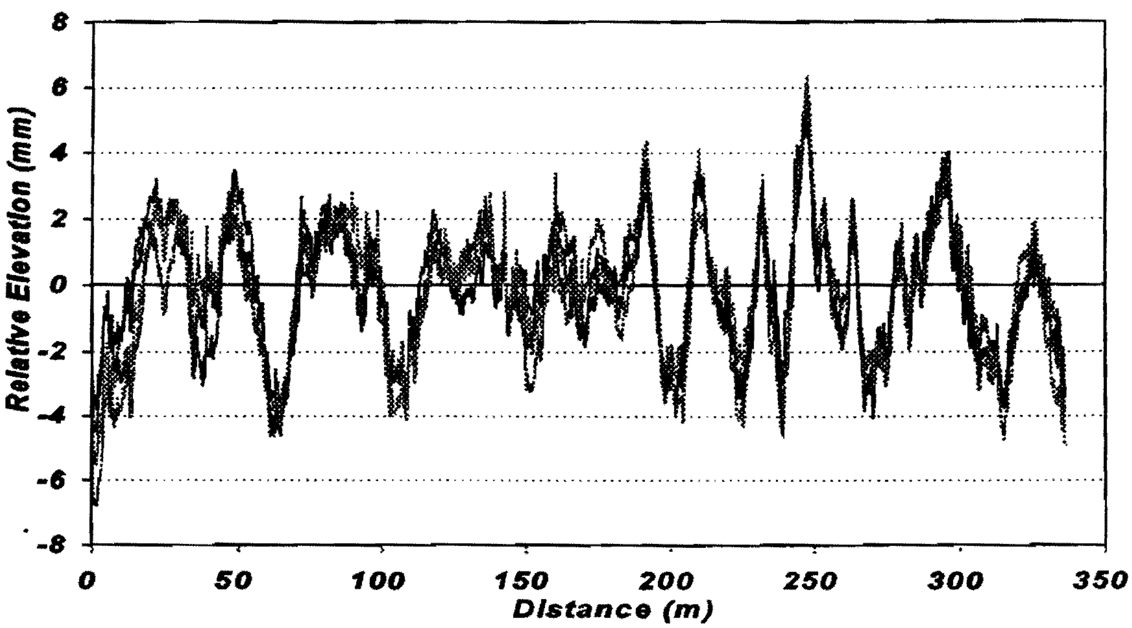

Figure A23. Original Profiles from LISA on SH47A, RWP.

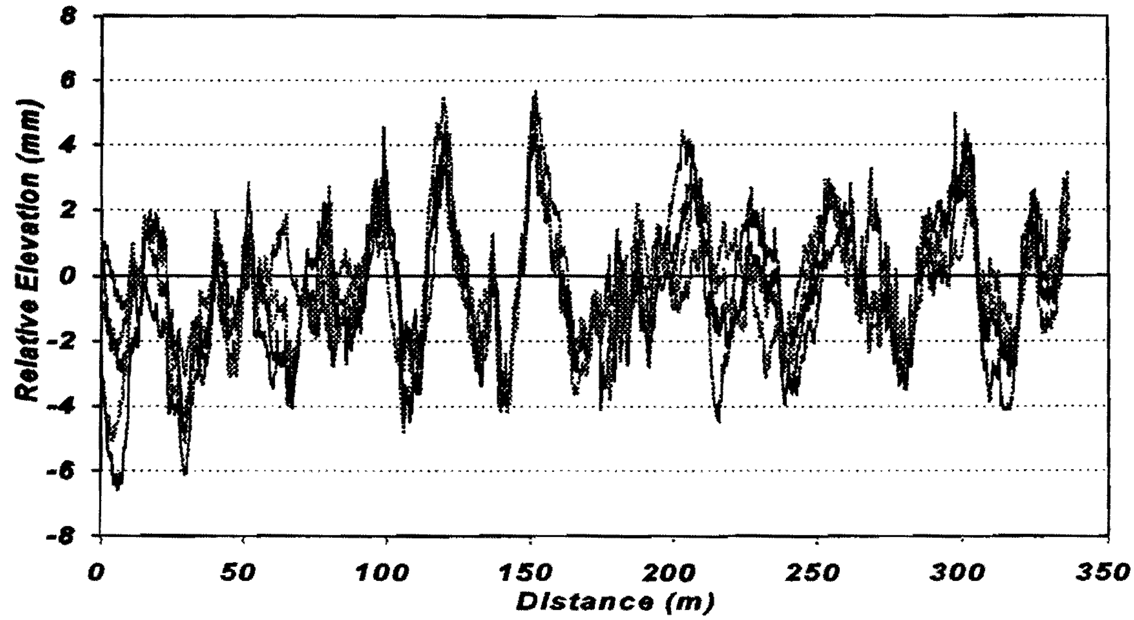

Figure A24. Original Profiles from LISA on SH47B, LWP.

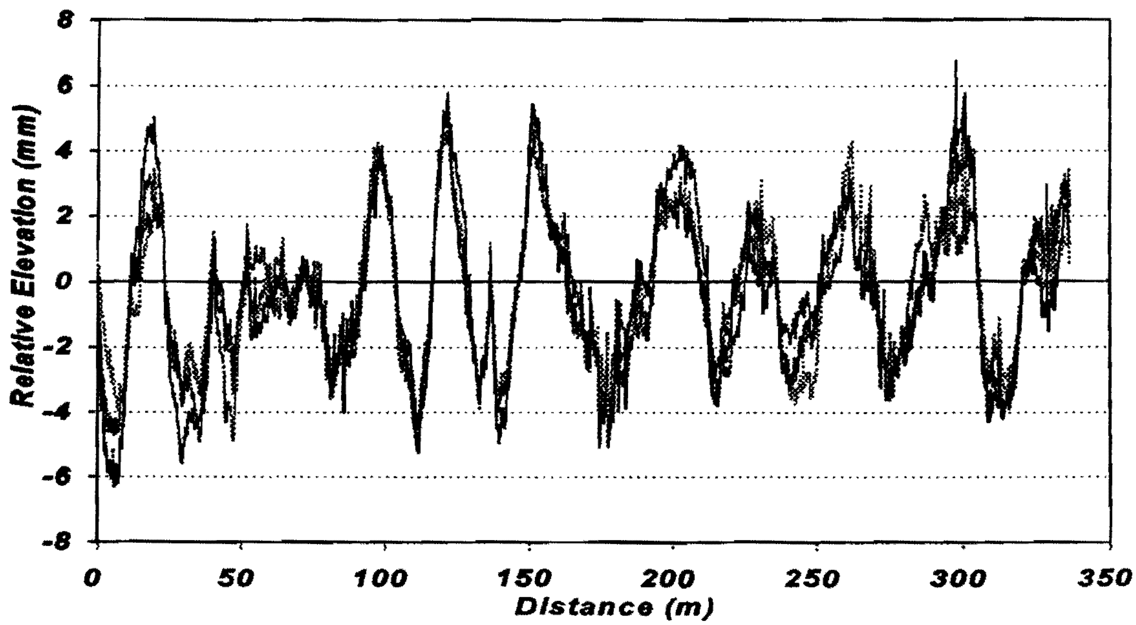

Figure A25. Original Profiles from LISA on SH47B, RWP.

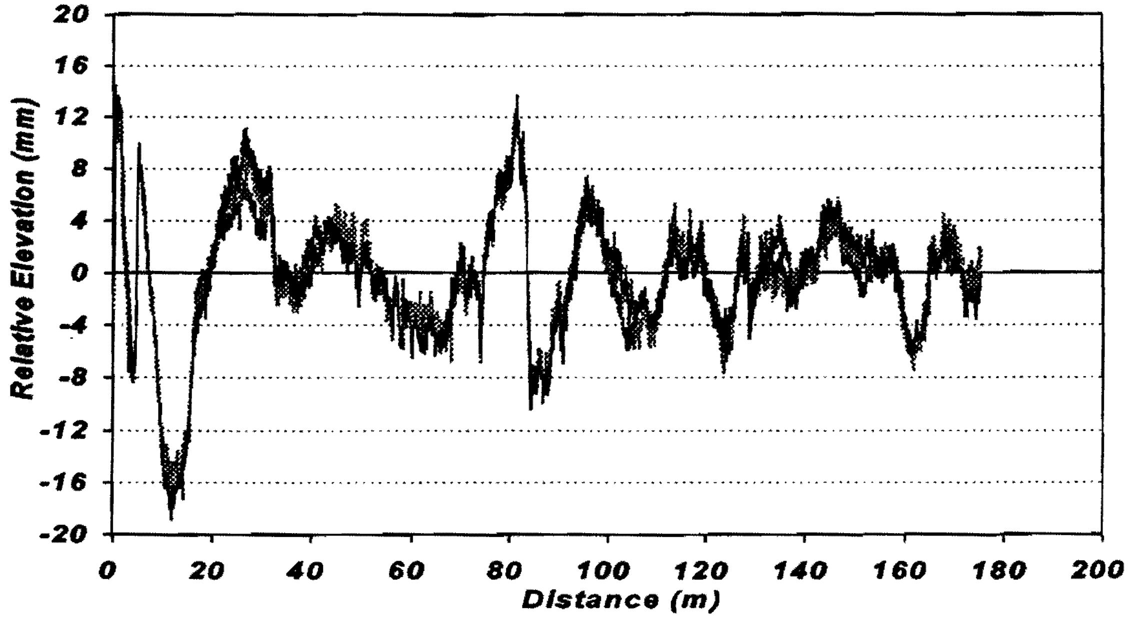

Figure A26. Original Profiles from Construction Profiler on Annex 1 Site.

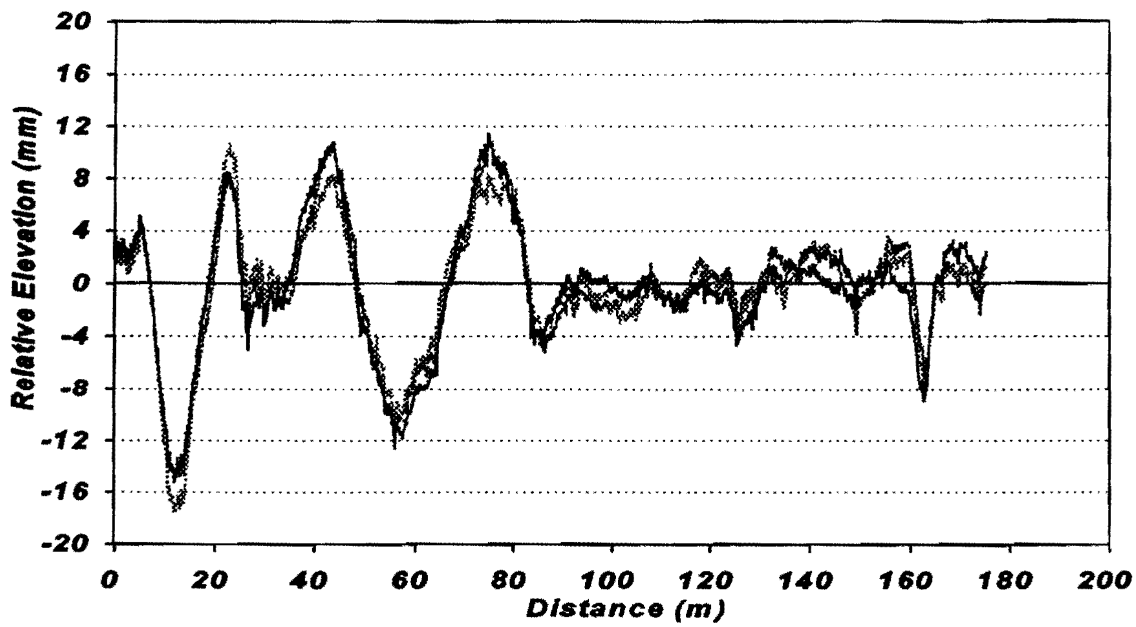

Figure A27. Original Profiles from Construction Profiler on Annex 2 Site.

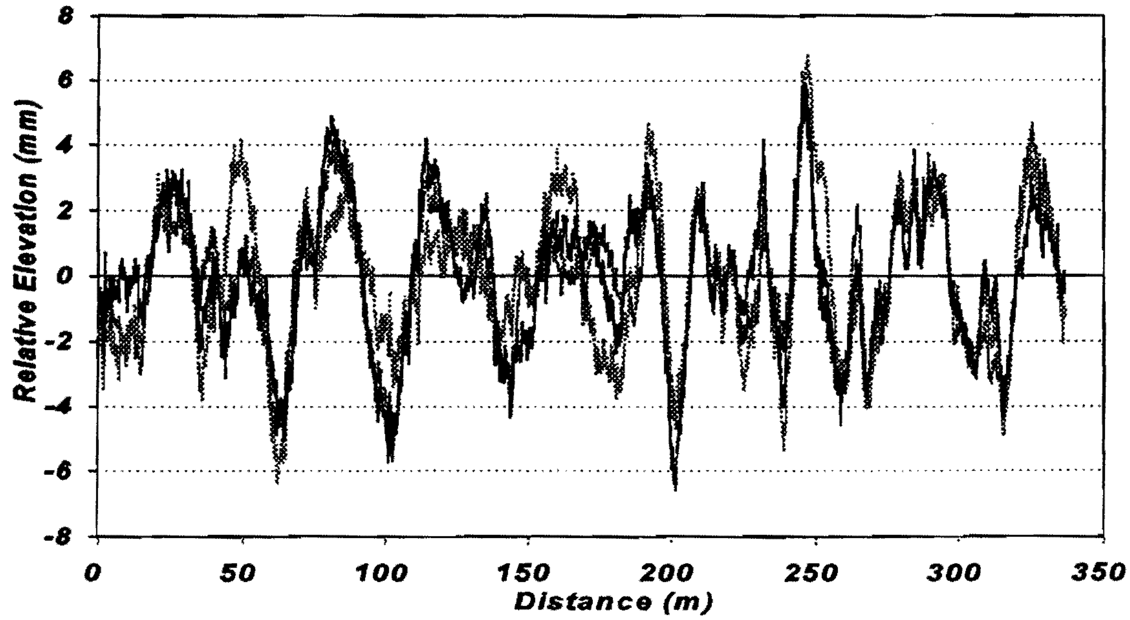

Figure A28. Original Profiles from Construction Profiler on SH47A, LWP.

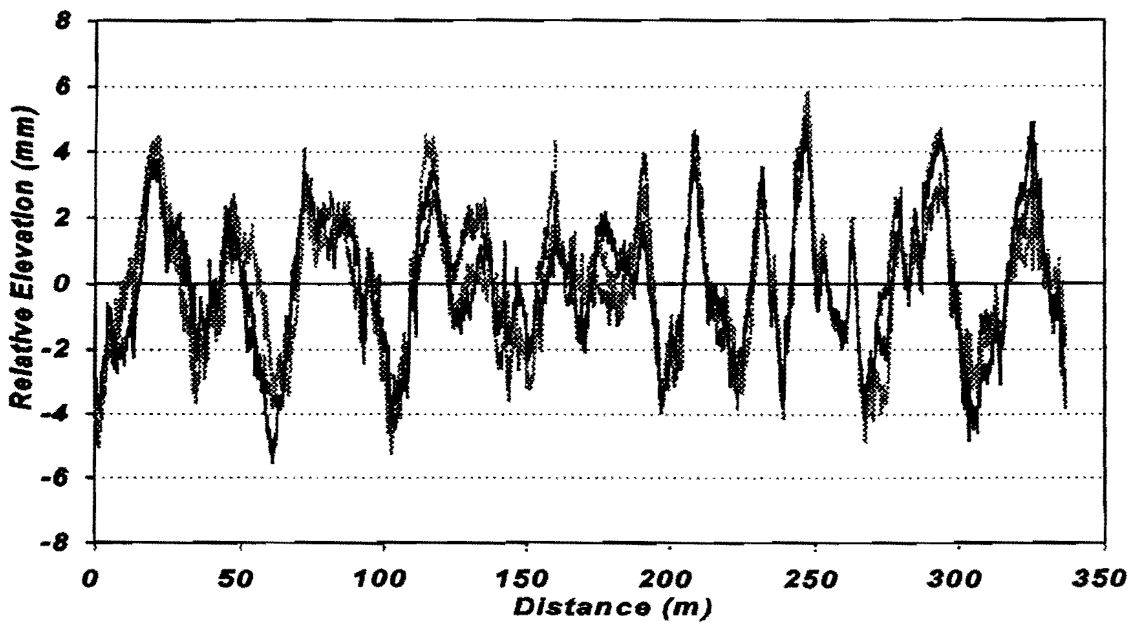

Figure A29. Original Profiles from Construction Profiler on SH47A, RWP.

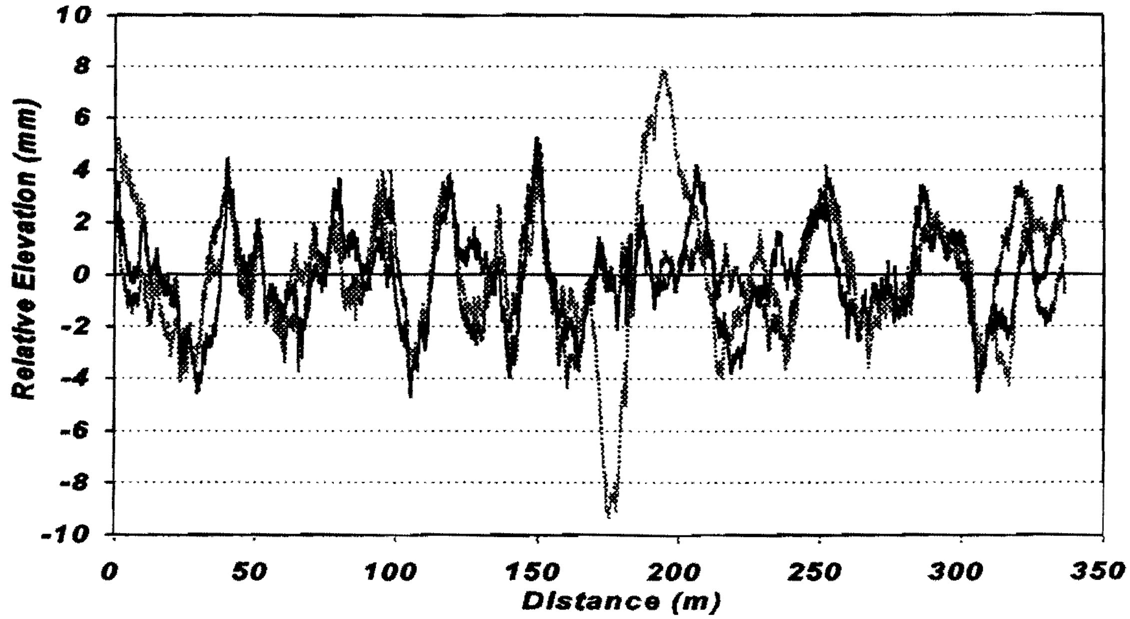

Figure A30. Original Profiles from Construction Profiler on SH47B, LWP.

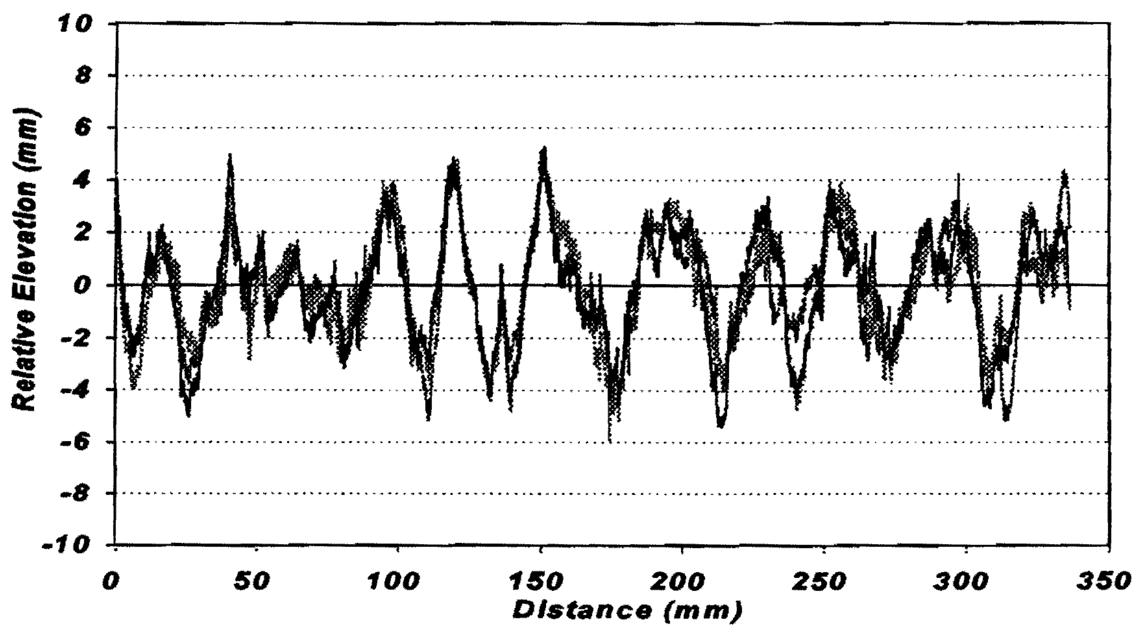

Figure A31. Original Profiles from Construction Profiler on SH47B, RWP.

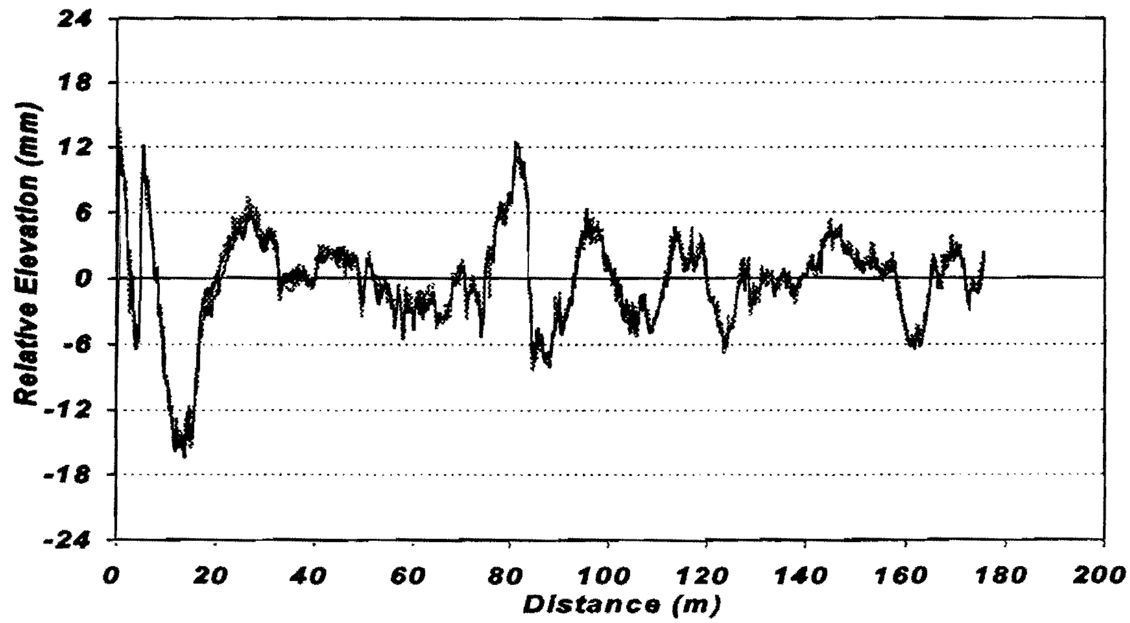

Figure A32. Original Profiles from TxDOT's Surface Profiler on Annex 1, LWP.

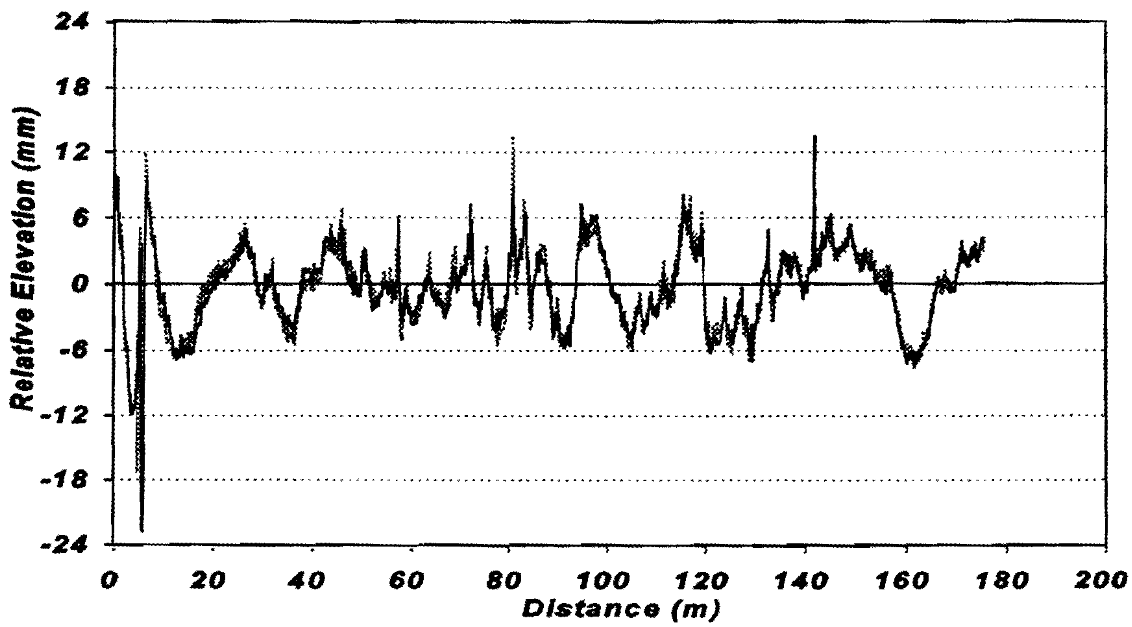

Figure A33. Original Profiles from TxDOT's Surface Profiler on Annex 1, RWP.

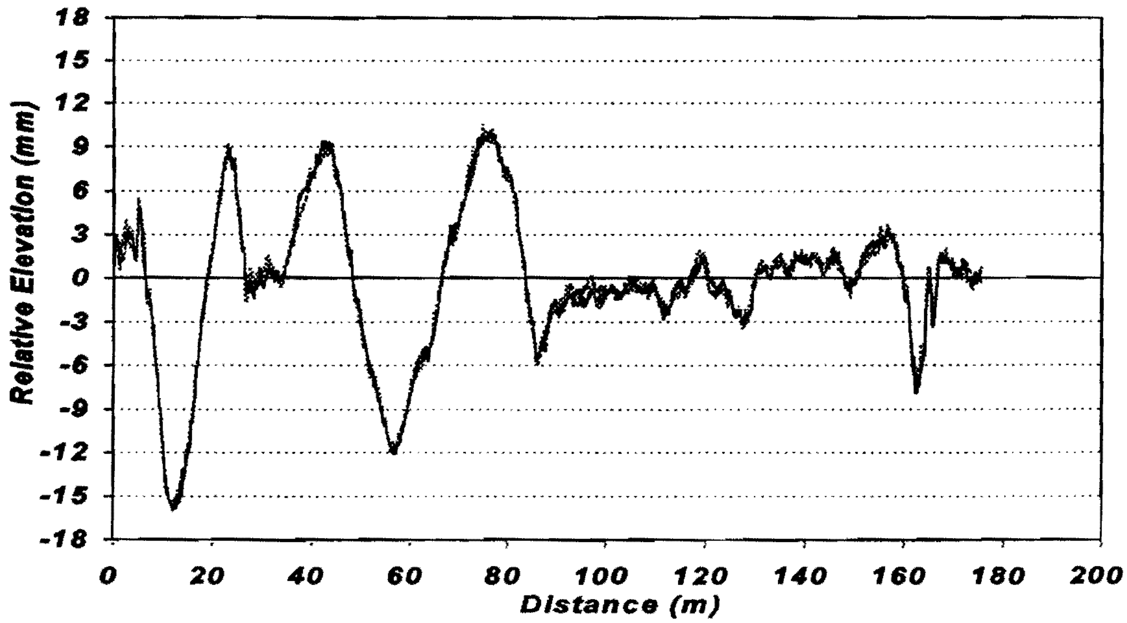

Figure A34. Original Profiles from TxDOT's Surface Profiler on Annex 2, LWP.

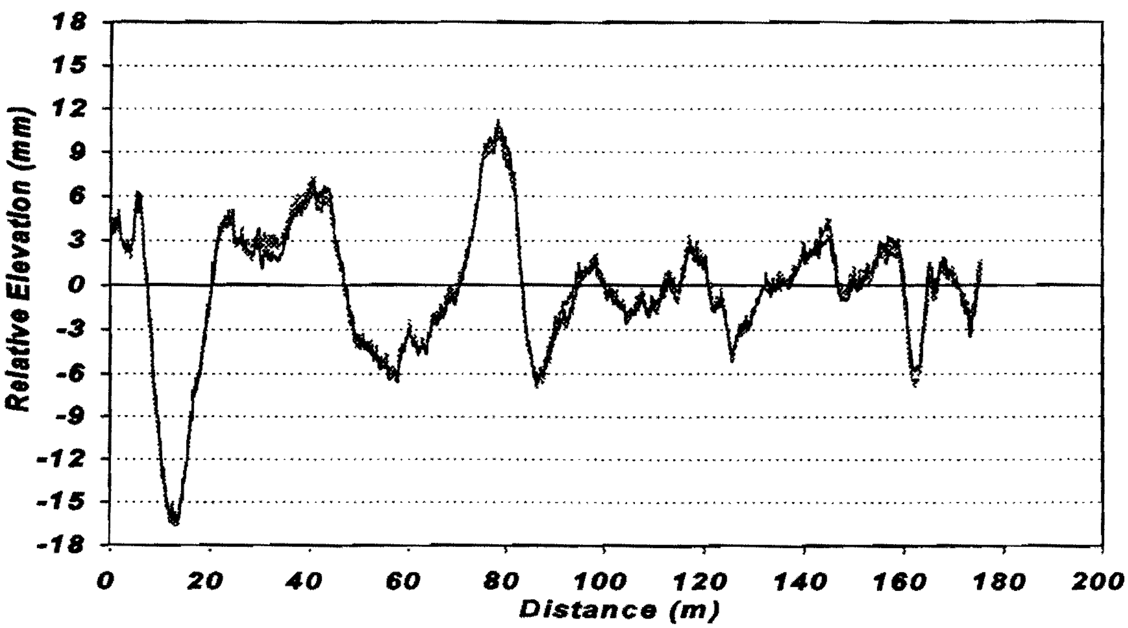

Figure A35. Original Profiles from TxDOT's Surface Profiler on Annex 2, RWP.

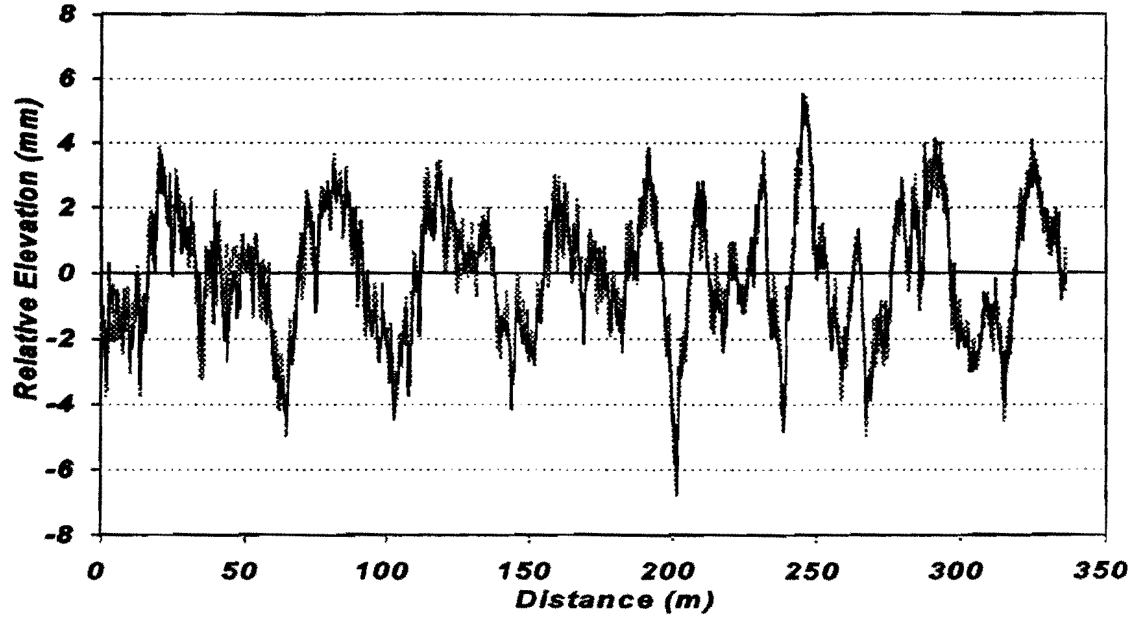

Figure A36. Original Profiles from TxDOT's Surface Profiler on SH47A, LWP.

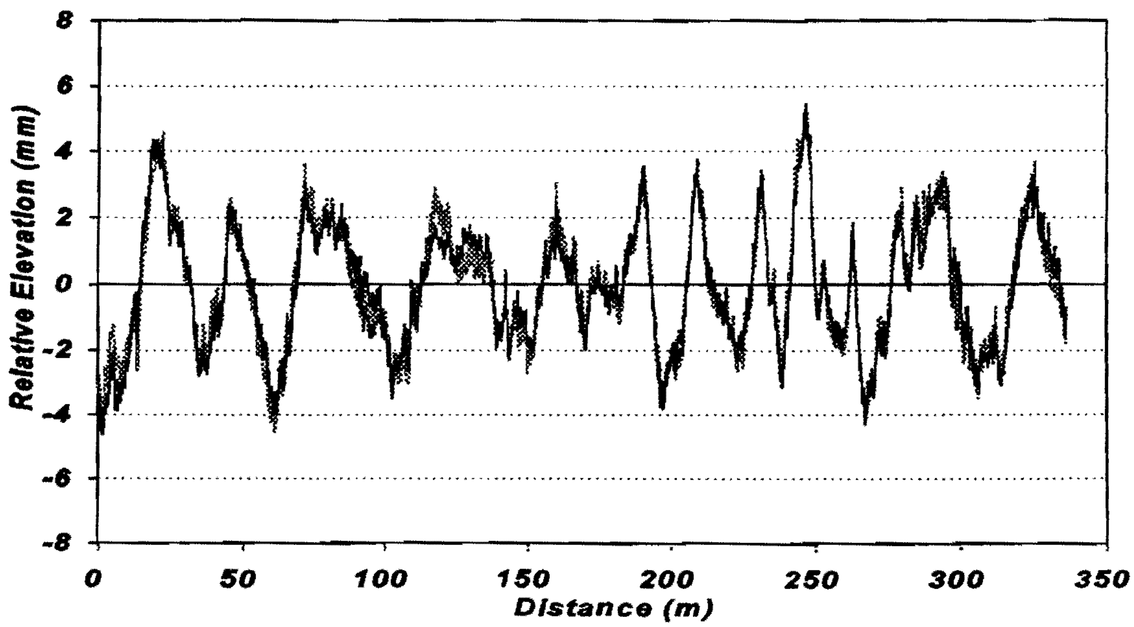

Figure A37. Original Profiles from TxDOT's Surface Profiler on SH47A, RWP.

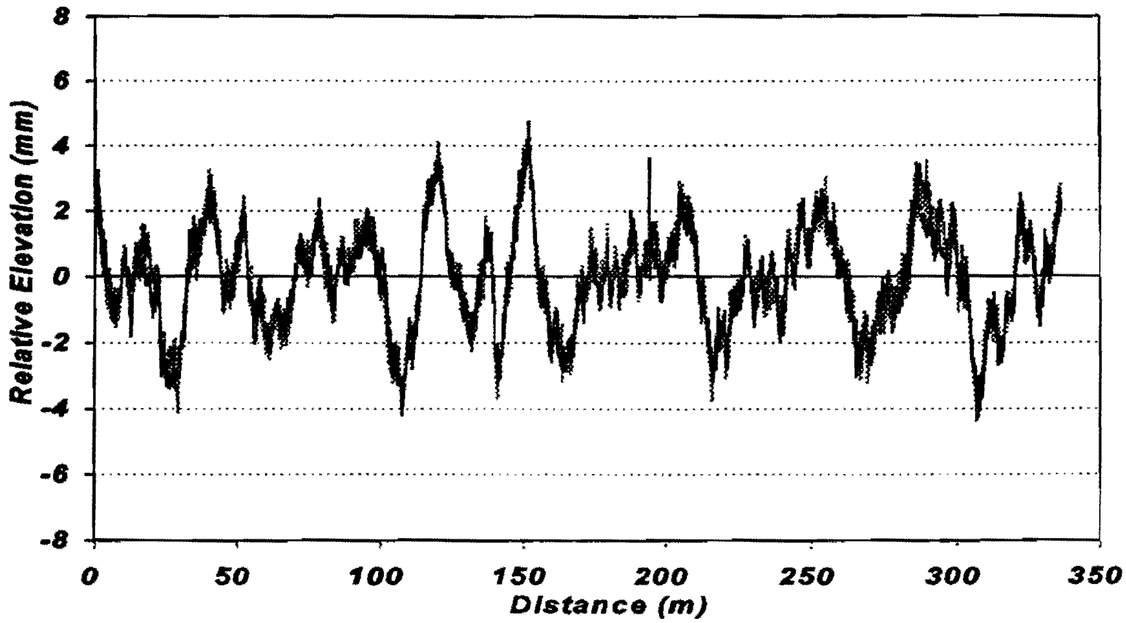

Figure A38. Original Profiles from TxDOT's Surface Profiler on SH47B, LWP.

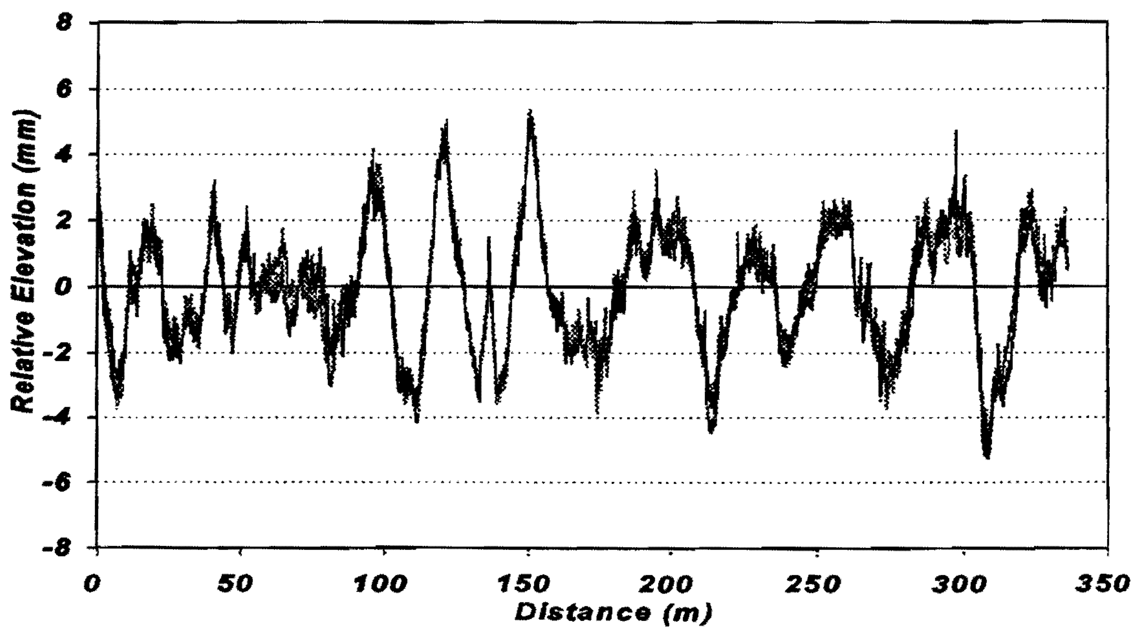

Figure A39. Original Profiles from TxDOT's Surface Profiler on SH47B, RWP.

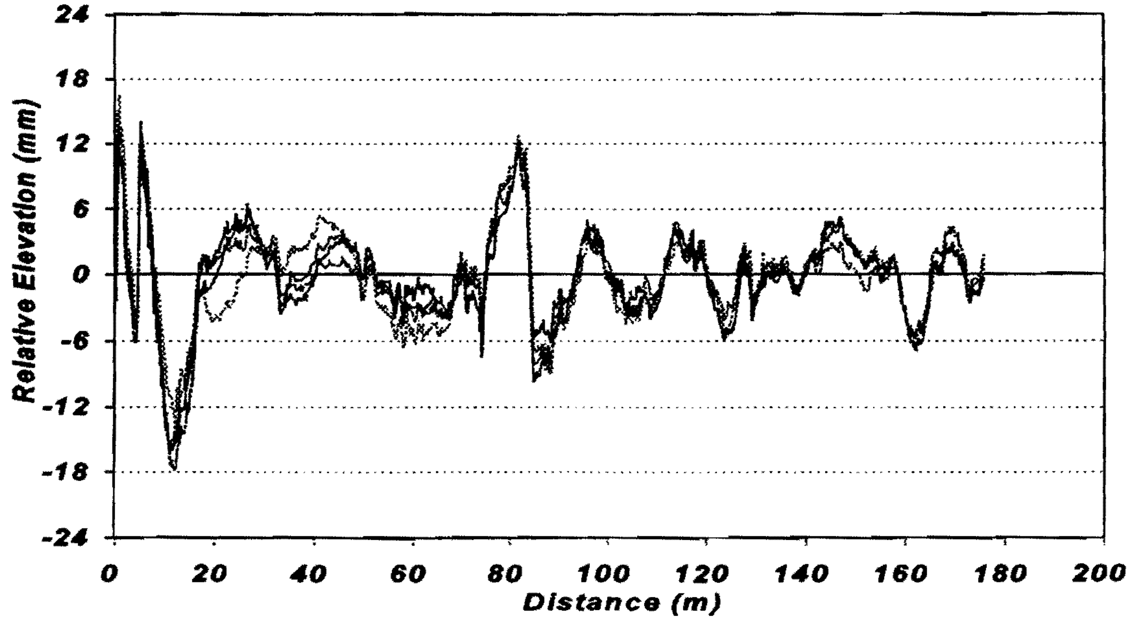

Figure A40. Original Profiles from TxDOT's Laser Rut/Profiler on Annex 1, LWP.

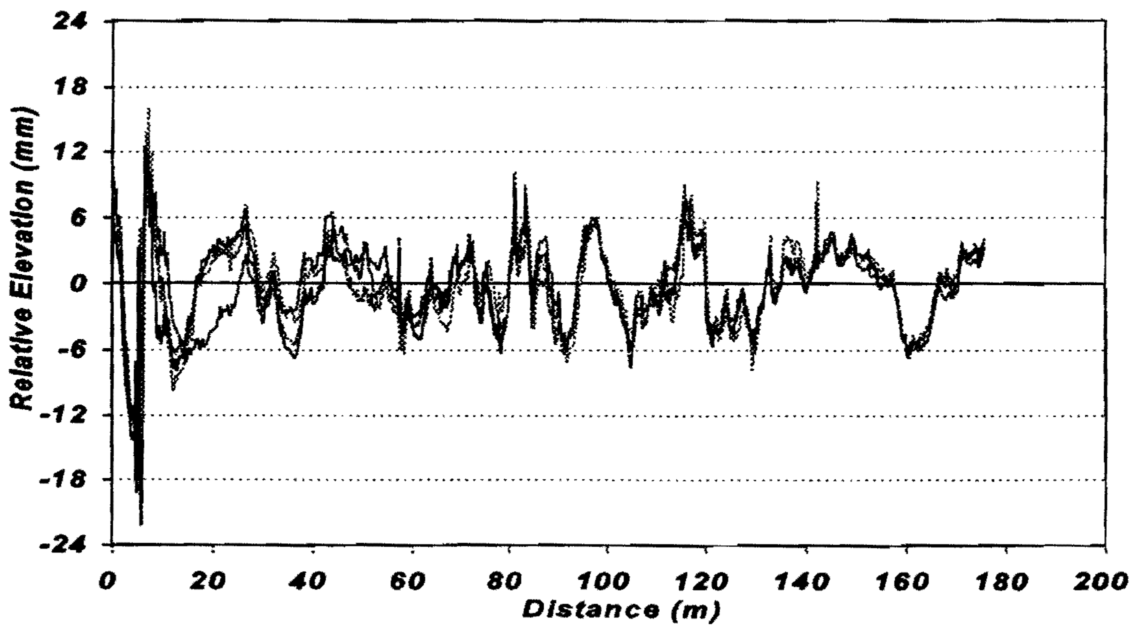

Figure A41. Original Profiles from TxDOT's Laser Rut/Profiler on Annex 1, RWP.

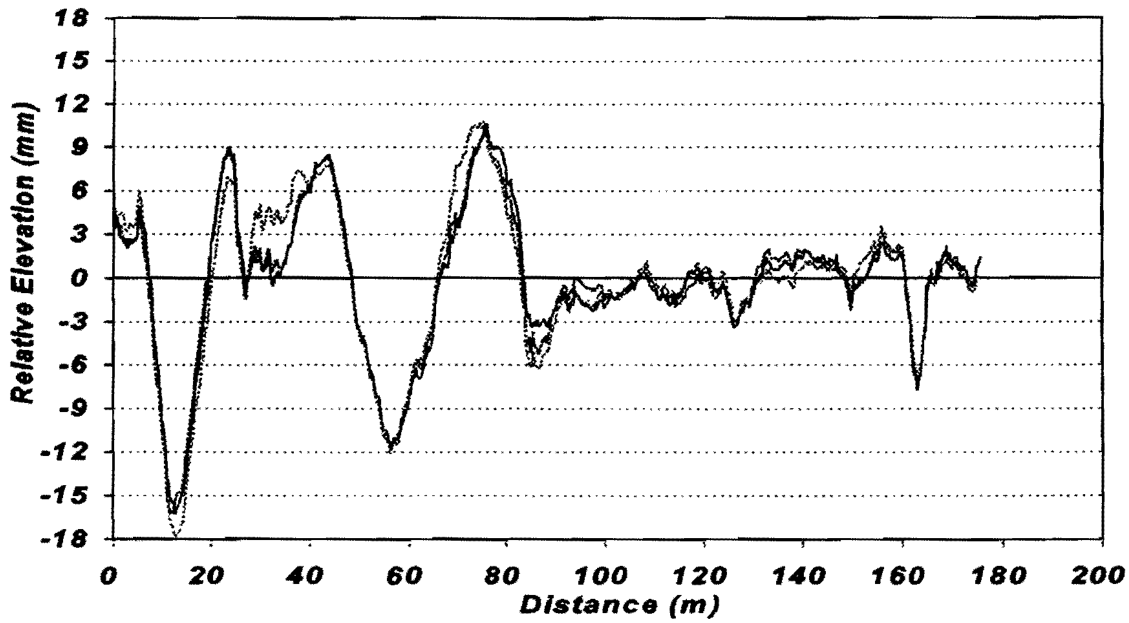

Figure A42. Original Profiles from TxDOT's Laser Rut/Profiler on Annex 2, LWP.

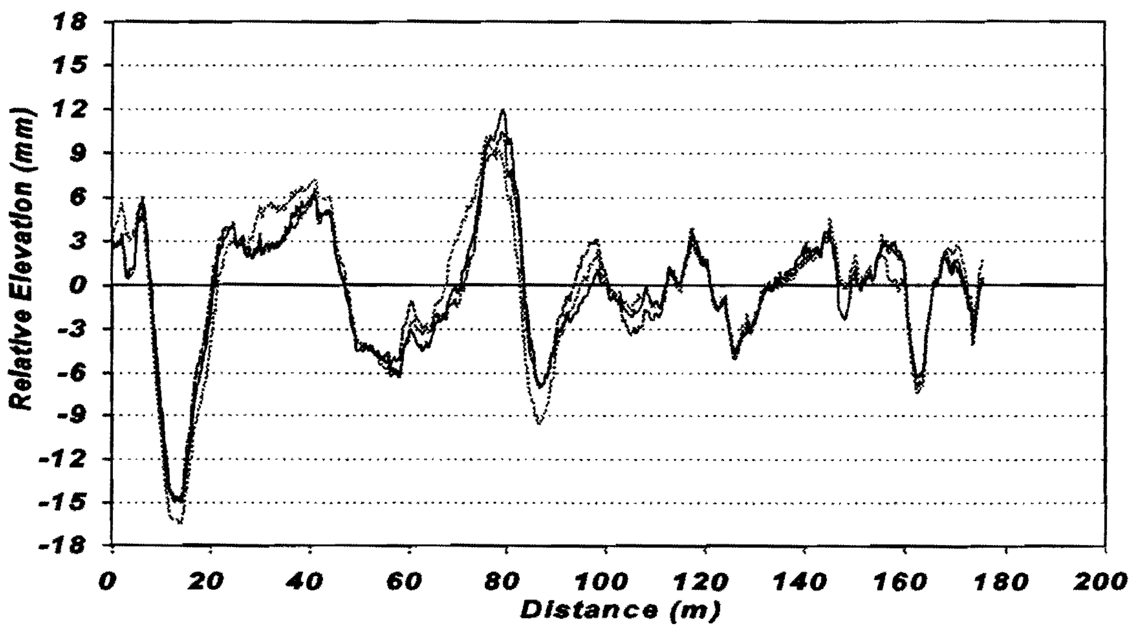

Figure A43. Original Profiles from TxDOT's Laser Rut/Profiler on Annex 2, RWP.

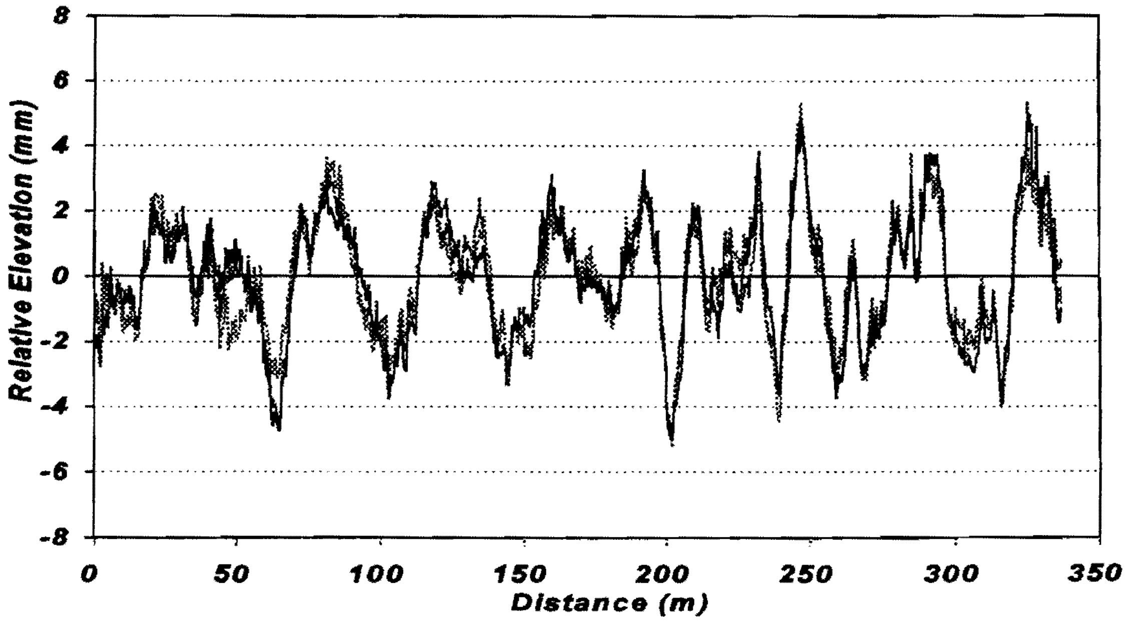

Figure A44. Original Profiles from TxDOT's Laser Rut/Profiler on SH47A, LWP.

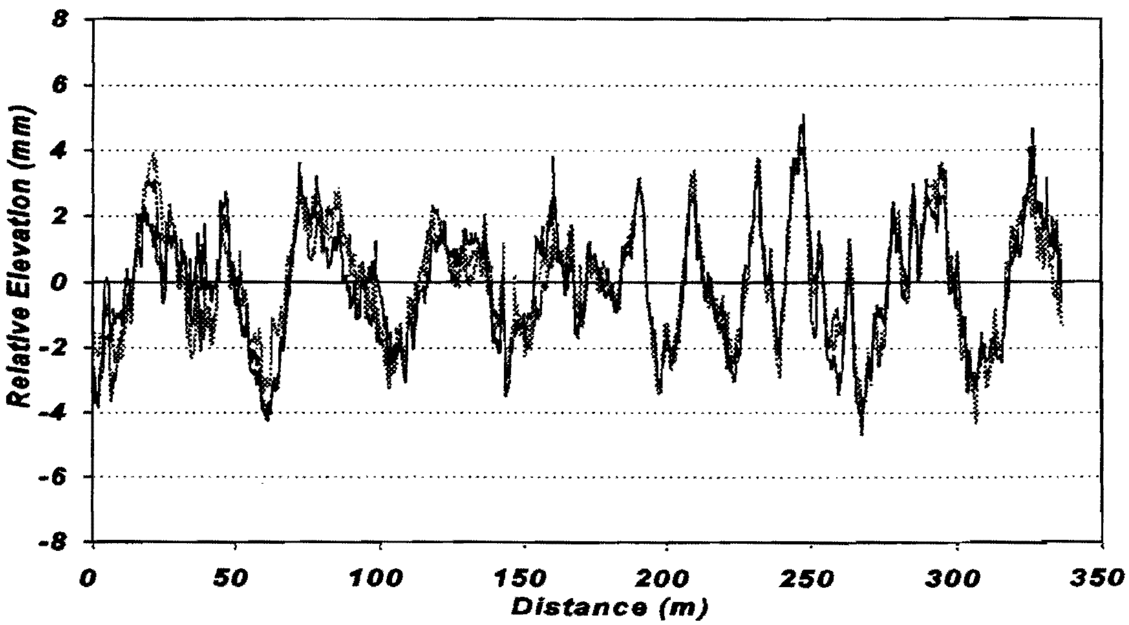

Figure A45. Original Profiles from TxDOT's Laser Rut/Profiler on SH47A, RWP.

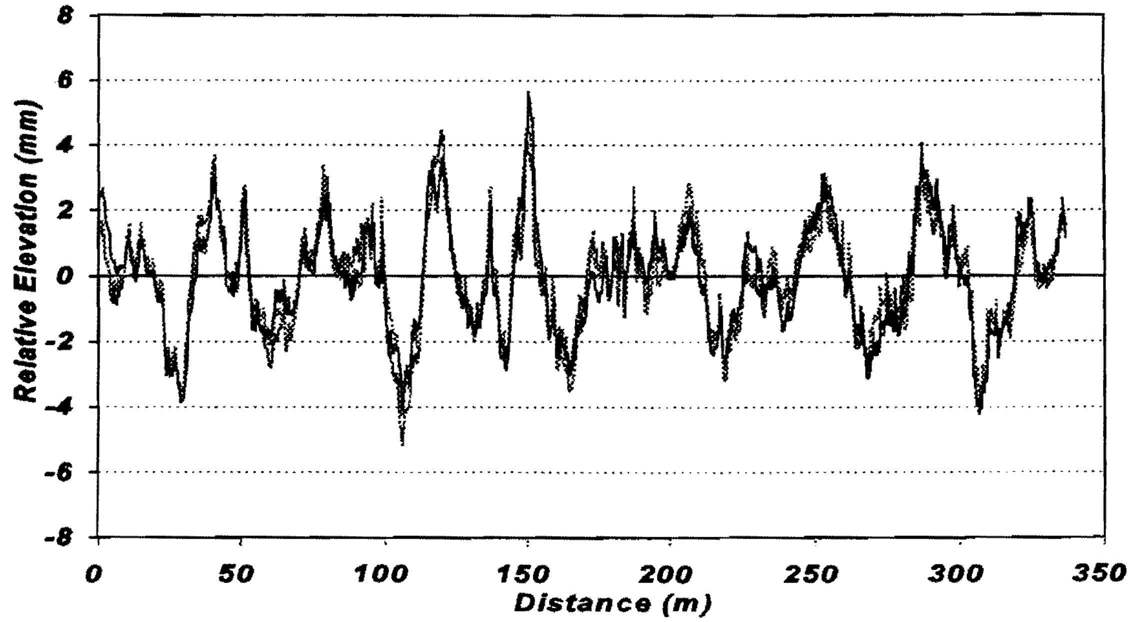

Figure A46. Original Profiles from TxDOT's Laser Rut/Profiler on SH47B, LWP.

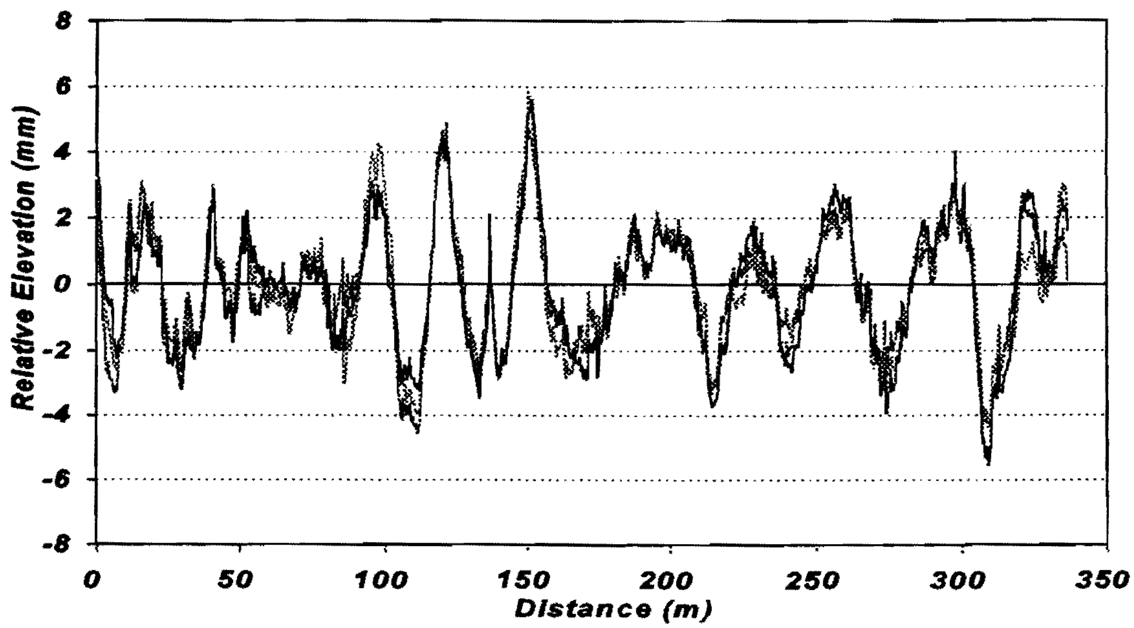

Figure A47. Original Profiles from TxDOT's Laser Rut/Profiler on SH47B, RWP.

APPENDIX B

SIGNIFICANCE OF LEAD-IN PROFILE TO THE EVALUATION OF ACCURACY AND REPEATABILITY OF PROFILE MEASUREMENTS

INTRODUCTION

Inertial profilers require a lead-in to reach operational speed and to stabilize the accelerometers prior to the start of a test section. Since the lead-in profile is used to initialize the high-pass filter incorporated with these profilers, the profiles determined on the test section are influenced by the upstream surface profile. It is therefore necessary to consider the effects of this upstream or lead-in profile in evaluating the accuracy and repeatability of profile measurements from the inertial profilers tested in this study. For this purpose, researchers used the rod and level data collected on Annex 1, Annex 2, and SH47A.

On each site, rod and level measurements were made on the left wheelpath for a distance of about 176 m. To evaluate the influence of the lead-in profile, a subsection was established on each site which covered the rod and level data on the left wheelpath for the last 77 m. Researchers then evaluated the filtered profiles for this subsection assuming different lead-ins that ranged in lengths from zero to three times the cutoff wavelength (CW). For the profile measurements made with the inertial profilers, the CW was set at 33 m.

Lead-ins were varied in increments of 0.5 CW so that lengths of 16.5, 33, 49.5, 66, 82.5, and 99 m were used, in addition to the case where no lead-in was assumed. Researchers then filtered the available rod and level data on the given lead-in and subsection using the high-pass filter implemented with TxDOT's profilers. In this evaluation, the rod and level profiles were also reflected to initialize the high-pass filter. Researchers then compared the filtered profiles on the 77 m subsection to establish the influence of lead-in data to profile measurements conducted with inertial profilers. The findings from this task are presented in the following.

COMPARISON OF FILTERED PROFILES FROM CASES CONSIDERED

Researchers used the filtered profiles evaluated with a lead-in of 3 CW as benchmarks for evaluating the accuracy of profiles determined at shorter lead-ins and with zero lead-in. Figures B1 to B3 compare the filtered subsection profiles for assumed lead-ins of zero and three times the cutoff wavelength (CW). It is observed that the profiles determined without the lead-in are initially out-of-sync with the corresponding profiles determined with the lead-

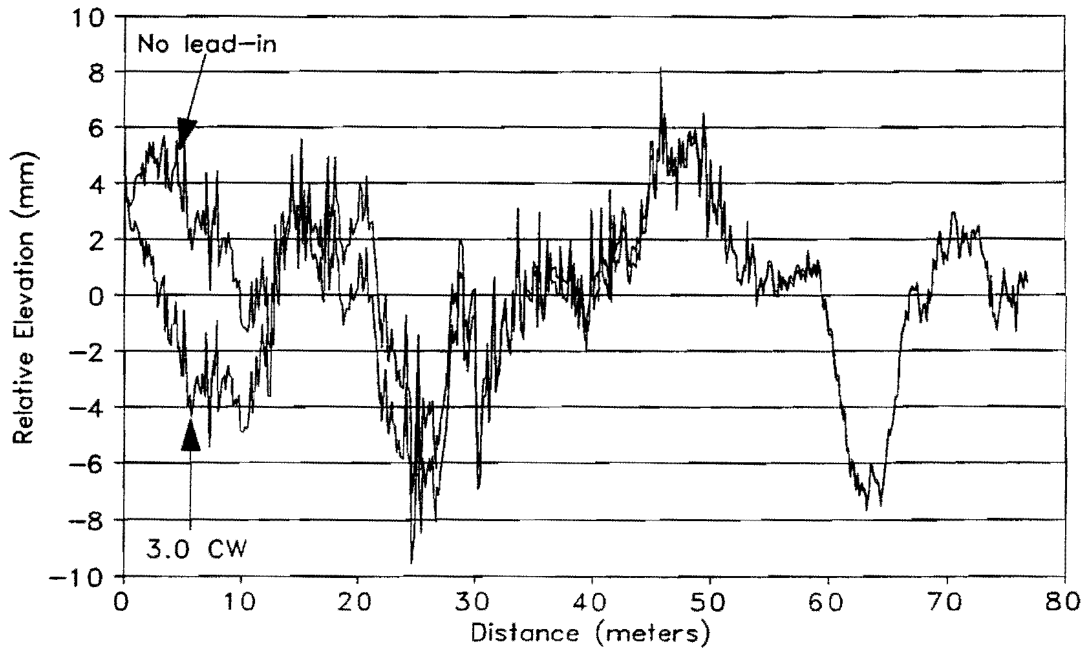

Figure B1. Comparison of Filtered Profiles Determined with No Lead-in and with a Lead-in of 3 CW Using Rod & Level Data on Annex 1.

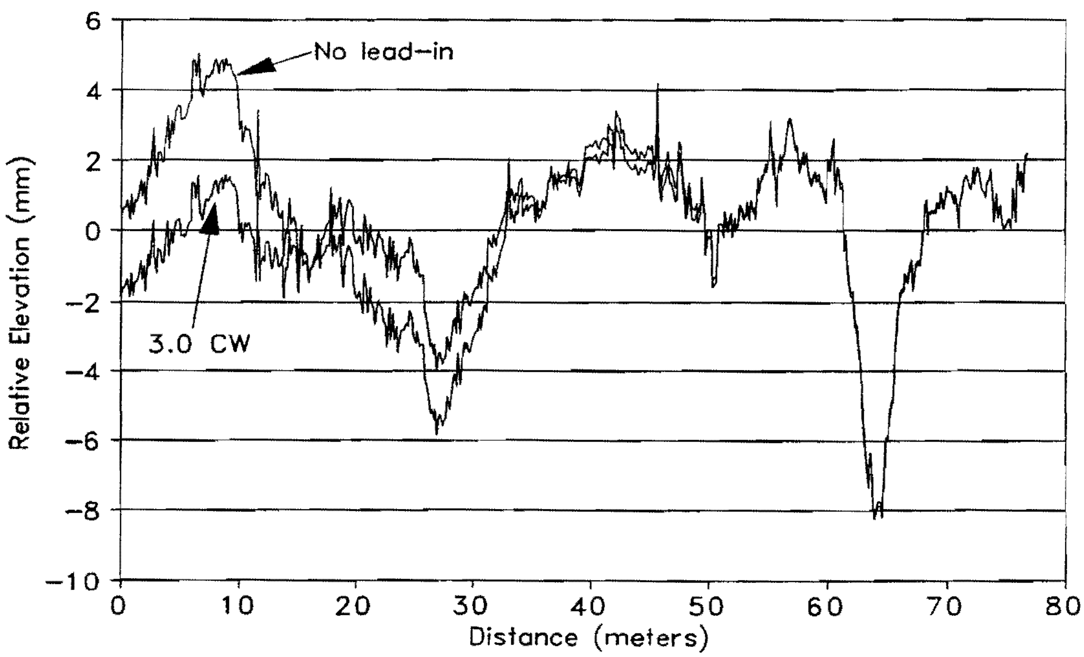

Figure B2. Comparison of Filtered Profiles Determined with No Lead-in and with a Lead-in of 3 CW Using Rod & Level Data on Annex 2.

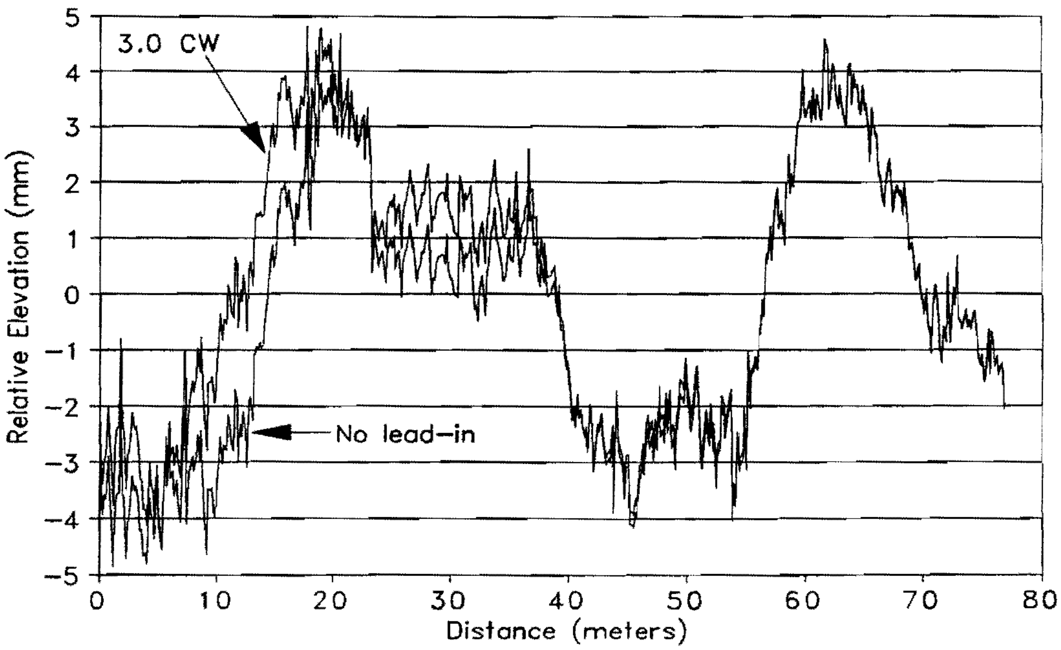

Figure B3. Comparison of Filtered Profiles Determined with No Lead-in and with a Lead-in of 3 CW Using Rod & Level Data on SH47A.

in. The differences between the profiles diminish with distance into the subsection and a point is reached at which the two profiles are in agreement. It is of interest to determine the distance it takes for the filtered profiles to be synchronous with each other. For this purpose, researchers calculated the point-to-point differences between the profiles and plotted the results in Figures B4 to B6.

It is observed from these figures that the differences between filtered profiles become insignificant at a distance of about 1.5 CW. At distances of two or more wavelengths, the differences are very close to zero. This finding is useful in evaluating the accuracy of profiles from the inertial profilers evaluated in this study. Since rod and level data are not available on the lead-in to each site, the filtered profiles based on rod and level and those from the inertial profilers are not expected to be comparable at distances less than 1.5 CW. Thus, in evaluating the point-to-point accuracy of measurements from the inertial profilers, researchers compared

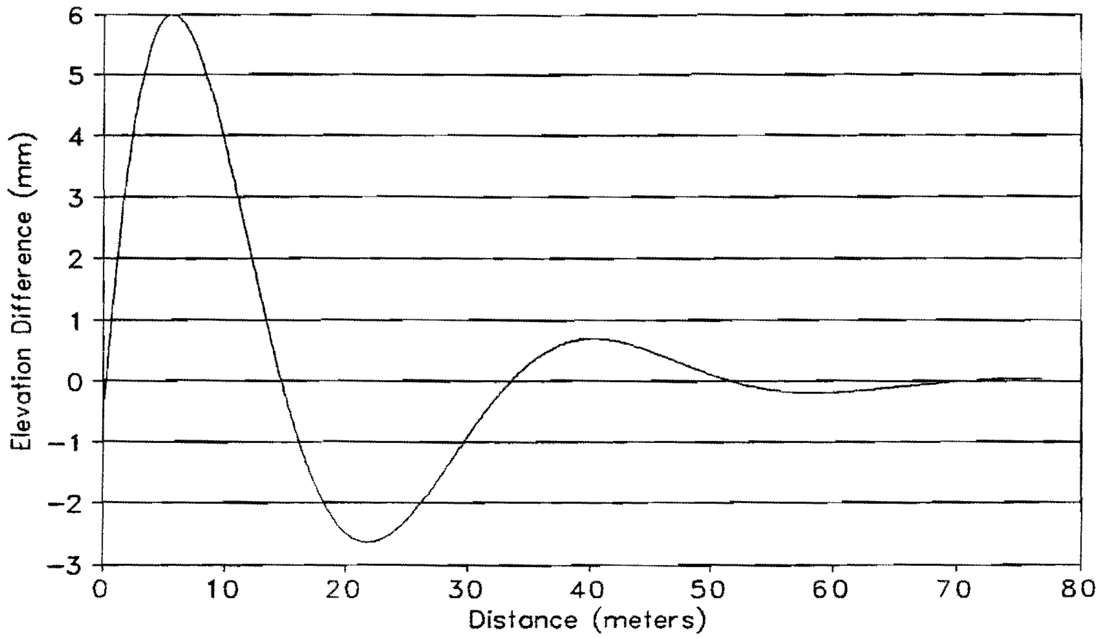

Figure B4. Differences Between Filtered Profiles Determined with No Lead-in and with a Lead-in of 3 CW Using Rod & Level Data on Annex 1.

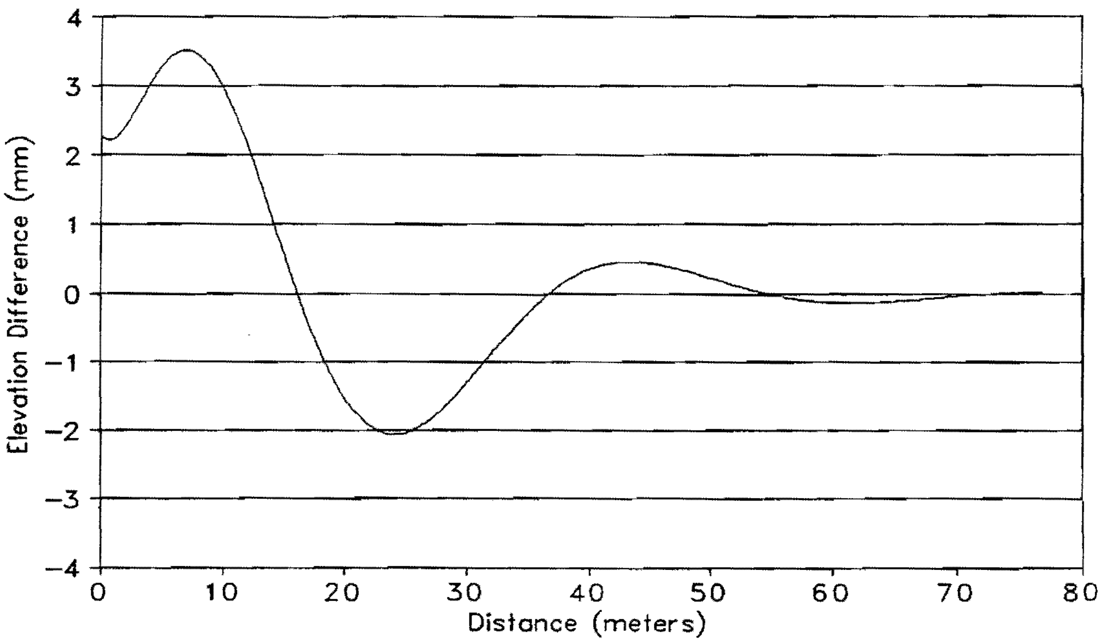

Figure B5. Differences Between Filtered Profiles Determined with No Lead-in and with a Lead-in of 3 CW Using Rod & Level Data on Annex 2.

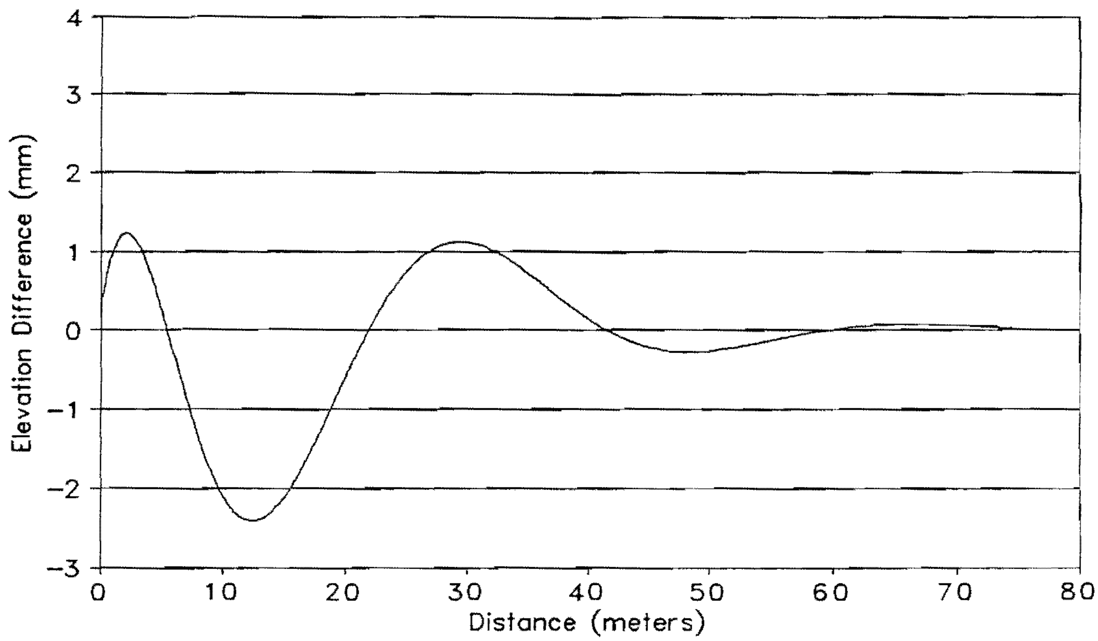

Figure B6. Differences Between Filtered Profiles Determined with No Lead-in and with a Lead-in of 3 CW Using Rod & Level Data on SH47A.

the measured elevations with corresponding data based on rod and level beginning at a distance of 1.5 CW from the start of a given site.

Figures B7 to B12 compare the filtered profiles on the subsection for the different lead-ins considered in this investigation. Researchers observed that differences in the profiles begin to diminish at a lead-in distance of 1.5 CW suggesting that the lead-in to a section must at least be this long to get reasonably accurate profiles of the section surveyed. Figures B8, B10, and B12 show that the filtered profiles associated with lead-ins of 1.5, 2, 2.5, and 3 times the cutoff wavelength overlap considerably. To establish the required length of lead-in, pairwise comparisons were made between the filtered profiles determined at a lead-in of 3 CW, and the other profiles determined at the shorter lead-ins. Researchers evaluated the point-to-point differences between filtered profiles and plotted the results in Figures B13 to B15. Each curve in the figures shows the elevation differences between the filtered profile determined at the specified lead-in and the corresponding profile determined at a lead-in of 3 CW. It is observed from the figures that lead-ins of 2 and 2.5 times the cutoff wavelength

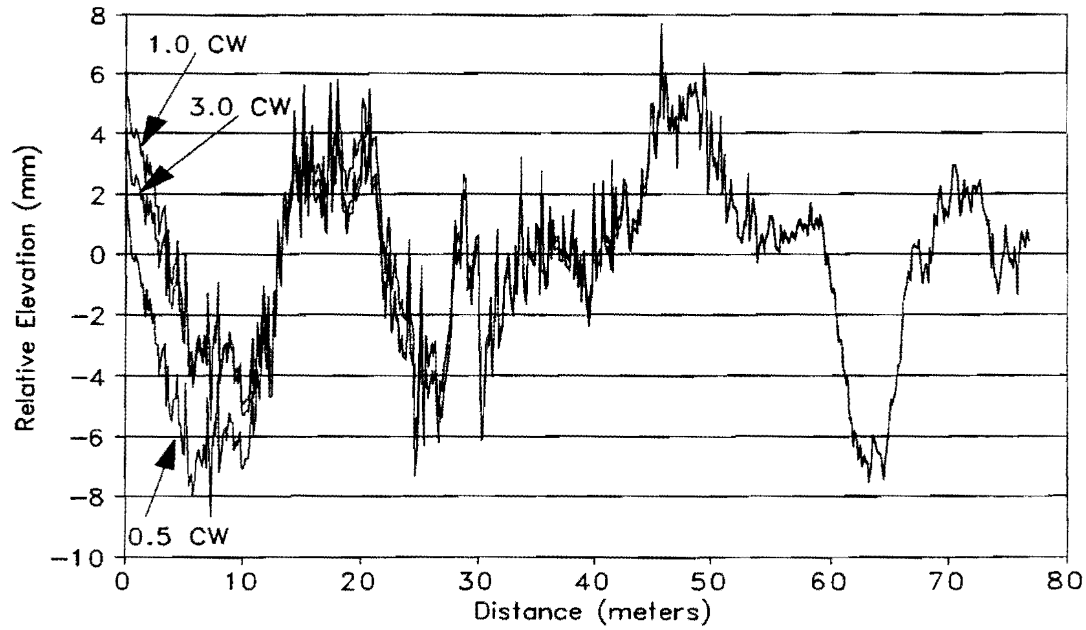

Figure B7. Comparison of Filtered Profiles Determined with Lead-ins of 0.5, 1.0, and 3.0 CW Using Rod & Level Data on Annex 1.

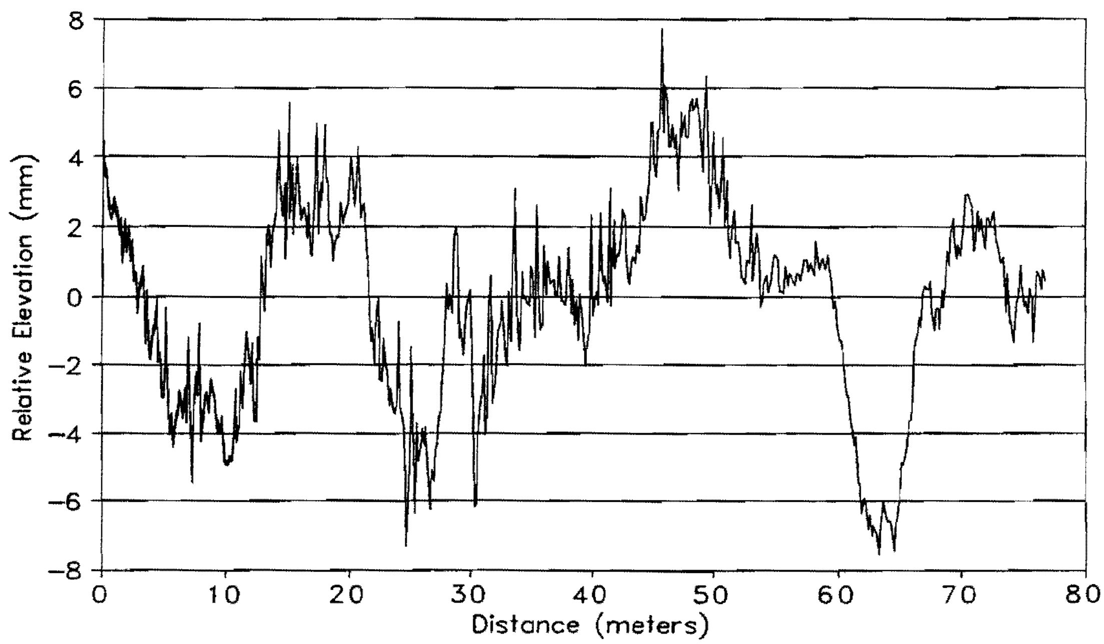

Figure B8. Comparison of Filtered Profiles Determined with Lead-ins of 1.5, 2.0, 2.5, and 3.0 CW Using Rod & Level Data on Annex 1.

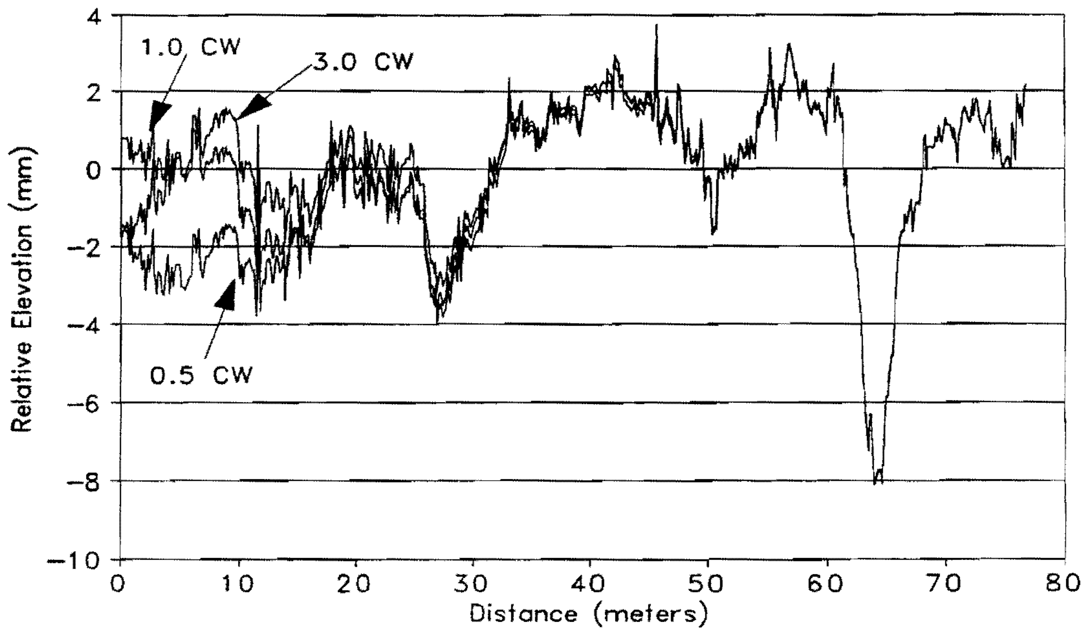

Figure B9. Comparison of Filtered Profiles Determined with Lead-ins of 0.5, 1.0, and 3.0 CW Using Rod & Level Data on Annex 2.

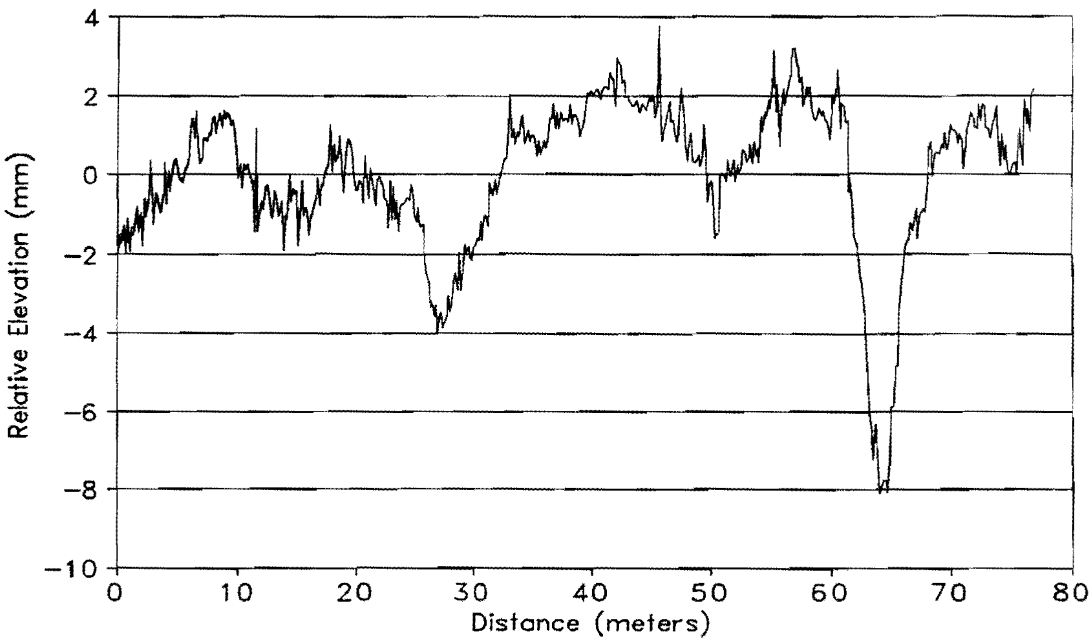

Figure B10. Comparison of Filtered Profiles Determined with Lead-ins of 1.5, 2.0, 2.5, and 3.0 CW Using Rod & Level Data on Annex 2.

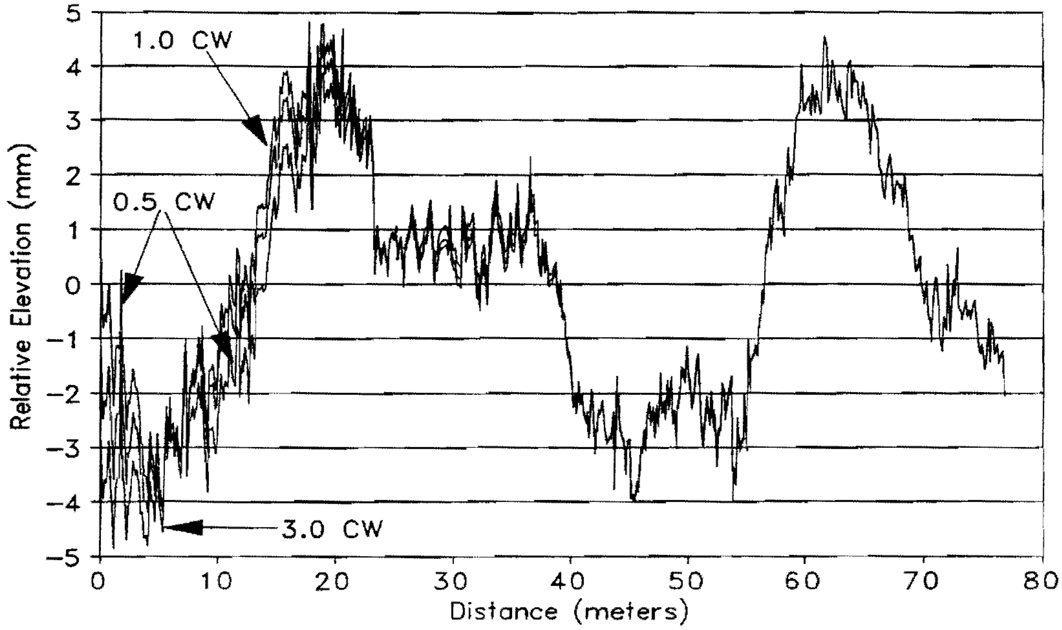

Figure B11. Comparison of Filtered Profiles Determined with Lead-ins of 0.5, 1.0, and 3.0 CW Using Rod & Level Data on SH47A.

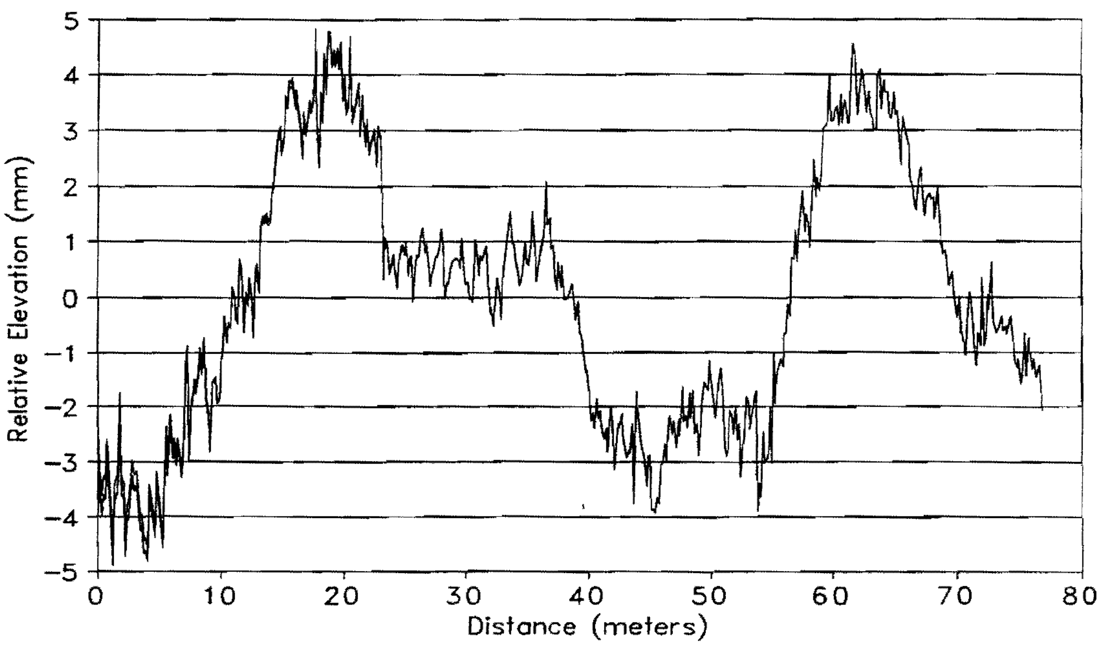

Figure B12. Comparison of Filtered Profiles Determined with Lead-ins of 1.5, 2.0, 2.5, and 3.0 CW Using Rod & Level Data on SH47A.

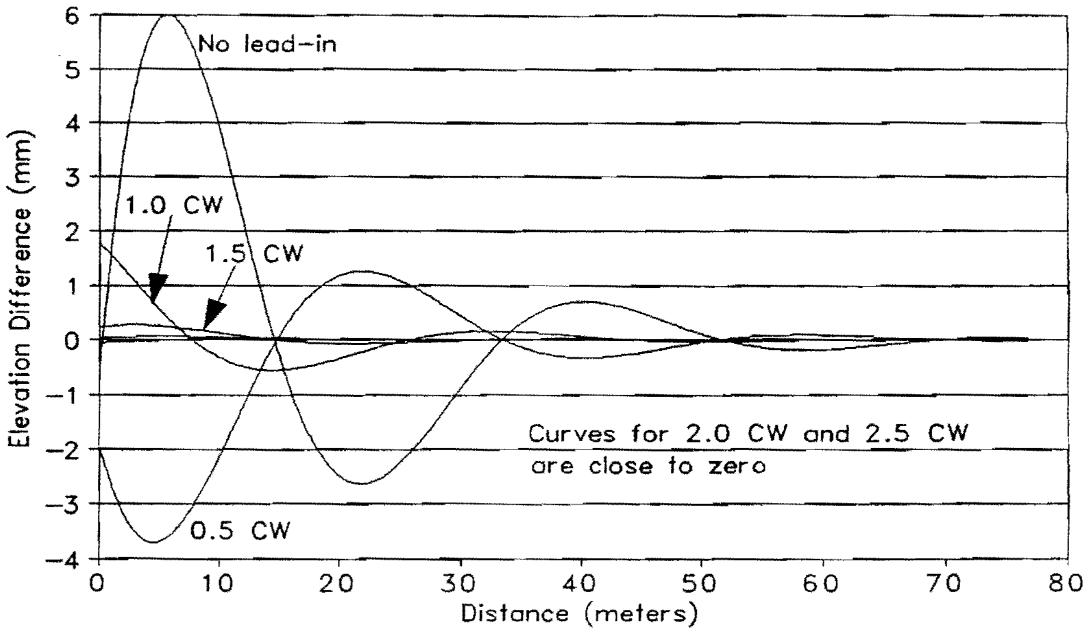

Figure B13. Differences Between Filtered Profiles Determined with a Lead-in of 3.0 CW and Corresponding Profiles Determined at Shorter Lead-ins (Annex 1).

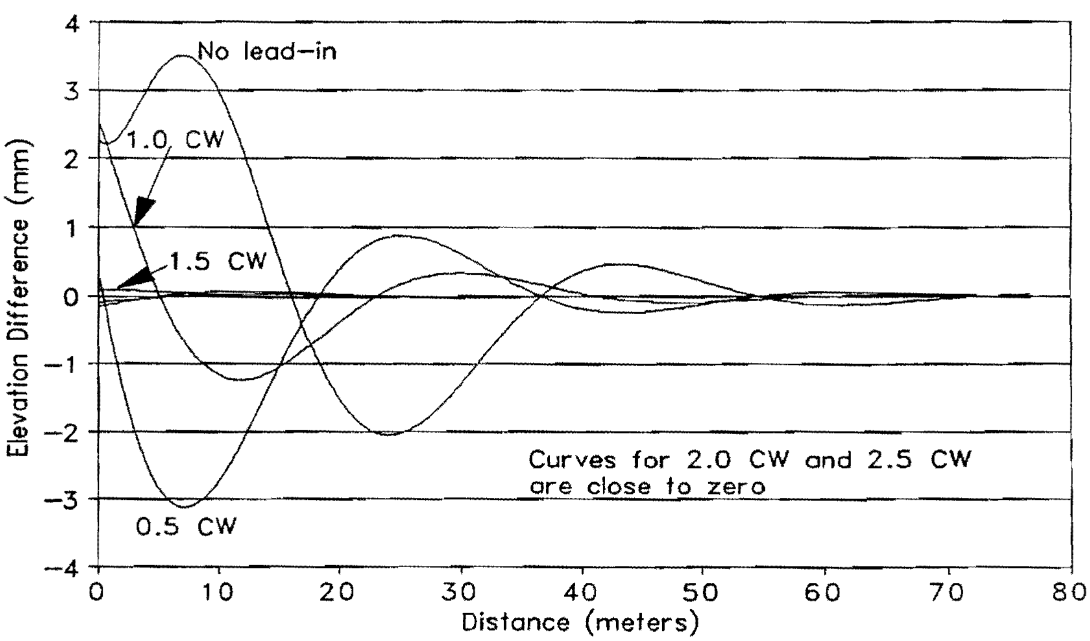

Figure B14. Differences Between Filtered Profiles Determined with a Lead-in of 3.0 CW and Corresponding Profiles Determined at Shorter Lead-ins (Annex 2).

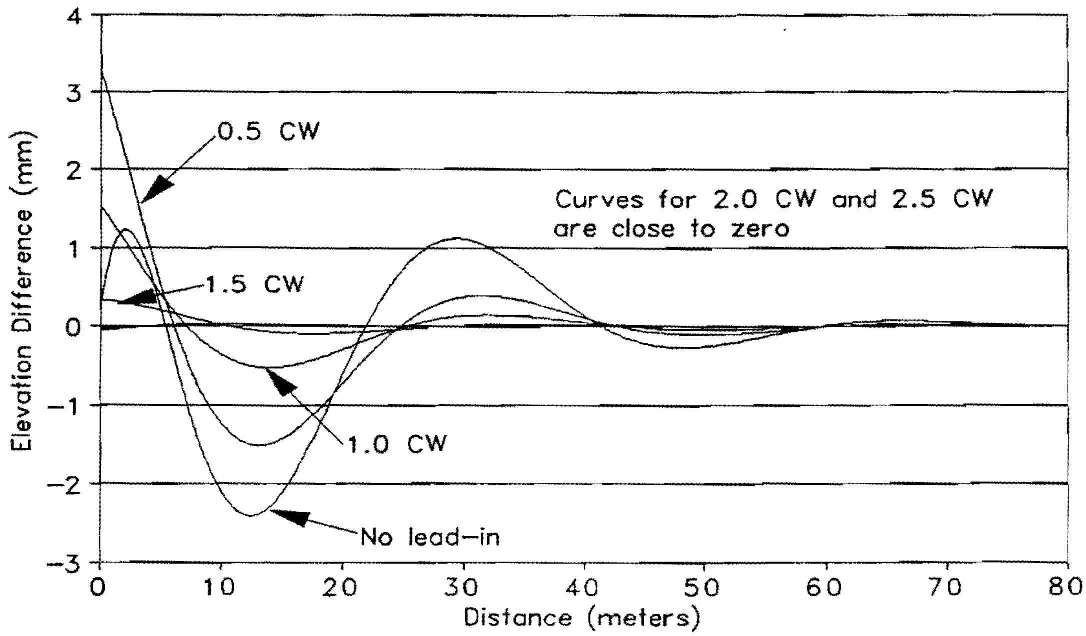

Figure B15. Differences Between Filtered Profiles Determined with a Lead-in of 3.0 CW and Corresponding Profiles Determined at Shorter Lead-ins (SH47A).

gave filtered profiles that are very close to the profile associated with a lead-in of 3 CW. For these lead-ins, the discrepancies from the benchmark profiles are very close to zero at all locations where data are reported. Consequently, researchers recommend using a lead-in of twice the cutoff wavelength when profiles are measured with inertial profilers.

EFFECT OF LEAD-IN ON IRIs CALCULATED FROM FILTERED PROFILES

In addition to evaluating the effect of the lead-in on the accuracy of profiles measured with inertial profilers, researchers evaluated its potential effect on the IRIs computed from the measured profiles. For this purpose, a subsection was established which spanned the last 110 m of the left wheelpath of each site tested. Two cases were considered:

1. Only the rod and level data for the 110 m subsection are filtered; and
2. The rod and level data for the subsection as well as the data for the 66 m interval preceding it are filtered.

The second case therefore included a lead-in to the subsection which covered a distance of 66 m, twice the cutoff wavelength used in the inertial profiler measurements. A distance of 2 CW was selected based on the results of the previous analysis.

Researchers filtered the available rod and level data for the cases considered and calculated the IRIs from the filtered profiles to establish the influence of the lead-in profile in the determination of this smoothness statistic. Table B1 shows the IRIs determined from the filtered profiles on the subsection. Rod and level data from replicate runs made on each test site were used in this investigation.

It is observed that the IRIs computed for the cases considered are very comparable. The differences in the IRIs computed with and without a lead-in are very slight, indicating that the lead-in profile has very little effect on the calculation of IRI. Figure B16 illustrates the excellent agreement between the IRIs determined for the two cases considered. The coefficient of determination, R^2, of the linear relationship between the IRIs is 0.999, with a standard error of estimate (SEE) of 0.016 mm/m.

Table B2 compares the standard deviations of the IRIs. It is observed that the variability in the computed IRIs is unaffected by the lead-in profile. The differences in standard deviations vary from about 2.3 to about 3.4 percent of the standard deviation of IRIs from filtered subsection profiles determined with a lead-in.

EFFECT OF LEAD-IN ON REPEATABILITY OF FILTERED PROFILES

The filtered profiles from the two cases considered in the preceding section are shown in Figures B17 to B22. Each figure reflects the excellent repeatability of the rod and level measurements as the filtered profiles associated with replicate runs are observed to overlap each other. Researchers computed the standard deviation of the filtered profiles, point-by-point, and determined the average of the standard deviations to quantify the repeatability of the filtered profiles. Table B3 presents the average standard deviations for profiles determined with and without the 66 m lead-in. It is observed that the point-to-point repeatability, as measured by the average standard deviation, is practically the same between the two cases considered. Since the filtered profiles are based on the rod and level data, their point-to-point repeatability is not expected to be influenced by the lead-in unless the variability in the original rod and level data differed between the assumed 66 m lead-in and the 110 m subsection. Thus, the average standard deviations shown in Table B3 reflect the consistency of the rod and level measurements on each site profiled.

Table B1. Comparison of IRIs from Filtered Profiles Determined with and Without a Lead-in.

Site	Run Number	IRI (mm/m)		Difference (mm/m)	Percent Difference[1]
		With Lead-in	No Lead-in		
Annex 1	1	2.358	2.338	0.020	0.85
	2	2.212	2.198	0.014	0.63
	3	2.274	2.265	0.009	0.40
	4	2.256	2.237	0.019	0.84
Annex 2	1	1.221	1.183	0.038	3.11
	2	1.245	1.222	0.023	1.85
	3	1.220	1.188	0.032	2.62
	4	1.201	1.185	0.016	1.33
	5	1.204	1.181	0.023	1.91
SH47A	1	1.059	1.065	-0.006	-0.57
	2	1.029	1.038	-0.009	-0.87
	3	0.856	0.869	-0.013	-1.52
	4	0.919	0.928	-0.009	-0.98

[1]Difference expressed as a percentage of the IRI determined with a lead-in.

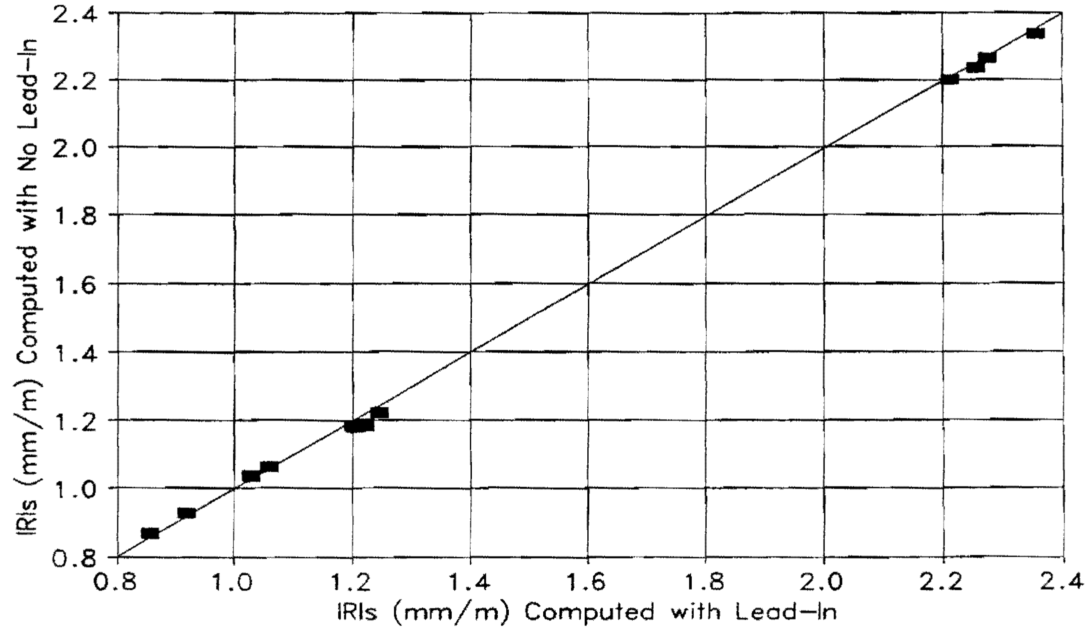

Figure B16. Comparison of IRIs Computed from Filtered Profiles Determined with and Without a Lead-in.

Table B2. Repeatability of IRIs Determined with and Without a Lead-in.

Site	Standard Deviation (mm/m)		Difference (mm/m)	Percent Difference[1]
	With Lead-in	No Lead-in		
Annex 1	0.0612	0.0591	0.0021	3.43
Annex 2	0.0175	0.0171	0.0004	2.29
SH47A	0.0947	0.0922	0.0025	2.64

[1]Difference expressed as a percentage of standard deviation of IRIs determined with a lead-in.

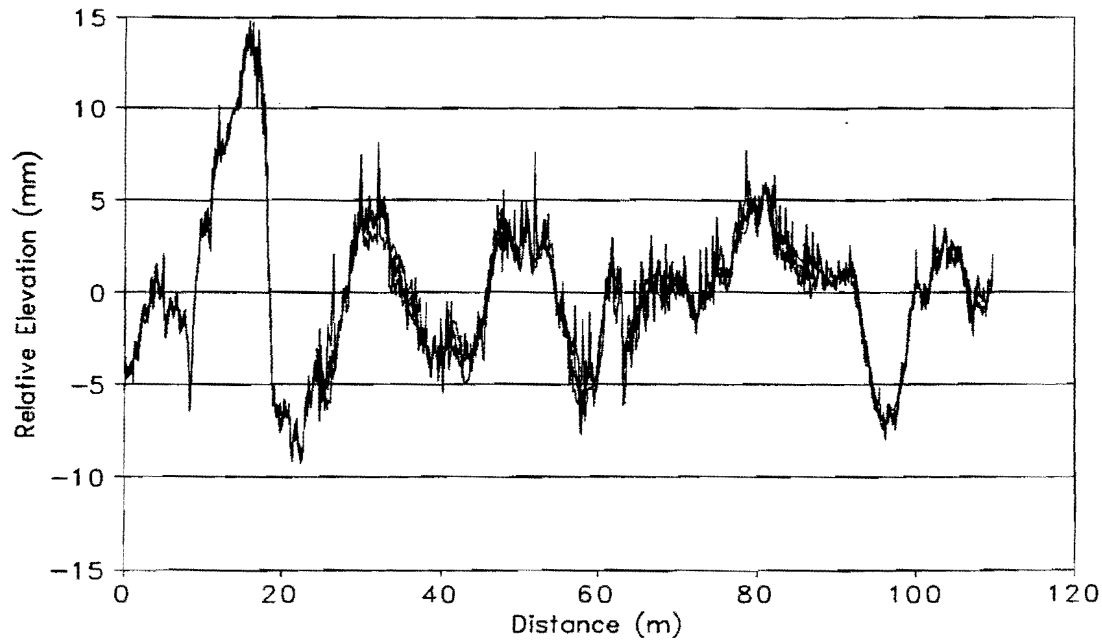

Figure B17. Comparison of Filtered Profiles Determined with a Lead-in Using Rod and Level Data on Annex 1.

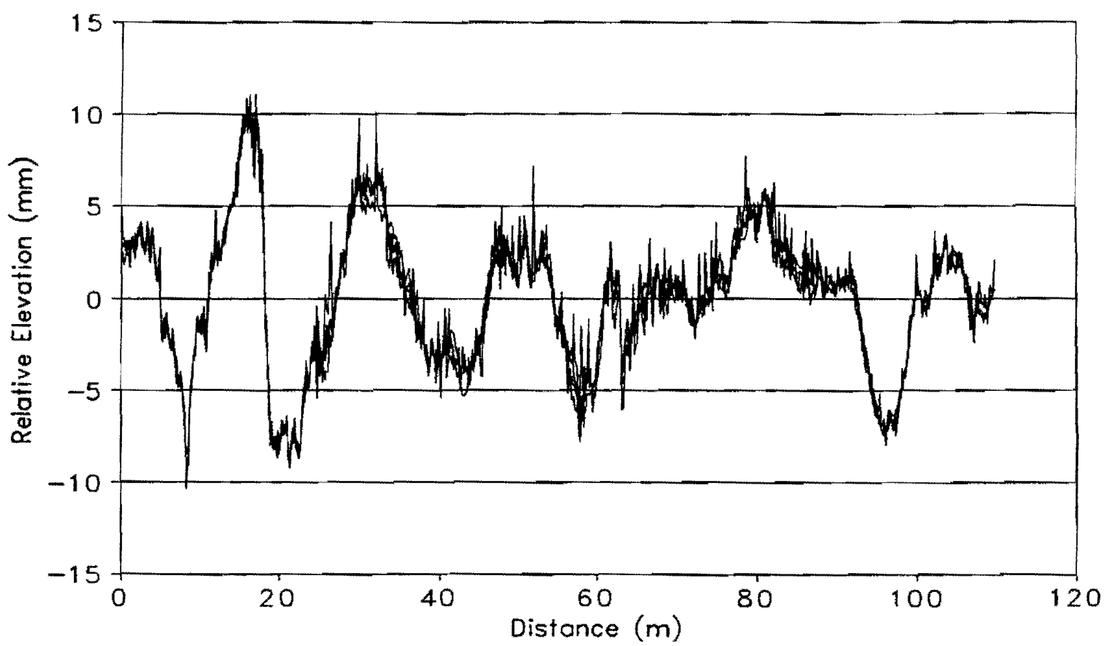

Figure B18. Comparison of Filtered Profiles Determined Without a Lead-in Using Rod and Level Data on Annex 1.

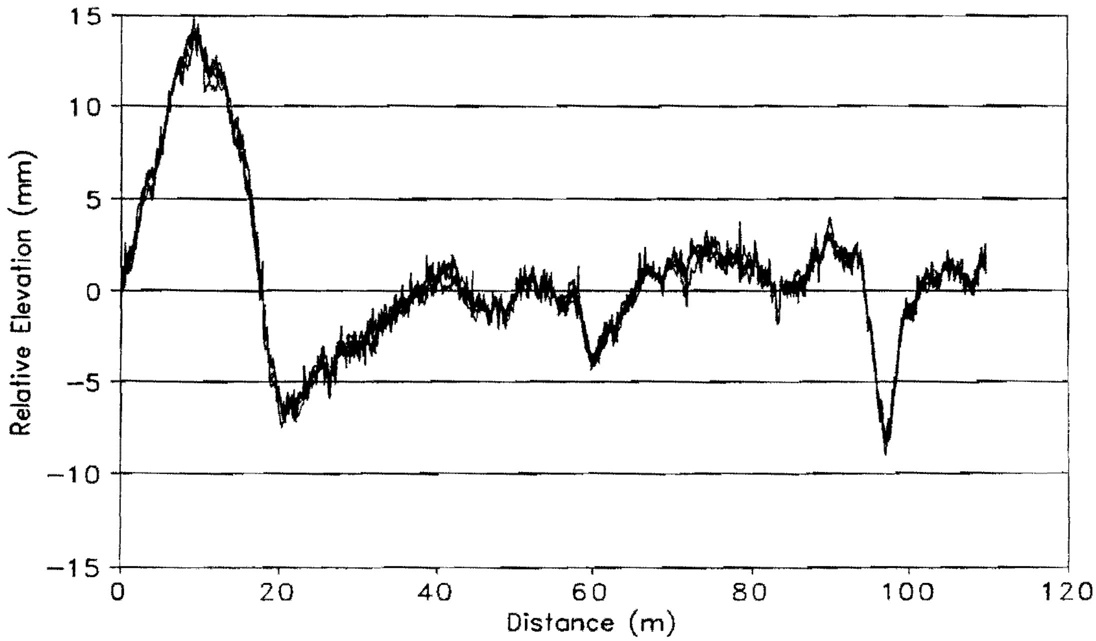

Figure B19. Comparison of Filtered Profiles Determined with a Lead-in Using Rod and Level Data on Annex 2.

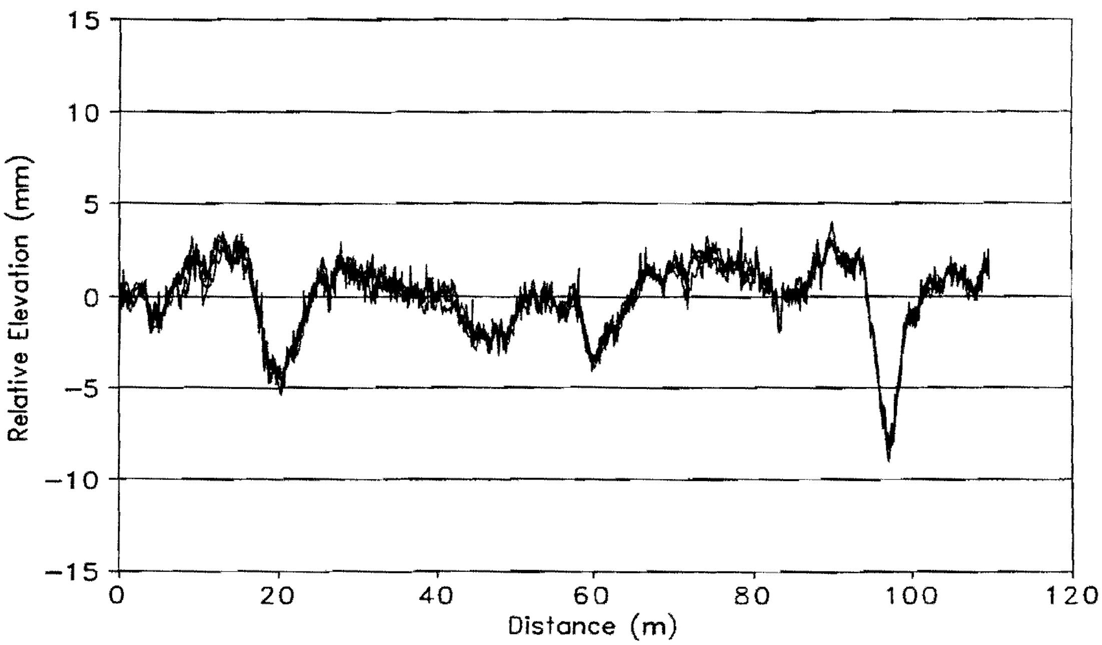

Figure B20. Comparison of Filtered Profiles Determined Without a Lead-in Using Rod and Level Data on Annex 2.

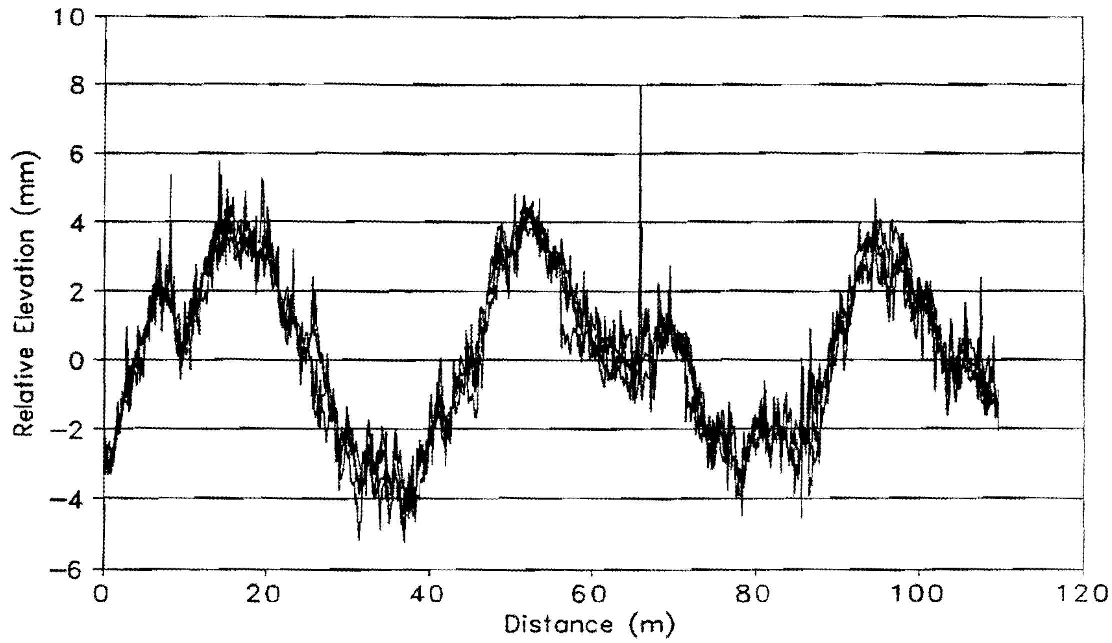

Figure B21. Comparison of Filtered Profiles Determined with a Lead-in Using Rod and Level Data on SH47A.

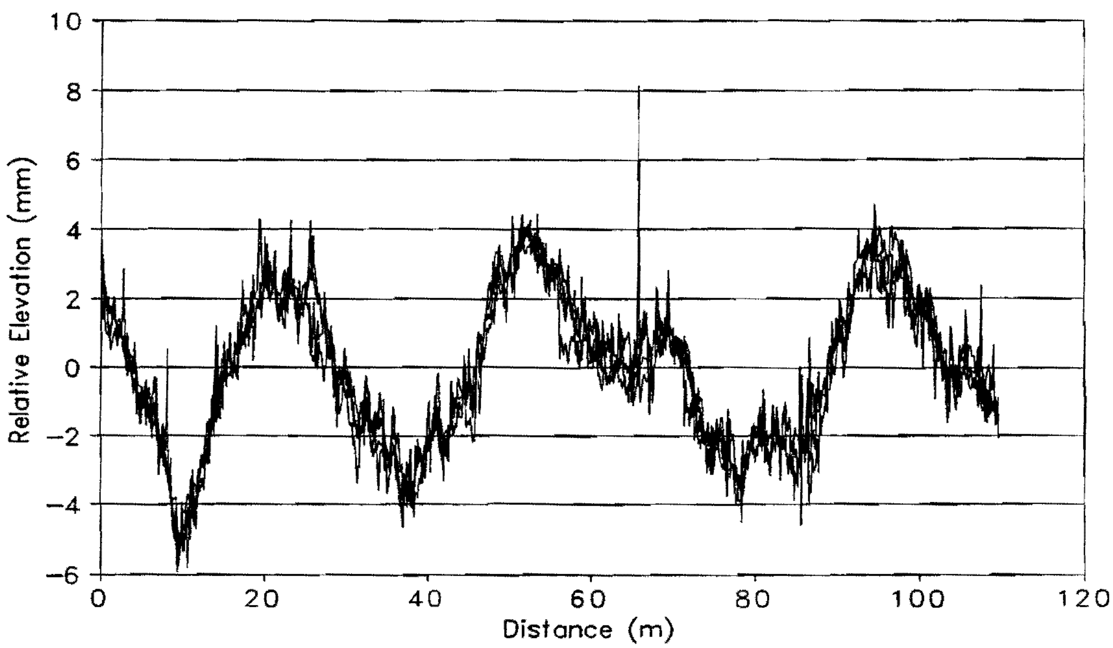

Figure B22. Comparison of Filtered Profiles Determined Without a Lead-in Using Rod and Level Data on SH47A.

Table B3. Repeatability of Filtered Profiles Determined with and Without a Lead-in.

Site	Average of Standard Deviations (mm/m)		Difference (mm/m)	Percent Difference[1]
	With Lead-in	No Lead-in		
Annex 1	0.5274	0.5282	0.0008	0.15
Annex 2	0.3734	0.3678	-0.0056	1.50
SH47A	0.4888	0.4902	0.0014	0.29

[1]Difference expressed as a percentage of average standard deviation of profile with lead-in.

APPENDIX C

INTERNATIONAL ROUGHNESS INDICES COMPUTED FROM MEASURED PROFILES

Table C1. Computed IRIs from CSC Profilair vs IRIs from Rod & Level.

Site	Segment	Wheelpath	Run Number	IRI (mm/m)	
				CSC	Rod & Level
Annex 1	1	Left	1	1.781	2.003
			2	1.828	1.917
			3		2.002
			4		1.907
Annex 2	1	Left	1	1.187	1.395
			2	1.234	1.472
			3		1.423
			4		1.408
			5		1.408
SH47A	1	Left	1	0.830	1.102
			2	0.794	1.085
			3		0.944
			4		0.953
	2	Left	1	1.051	
			2	0.933	
	1	Right	1	0.725	
			2	0.696	
	2	Right	1	0.937	
			2	0.835	
SH47B	1	Left	1	0.804	
			2	0.800	
	2	Left	1	0.599	
			2	0.649	
	1	Right	1	0.815	
			2	0.790	
	2	Right	1	0.697	
			2	0.719	

Table C2. Computed IRIs from Walking Profiler vs IRIs from Rod & Level.

Site	Segment	Wheelpath	Run Number	IRI (mm/m)	
				WPR	Rod & Level
Annex 1	1	Left	1	1.866	2.003
			2	1.859	1.917
			3	1.862	2.002
			4		1.907
Annex 2	1	Left	1	1.305	1.395
			2	1.263	1.472
			3	1.302	1.423
			4		1.408
			5		1.408
SH47A	1	Left	1	0.845	1.102
			2	0.847	1.085
			3	0.858	0.944
			4		0.953
		Right	1	0.773	
			2	0.736	
			3	0.717	
	2	Left	1	1.051	
			2	1.061	
			3	1.034	
		Right	1	0.893	
			2	0.909	
			3	0.895	

Table C2. Computed IRIs from Walking Profiler vs IRIs from Rod & Level (continued).

Site	Segment	Wheelpath	Run Number	IRI (mm/m)	
				WPR	Rod & Level
SH47B	1	Left	1	0.865	
			2	0.865	
			3	0.867	
		Right	1	0.847	
			2	0.848	
			3	0.846	
	2	Left	1	0.684	
			2	0.687	
			3	0.689	
		Right	1	0.809	
			2	0.798	
			3	0.782	

Table C3. Computed IRIs from LISA vs IRIs from Rod & Level.

Site	Segment	Wheelpath	Run Number	IRI (mm/m)	
				LISA	Rod & Level
Annex 1	1	Left	1	2.014	2.085
			2	2.039	2.004
			3	2.033	2.041
			4	2.122	1.979
			5	2.090	
Annex 2	1	Left	1	1.478	1.388
			2	1.365	1.448
			3	1.504	1.405
			4	1.421	1.382
			5	1.470	1.388
SH47A	1	Left	1	0.953	1.077
			2	0.944	1.080
			3	0.877	0.915
			4	0.892	0.912
			5	0.939	
	2	Left	1	1.131	
			2	1.083	
			3	1.090	
			4	1.066	
			5	1.073	
	1	Right	1	0.828	
			2	0.867	
			3	0.826	
			4	0.873	
			5	0.856	

Table C3. Computed IRIs from LISA vs IRIs from Rod & Level (continued).

Site	Segment	Wheelpath	Run Number	IRI (mm/m)	
				LISA	Rod & Level
SH47A	2	Right	1	0.987	
			2	0.956	
			3	0.953	
			4	0.958	
			5	1.000	
SH47B	1	Left	1	0.833	
			2	0.950	
			3	0.931	
			4	0.923	
			5	0.929	
	2	Left	1	0.946	
			2	0.861	
			3	0.773	
			4	0.778	
			5	0.829	
	1	Right	1	0.899	
			2	0.853	
			3	0.935	
			4	0.921	
	2	Right	1	0.921	
			2	0.872	
			3	0.916	
			4	0.931	

Table C4. Computed IRIs from T6400 Profiler vs IRIs from Rod & Level.

Site	Segment	Wheelpath	Run Number	IRI (mm/m)	
				T6400	Rod & Level
Annex 1	1	Left	1	2.350	2.170
			2	2.276	2.081
			3	2.313	2.141
			4	2.259	2.057
			5	2.166	
Annex 2	1	Left	1	1.751	1.486
			2	1.585	1.535
			3	1.456	1.515
			4	1.663	1.486
			5	1.63	1.507
SH47A	1	Left	1	0.928	1.080
			2	0.901	1.075
			3	0.850	0.915
			4	0.863	0.913
			5	0.959	
	2	Left	1	1.129	
			2	1.159	
			3	1.083	
			4	1.160	
			5	1.331	
	1	Right	1	0.765	
			2	0.775	
			3	0.717	
			4	0.773	
			5	0.750	

Table C4. Computed IRIs from T6400 Profiler vs IRIs from Rod & Level (continued).

Site	Segment	Wheelpath	Run Number	IRI (mm/m)	
				T6400	Rod & Level
SH47A	2	Right	1	0.993	
			2	1.013	
			3	1.024	
			4	1.020	
			5	0.974	

Table C5. Computed IRIs from Construction Profiler vs IRIs from Rod & Level.

Site	Segment	Wheelpath	Run Number	IRI (mm/m)	
				CPR	Rod & Level
Annex 1	1	Left	1	2.315	2.114
			2	2.294	2.025
			3	2.341	2.072
			4		2.007
Annex 2	1	Left	1	1.372	1.392
			2	1.449	1.451
			3	1.370	1.402
			4		1.370
			5		1.417
SH47A	1	Left	1	0.913	1.086
			2	0.871	1.089
			3	0.875	0.923
			4		0.914
	2	Left	1	1.003	
			2	1.010	
			3	1.031	
	1	Right	1	0.835	
			2	0.822	
			3	0.813	
	2	Right	1	0.944	
			2	0.902	
			3	0.914	

Table C5. Computed IRIs from Construction Profiler vs IRIs from Rod & Level (continued).

Site	Segment	Wheelpath	Run Number	IRI (mm/m)	
				CPR	Rod & Level
SH47B	1	Left	1	0.921	
			2	0.856	
			3	0.822	
	2	Left	1	0.725	
			2	0.768	
			3	0.766	
	1	Right	1	0.798	
			2	0.816	
			3	0.818	
	2	Right	1	0.794	
			2	0.859	
			3	0.890	

Table C6. Computed IRIs from Laser Rut/Profiler (LRP) vs IRIs from Rod & Level.

Site	Segment	Wheelpath	Run Number	IRI (mm/m)	
				LRP	Rod & Level
Annex 1	1	Left	1	2.083	2.114
			2	1.953	2.025
			3	2.114	2.072
			4	2.055	2.007
		Right	1	2.335	
			2	2.490	
			3	2.364	
			4	2.340	
Annex 2	1	Left	1	1.324	1.392
			2	1.260	1.451
			3	1.310	1.402
			4		1.370
			5		1.417
		Right	1	1.416	
			2	1.320	
			3	1.376	
SH47A	1	Left	1	0.790	1.086
			2	0.757	1.089
			3	0.717	0.923
			4		0.914
	2	Left	1	1.021	
			2	1.001	
			3	0.957	

Table C6. Computed IRIs from Laser Rut/Profiler (LRP) vs IRIs from Rod & Level (continued).

Site	Segment	Wheelpath	Run Number	IRI (mm/m)	
				LRP	Rod & Level
SH47A	1	Right	1	0.778	
			2	0.786	
			3	0.831	
	2	Right	1	0.978	
			2	0.976	
			3	0.939	
SH47B	1	Left	1	0.878	
			2	0.942	
			3	0.861	
	2	Left	1	0.774	
			2	0.821	
			3	0.727	
	1	Right	1	0.859	
			2	0.811	
			3	0.829	
	2	Right	1	0.707	
			2	0.697	
			3	0.706	

Table C7. Computed IRIs from TxDOT's Surface Profiler (SP) vs IRIs from Rod & Level.

Site	Segment	Wheelpath	Run Number	IRI (mm/m)	
				SP	Rod & Level
Annex 1	1	Left	1	1.868	2.114
			2	1.883	2.025
			3	1.885	2.072
			4		2.007
		Right	1	2.436	
			2	2.668	
			3	2.557	
Annex 2	1	Left	1	1.431	1.392
			2	1.465	1.451
			3	1.520	1.402
			4	1.623	1.370
			5		1.417
		Right	1	1.512	
			2	1.525	
			3	1.512	
			4	1.512	
SH47A	1	Left	1	1.111	1.086
			2	1.103	1.089
			3	1.072	0.923
			4	1.078	0.914
	2	Left	1	1.415	
			2	1.395	
			3	1.356	
			4	1.345	

Table C7. Computed IRIs from TxDOT's Surface Profiler (SP) vs IRIs from Rod & Level (continued).

Site	Segment	Wheelpath	Run Number	IRI (mm/m)	
				SP	Rod & Level
SH47A	1	Right	1	0.971	
			2	1.057	
			3	0.981	
			4	1.070	
	2	Right	1	1.246	
			2	1.271	
			3	1.282	
			4	1.295	
SH47B	1	Left	1	0.763	
			2	0.742	
			3	0.800	
			4	0.720	
	2	Left	1	0.756	
			2	0.763	
			3	0.737	
			4	0.748	
	1	Right	1	0.798	
			2	0.764	
			3	0.770	
			4	0.757	
	2	Right	1	0.751	
			2	0.749	
			3	0.750	
			4	0.708	

APPENDIX D
SUGGESTED GUIDELINES FOR EVALUATING PAVEMENT PROFILERS

Presented in this appendix are suggested guidelines for evaluating pavement profilers to establish their acceptability for quality control and quality assurance of surface smoothness in pavement construction projects. The guidelines are drawn from the experience gained by researchers in evaluating profiling equipment in this research study.

Establishing Test Sections

To ensure that accurate, precise, uniform, and comparable profile measurements are obtained during construction, TxDOT should establish a facility for evaluating and certifying pavement profilers to be used on pavement construction projects. This facility should have at least two test sections which cover the range in surface smoothness of interest for pavement construction applications. Researchers recommend that each test section have a length equal to 161 m, the test interval used in the existing TxDOT smoothness specification. There should be sufficient lead-in to each section so that inertial profilers can reach the required operational speed, and the accelerometers can stabilize prior to the start of the section. A lead-in length of twice the cutoff wavelength is recommended. Sufficient distance must also be provided at the end of a test section for an inertial profiler to slow down and safely come to a complete stop.

The profiles on the test sections and the lead-ins should be measured on a regular basis with static methods such as the rod and level, Dipstick, and/or other suitable devices that provide true profiles and meet the resolution requirements of ASTM E 1364. This will establish reference profiles for evaluating surface profilers. It is noted that reference profile data on the lead-ins are required to evaluate the accuracy of data from inertial profilers.

As a minimum, reference elevations should be collected at 300 mm intervals, although a closer spacing, such as 150 mm, is preferred. It is noted that the rod and level data collected in this study to evaluate pavement profilers were measured at 152.4 mm intervals. Researchers recommend that each wheelpath be surveyed on the test sections and the lead-ins. In this way, if two test sections are established, there will be reference data available on four wheelpaths to evaluate inertial profilers. In addition, the profile data on the lead-ins will provide additional benchmark data for evaluating devices that give true profile.

For the purpose of establishing a reference to evaluate profile equipment, rod and level measurements should conform, as a minimum, to the requirements for a second order, Class II survey, established by the Federal Geodetic Control Committee (FGCC). Applicable provisions of this specification are given in Appendix E. Guidelines for field testing are also given by SHRP (1994). If devices that measure and integrate differential elevations are used to establish the reference profiles, rod and level measurements should be collected at certain intervals to verify and correct as necessary, the profiles measured with these other devices. As a minimum, the elevations at the beginning and at the end of a given wheelpath should be measured with the rod and level to verify profiles from devices that measure and integrate differential elevations to determine true profile.

Collecting Profile Data

Researchers recommend that the wheelpaths of the test sections and lead-ins be delineated to guide the equipment operator when measurements are made for the purpose of evaluating a given profiler. The interval between wheelpaths may be based on the distance between the lasers of the inertial profilers used by TxDOT. For example, the department's Laser Rut/Profiler and Surface Profiler have two lasers spaced at 1.65 m to provide profiles in both wheelpaths simultaneously. Three to five replicate runs should be made on each wheelpath following the prescribed direction of measurement. For inertial profilers, it is important to establish the beginning of the test section in the profile data so that repeat measurements may be lined up and compared with the reference profiles. In connection with this, some profilers have sensors that allow data collection to be triggered automatically at a prescribed location. For inertial profilers that do not have this feature, a plywood strip may be laid at a known location on the test wheelpath to insert a marker in the profile data for locating the beginning of the wheelpath or section.

Data from inertial profilers should be collected following the set of standard parameters used by TxDOT. This will require using the same filter and cutoff wavelength presently implemented in TxDOT's profilers. This filter, which is a second order Butterworth that is cascaded, should be made available to equipment developers. Using the same filter and cutoff wavelength will provide consistency between profile measurements made in conjunction with the smoothness specification, and those that are conducted as part of TxDOT's pavement condition surveys, sponsored research projects, field investigations, and other activities for which profiles are collected. In addition, researchers recommend a reporting interval of 150 mm or less and a resolution of 0.1 mm or finer for the reported elevations from a given inertial profiler. Many of the devices that are available already meet or exceed these requirements.

Analyzing Profile Data

The reference or benchmark profiles are used to evaluate the accuracy and repeatability of profiles from a given equipment. Since the reference profiles are true profiles, no filtering is necessary when evaluating devices that also provide estimates of the true profile. However, for evaluating inertial profilers, it will be necessary to filter the reference profiles to evaluate the accuracy of the data from these devices. For this purpose, the reference profiles measured on the lead-in and the test wheelpath must be filtered the same way as the profile data collected with a given inertial profiler. Consistent with the recommendation given previously, this filter should be the second order, cascaded Butterworth filter. In addition, for the purpose of evaluating profile accuracy as described herein, the lead-in should be twice the cutoff wavelength and the reference profile over this length should be established as suggested previously.

To evaluate the accuracy of the test profiles from a given equipment, the profiles should be synchronized, as need be, so that the interval between reported elevations is the same as the interval between points in the reference profiles. This synchronization of the test data should be accomplished using a method that preserves the frequency content of the original data. The test data and reference profiles are also aligned with respect to the beginning of the section or wheelpath. To evaluate accuracy, the average of the synchronized profiles from the given equipment, as well as the average of the reference profiles are determined. Following ASTM E 950, this is accomplished by computing the mean of the elevations from replicate runs on a point-by-point basis. The average synchronized profile from a given equipment is then compared with the corresponding average reference profile.

Specifically, differences in elevations are computed, point-by-point. The average of these discrepancies as well as the average of the absolute discrepancies are then determined.

The average discrepancy is a measure of the bias in the data from a given profiler. It indicates the presence of consistent or systematic differences between a given profile and the reference profile. The closer this statistic is to zero, the smaller the bias in the profile measurements relative to the reference used. ASTM E 950 specifies the following requirements for equipment bias:

Equipment Classification	Bias (mm)
1	≤ 1.25
2	Above 1.25 and ≤ 2.50
3	Above 2.50 and ≤ 6.25

From analysis of the accuracy of the pavement profilers evaluated in this study, the above requirements are rather lenient and do not provide enough differentiation. If the above requirements are used, all of the inertial profilers classify as Class 1, as noted in Chapter II. There are also no corresponding specifications on the average of the absolute discrepancies. This statistic is a measure of how well the test data from a given profiler matches the reference profile. Note that the bias and average of the absolute discrepancies are different measures. A profile may not match the reference very well but still show no bias if the differences cancel out, i.e., are not consistent or systematic. Likewise, a profile may be very accurate, in terms of the average absolute discrepancy, but show a discernible bias. Consequently, it is necessary to consider these two statistics when evaluating the point-to-point accuracy of pavement profiles. In this regard, researchers propose the rating system based on Table D1 to quantify the accuracy of profiles from inertial profilers. In this system, the absolute value of the average discrepancy, μ_1, and the average of the absolute discrepancies, μ_2, are used with Table D1 to arrive at a score for the accuracy of the profile data measured on a given wheelpath. This is done for each wheelpath tested. The average of the scores obtained for a given profiler is then used as a measure of its accuracy. The higher the average score, the better the accuracy of pavement profiles from a given profiler relative to the reference profiles. If the proposed rating system is used with the statistics computed for the different inertial profilers

Table D1. Proposed Scoring Scheme to Evaluate Accuracy of Inertial Profilers.[1]

Average of Absolute Discrepancies, μ_2 (mm)	Absolute Value of Average Discrepancy, μ_1 (mm)				
	≤ 0.10	$0.10 < \mu_1 \leq 0.15$	$0.15 < \mu_1 \leq 0.30$	$0.30 < \mu_1 \leq 0.50$	$0.50 < \mu_1 \leq 0.80$
≤ 1.0	100	95	90	85	80
$1.0 < \mu_2 \leq 1.5$	95	90	85	80	75
$1.5 < \mu_2 \leq 2.0$	90	85	80	75	70
$2.0 < \mu_2 \leq 3.0$	85	80	75	70	65
$3.0 < \mu_2 \leq 4.0$	80	75	70	65	60

[1] No score is earned for $\mu_1 > 0.80$ mm or $\mu_2 > 4.0$ mm.

evaluated in this study (given in Table 14 of Chapter II), the average scores shown in Table D2 are obtained. The average of the scores determined for the different wheelpaths tested may be used to rank the accuracy of the different profilers relative to the reference profiles used. Researchers recognize that the rating scheme illustrated may undergo changes as more data become available from operation of the test facility proposed in this report. However, the concept of using a rating system with the absolute average discrepancy (μ_1), and the average of the absolute discrepancies (μ_2) as criteria, provides a rational basis for evaluating the accuracy of profiling equipment. In reporting the accuracy of a given profiler, researchers recommend that the statistics, μ_1 and μ_2, be reported along with the scores obtained to identify where a given profiler needs improvement.

In addition to accuracy, the repeatability of pavement profiles needs to be evaluated. This evaluation is done on the same profiles used to determine equipment accuracy. For this purpose, the standard deviation of the measured elevations from repeat measurements is calculated at each reporting location. The average of the computed standard deviations is then compared to the corresponding statistic determined from the reference profiles to evaluate equipment repeatability. This is different from the requirements specified in ASTM E 950 where the repeatability of inertial profilers is established using absolute criteria on the average of the standard deviations of elevation measurements from repeat runs. In that

Table D2. Illustration of Proposed Rating System to Evaluate Accuracy of Inertial Profilers.

Profiler	Site	Average Discrepancy (mm)	Average of Absolute Discrepancies, μ_2 (mm)	μ_1	Score	Average Score
LISA	Annex 1	0.1170	1.1627	0.1170	90	83
	Annex 2	0.6062	2.3803	0.6062	65	
	SH47A	0.0156	1.2382	0.0156	95	
T6400	Annex 1	0.0079	2.4787	0.0079	85	87
	Annex 2	0.3843	1.8495	0.3843	75	
	SH47A	-0.0327	0.9126	0.0327	100	
CPR	Annex 1	-0.0700	1.3183	0.0700	95	95
	Annex 2	0.1478	1.4391	0.1478	90	
	SH47A	-0.0404	0.7826	0.0404	100	
LRP	Annex 1	-0.0591	0.7123	0.0591	100	98
	Annex 2	0.0510	1.1062	0.0510	95	
	SH47A	-0.0758	0.6841	0.0758	100	
SP	Annex 1	-0.0047	0.7916	0.0047	100	98
	Annex 2	0.0627	1.2133	0.0627	95	
	SH47A	-0.0542	0.6782	0.0542	100	

specification, an inertial profiler is classified based on repeatability according to the following criteria:

Equipment Classification	Average Standard Deviation (mm)
1	≤ 0.38
2	Above 0.38 and ≤ 0.76
3	Above 0.76 and ≤ 2.50

In the procedure proposed, repeatability is established based on the reference profiles measured on the test wheelpaths. Specifically, the average of the standard deviations for a given profiler, denoted by σ_p, is divided by the corresponding statistic for the reference profiles, denoted by σ_0. This ratio is used with Table D3 to establish a score for the repeatability of the test data on a given wheelpath. The average of the scores determined for different wheelpaths tested is computed to establish the repeatability of a given profiler. If this scheme is used with the statistics shown in Table 5 (Chapter II) to establish the repeatability of the different profilers evaluated in this study, the results shown in Table D4 are obtained. It is observed that the scores are generally better for the smooth pavement where all profilers earned scores. Thus, the results may be used to establish the range of application of a given profiler. In this regard, Table D4 indicates that the van-mounted inertial profilers demonstrated better repeatability than their lightweight inertial counterparts for the full range of roughness considered in the equipment evaluation. This demonstrates the importance of testing profilers over the range of roughness of interest to highway engineers. Consequently, in reporting the results of the repeatability test, researchers recommend that the ride statistic (e.g., IRI or Present Serviceability Index) of the test wheelpath, be reported along with the corresponding averages of the standard deviations, σ_p, and σ_0, their ratio, and the score corresponding to this ratio.

The average score obtained based on repeatability can be combined with the corresponding average score based on accuracy to get a composite rating for a given profiler. In this regard, the overall average of the scores may be computed, as illustrated in Table D5. In this way, an overall rating reflecting both the accuracy and repeatability of a given profiler is determined.

Table D3. Proposed Scoring Scheme to Evaluate Repeatability of Pavement Profilers.

Ratio of Average Standard Deviations, σ_p/σ_0	Score
< 0.5	105
$0.5 \leq \sigma_p/\sigma_0 < 1.0$	100
$1.0 \leq \sigma_p/\sigma_0 < 1.5$	95
$1.5 \leq \sigma_p/\sigma_0 < 2.0$	90
$2.0 \leq \sigma_p/\sigma_0 < 2.5$	85
$2.5 \leq \sigma_p/\sigma_0 < 3.0$	80
$3.0 \leq \sigma_p/\sigma_0 < 3.5$	75
$3.5 \leq \sigma_p/\sigma_0 < 4.0$	70
$4.0 \leq \sigma_p/\sigma_0 < 4.5$	65
$4.5 \leq \sigma_p/\sigma_0 < 5.0$	60
≥ 5.0	No score earned

Table D4. Illustration of Proposed Rating System to Evaluate Repeatability of Profilers.

Profiler	Site	Average Standard Deviation (mm)		σ_p/σ_0	Score[1]	Average Score[1]
		Profiler	Rod and Level			
	Annex 1	8.1339	1.1668	6.97	—	
CSC	Annex 2	9.6013	0.7979	12.03	—	—
	SH47A	3.9057	1.1332	3.45	75	
	Annex 1	0.7729	1.1668	0.66	100	
WPR	Annex 2	1.6123	0.7979	2.02	85	93
	SH47A	1.2311	1.1332	1.09	95	
	Annex 1	1.4962	0.3601	4.15	65	
LISA	Annex 2	1.0068	0.3028	3.32	75	77
	SH47A	0.8027	0.4097	1.96	90	
	Annex 1	3.4940	0.3826	9.13	—	
K. J. Law	Annex 2	5.1029	0.3477	14.68	—	—
	SH47A	1.7704	0.4361	4.06	65	
	Annex 1	0.8263	0.3998	2.07	85	
CPR	Annex 2	0.9357	0.3676	2.55	80	83
	SH47A	0.9358	0.4552	2.06	85	
	Annex 1	1.1474	0.3995	2.87	80	
LRP	Annex 2	0.6873	0.3648	1.88	90	90
	SH47A	0.4368	0.4518	0.97	100	
	Annex 1	0.5071	0.3995	1.27	95	
SP	Annex 2	0.3316	0.3648	0.91	100	98
	SH47A	0.3183	0.4518	0.70	100	

[1] No score is earned for $\sigma_p/\sigma_0 \geq 5$.

Table D5. Composite Rating of Inertial Profilers Based on Accuracy and Repeatability.

Profiler	Average Score		Composite Score
	Accuracy	Repeatability	
LISA	83	77	80
T6400	87	—	—
CPR	95	83	89
LRP	98	90	94
SP	98	98	98

Finally, researchers recommend that the summary smoothness statistic reported by a given profiler be verified simply by using the profiles obtained with the agency's computer program to determine the summary ride statistic from pavement profile. The summary ride statistic reported by the given profiler should match the statistic determined from the agency's algorithm or computer program. Otherwise, there is a potential problem with the profiler's algorithm to compute the ride statistic.

APPENDIX E

PROPOSED REQUIREMENTS FOR ESTABLISHING REFERENCE DATA TO EVALUATE PAVEMENT PROFILERS USING ROD AND LEVEL

Presented in this appendix are proposed requirements for conducting rod and level measurements for the purpose of establishing reference data to evaluate pavement profilers. These requirements are included in Section 3.5 of the FGCC specifications on Geodetic Leveling. They are intended to supplement the guidelines established by SHRP (1994). Applicable provisions of the FGCC specifications are presented in the following.

Instrumentation

A. Leveling Instrument

1. Minimum repeatability of line of sight - 0.5 seconds (0.5"). For electronic digital/bar-code leveling systems, the requirement is 0.8".
2. Leveling rod construction - Invar, Single Scale. Invar has a very low coefficient of thermal expansion which minimizes changes in length due to temperature changes. This requirement is particularly important when the rod and level survey is to be made over a period of time during which air temperatures are expected to vary over a significant range.
3. Combined Instrument and Rod Resolution - least count of 1.0 mm. For electronic digital/bar-code leveling systems, the requirement is 0.1 mm. The resolution must be fine enough to permit proper statistical analysis of the data.

Calibration Procedures

A. Leveling Instrument

1. Maximum collimation error, single line of sight - 0.05 mm/m. Collimation error is associated with the line of sight of the instrument being off-level when the instrument is properly leveled.
2. Maximum collimation error, reversible compensator-type instruments, mean of two lines of sight - 0.02 mm/m.
3. Time interval between collimation error determinations - not longer than 7 days for reversible compensator; for other types, collimation error determinations must be made daily.

4. Maximum angular difference between two lines of sight, reversible compensator - 40".

B. Leveling Rod

1. Minimum scale calibration standard - according to manufacturer.
2. Leveling rod bubble verticality maintained to within 10 minutes (10').

Field Procedures

A. Difference of forward and backward sight lengths

1. ≤ 10 m per setup
2. ≤ 10 m per section

Differences in backsight and foresight distances should be closely observed. Many of the systematic errors present in leveling are minimized when these differences are reduced.

B. Maximum sight length - 70 m unless manufacturer recommends one that is less. The requirement on maximum sight length helps to minimize errors due to refraction of the line of sight through air, and ensures that the rod can be read correctly.

C. Minimum ground clearance of line of sight - 0.5 m. This requirement is established to ensure that the line of sight does not pass through the layer of air close to the ground. Significant refraction can result under certain atmospheric conditions.